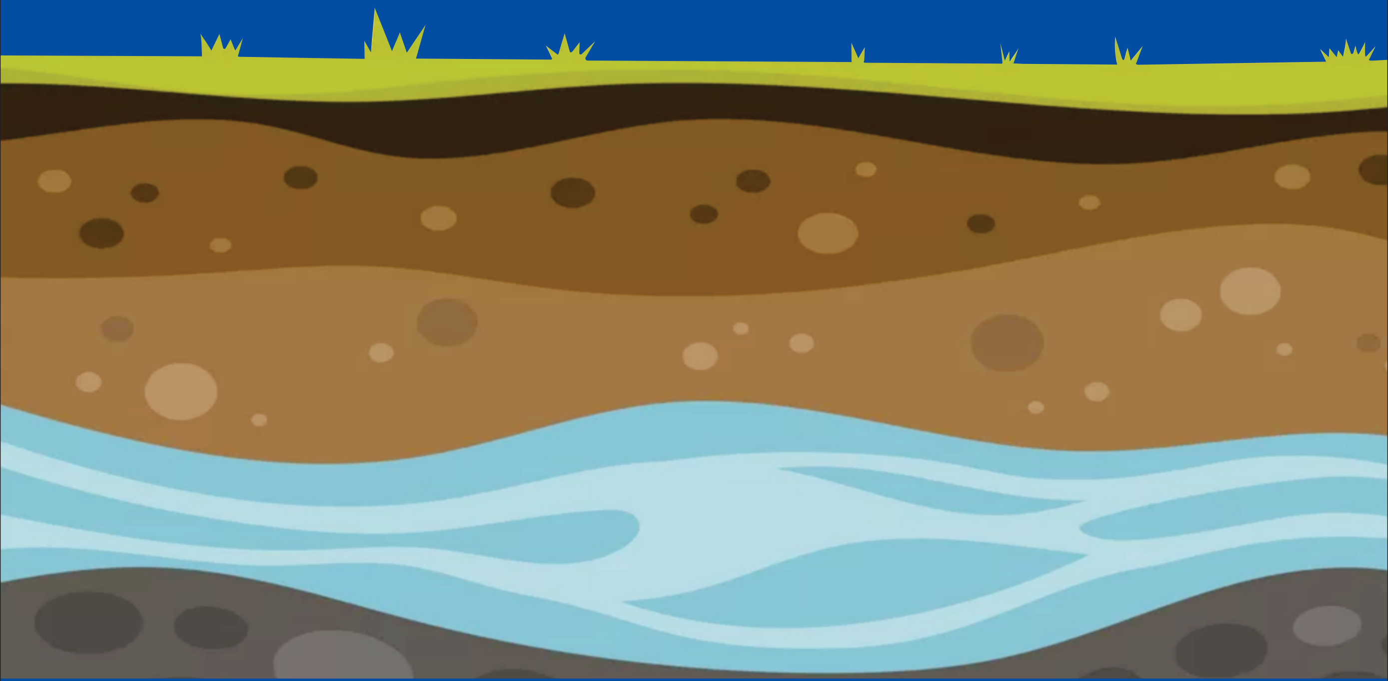
10th INTERNATIONAL GROUNDWATER CONFERENCE

Groundwater Vision 2047

Towards Water Security under Changing Climate

March 05-07, 2025, NIH Roorkee, India



Editors

Santosh Murlidhar Pingale
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Organized by

National Institute of Hydrology, Roorkee, India

in association with

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National Mission for Clean Ganga, India

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Hochschule für Technik und Wirtschaft Dresden, Germany

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Groundwater Vision 2047
Towards Water Security under Changing Climate

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Preface

Groundwater is a vital natural resource with significant economic, strategic and environmental value. However, it is under stress in many regions worldwide due to increasing urbanization, industrialization, changing climatic, increased demands and other human-driven activities. The depletion of groundwater levels and the deterioration of water quality are particularly concerning issues in numerous areas. To address these challenges, effective groundwater resource management strategies must be developed to reverse the decline in water quality and depleting water levels, ensuring the sustainability of this precious yet limited resource. Currently, India stands as the world's largest and fastest-growing consumer of groundwater. Groundwater is a crucial resource, integral to life and indispensable for comprehensive growth and development of the country in achieving its holistic vision of a developed nation by 2047, the 100th year of its independence.

The International Groundwater Conference 2025, is centered around the main theme "Groundwater Vision 2047: Towards Water Security under Changing Climate". The conference will cover a wide range of topics including groundwater assessment, management and modelling under varied climatic and geological settings; agriculture water management; climate change; environmental flows and river rejuvenation; mountain hydrology and spring-shed management; coastal water resources management; and advanced techniques in groundwater monitoring, management and exploration, etc. The issues are of significant concern to India and are critical for policy makers, water managers and researchers in the country. The overarching theme aligns with India's vision for sustainable and inclusive growth through a multipronged strategy aimed at eradicating poverty by increasing livelihood opportunities, providing social safety net and developing infrastructure for growth, for which sustainable groundwater management is essential.

Researchers from both developed and developing nations are working on various facets of groundwater, such as advancing tools and techniques for monitoring resources, sub-surface characterization, aquifer mapping and modeling, and crafting effective management policies. The IGWC 2025 aims to unite scientists, researchers, planners, policymakers, engineers, water resource managers, students, NGOs, and other stakeholders in the groundwater and environmental sectors. The event will provide a platform for exchanging ideas, knowledge, experiences, techniques, and expertise, offering an opportunity to present research findings, discuss challenges, and explore scientific advancements in water resources development and management under the influence of climate change. The focus is on ensuring a water-secure future and promoting sustainable development, with special emphasis on groundwater.

IGWC 2025 is organized by the National Institute of Hydrology (NIH), Roorkee in association with the Central Ground Water Board, New Delhi, India; Association of Global Groundwater Scientists (AGGS), Coimbatore, India; National Mission for Clean Ganga (NMCG), New Delhi, India; National River Conservation Directorate (NRCD), New Delhi, India; British Geological Survey (BGS), United Kingdom; Hochschule für Technik und

Wirtschaft (HTWD) Dresden, Germany and KTH-Royal Institute of Technology, Stockholm, Sweden.

Focusing on the latest research and technological advancements from around the world, IGWC 2025 aims to deliver meaningful outcomes and offer a vision for 2047 to safeguard groundwater resources, not only in India but globally. This Proceedings Volume includes 41 abstracts from keynote speakers and 311 abstracts from delegates and experts, both from India and abroad. We hope that the research abstracts in this Volume will lead to practical recommendations for developing a framework to implement various programs and initiatives by both government and non-government organizations working in the water sector in general and groundwater in particular.

Our sincere and heartfelt gratitude to the Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, Government of India, for providing administrative and financial support in the successful organization of IGWC 2025. We are profoundly thankful to all the authors, reviewers, and sponsors, who have been instrumental in the development and printing of this Proceedings Volume.

Editors

About the IGWC Series

Groundwater has emerged as a major resource in safeguarding agriculture and drinking water security in many parts of the globe. However, groundwater depletion, contamination, and governance challenges continue to persist despite decades of groundwater research. Searching solutions for the conservation and sustainable management of groundwater is likely to play a crucial role in meeting the water demands of the population in future, under a changing climate and to ensure food and water security for both the developed and developing nations. Keeping in view the significance of groundwater in the economic growth and development of a country, a series of International Conferences on Groundwater are being organised regularly by the Association of the Global Groundwater Scientists (AGGS) in collaboration with other academic and research organizations, to deliberate on various issues related to groundwater including the recent advances in groundwater research. A total of 09 such conferences have been organised so far including the recent ones in 2012, 2015, 2017, 2019 and 2022. The present conference (IGWC 2025) is the 10th such conference in this series which is being organised at the National Institute of Hydrology, Roorkee, during 5th to 7th March, 2025.

The key issues and challenges expected in groundwater management are needed to be clearly identified and framework for systematic and scientific research needs to be determined from time to time with formulation of specific and pinpointed recommendations for future work. The international conferences in IGWC series have served as the meeting points for groundwater experts and professionals, for this purpose. Therefore, the aim of IGWC 2025 also is to provide a common platform for researchers, academicians, policy makers, water managers, technocrats, industrialists and NGO's, to discuss and deliberate on the current groundwater issues as well as Groundwater Vision 2047, in the face of growing challenges of the needs of rising population and confronting climate uncertainties in water resources planning and management.

During the conference the implications of this perspective on data collection, scientific investigations, governance, and management are also expected to be discussed at length, with a motivation to highlight a wider, complex, interdisciplinary, and systems approach to groundwater assessment and management. It is intended and hoped that a suite of new (or existing but underutilized) concepts and interdisciplinary and transdisciplinary methodologies would emerge out of the deliberations, to aid and promote transformations towards sustainability and resilience of the groundwater systems.

Looking at the aforementioned aspects, the themes of the conference have been identified as:

1. Vision 2047: Impact of Climate Change on Groundwater & Adaptation Measures
2. Vision 2047: Environmental Flow and Rejuvenation of River Ganga
3. Vision 2047: Mountain Hydrology & Springshed Management
4. Water Resources in Arid & Semi-Arid Regions
5. Groundwater Contamination and Remediation
6. Groundwater Modeling and Management

7. Advanced Techniques for GW Exploration & Assessment
8. Augmentation of Groundwater Resources
9. Coastal Water Resources Management
10. Policy, Regulation, Governance & Community Participation for Groundwater Management
11. Application of AI, ML, IoT, Cloud Computing & Other Advanced Techniques
12. Vadose Zone Hydrology and Agriculture Water Management
13. Protection of Groundwater Dependent Ecosystems
14. Isotopic Techniques in Groundwater Investigations & Management

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KEYNOTES

USING GROUNDWATER TO ADAPT TO CLIMATE CHANGE AND INCREASE WATER SECURITY

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From the earliest times, the use of groundwater has been critical for human life and sustaining and growing livelihoods. Access to groundwater has solved many water security issues through the centuries, and since the second half of the 20th century has helped underpin growth in many countries. In this 21st century, there are new challenges to contend with. Human influence has increased the chance of compound extreme climate events with more frequent and intense heatwaves, droughts and heavy precipitation. With every increment of global warming, changes in extremes and the associated risks and impacts will escalate, becoming increasingly complex and difficult to manage. With this growing variability and uncertainty in both the volume and timing of precipitation, demand for groundwater is increasing rapidly with half the earth's population now dependant on groundwater for their drinking water. Groundwater resources are already being used by households, farmers, industry and municipalities to adapt to increases in weather variability and further changes in climate are likely to increase the use of groundwater for adaptation. This poses the question - how resilient is groundwater to climate change? Will it continue to provide the water security required by households, cities and nations? There are three factors that help determine intrinsic groundwater resource resilience: aquifer storage volume, transmissivity (permeability) and long-term recharge.

Groundwater in larger aquifer systems have long residence times and response times, meaning that their large natural storage can buffer short term changes in climate, while low storage aquifers which provide good yields in normal years, can begin to suffer in droughts if demand is high. With changes in the modality of precipitation, thinking of groundwater recharge over the long term becomes more important recharge may not occur every year, but become more episodic. Other sources of recharge, for example from rivers, and canals can also increase the resilience of a groundwater system to change but are rarely accounted. Finally, how easily groundwater flows within the aquifer (transmissivity), is often a controlling factor on whether individual wells and tubewells dry up during a drought period – there can be groundwater within the aquifer, but the cone of depression around the individual tubewell reduces the flow from the aquifer to the pump. These three intrinsic factors, combined with the anthropogenic forcing of water demand and pollution, help to characterise and forecast how groundwater can support adaptation to climate change and provide increased water security.

Within India, groundwater is used extensively to buffer existing climate variability, and the aquifer conditions markedly influence water security. The Indo-Gangetic Basin Aquifer is one of the most productive aquifers in the world and is marked by its large storage and active recharge. Therefore, with some notable exceptions, it has largely been able to cope with the high demands put on it by the >10 million tube wells. The high permeability of the aquifer also means that the yield of individual tube wells changes little from season to season, and only tube wells in areas suffering long term depletion are subject to declining yields. Long term recharge to the aquifer system is highly complex and can be contested. Recharge from rainfall is more or less predictable, and dependent on the Indian Monsoon, however river flow (mostly indirectly through canal leakage) is likely to provide much of the long-term groundwater recharge, particularly in less humid areas. This spatially and temporally dynamic for groundwater recharge is impacted by climate change: directly through changes to the Indian Monsoon; indirectly through glacial melt and river flow; and management of reservoirs and canal irrigation. In contrast, the low storage crystalline aquifers of Peninsular India offer much less resilience to climate change, rendering groundwater a risky solution to water insecurity. Long term monitoring in the Cauvery Catchment has shown that groundwater levels can progressively decline due to high demand, which depletes the more productive parts of the aquifer, resulting in tubewells which have lower yields, and some shallow sources drying up altogether. Occasional heavy monsoon seasons can replenish the aquifers, meaning that long-term depletion is less of an issue, however the aquifers are more susceptible to short term drought. Drilling deeper here is rarely the answer, as the aquifers become less productive and have less storage capacity at depth. The widespread use of managed aquifer recharge may impact highly localised water security, but there is little evidence that it makes a regional impact here. So, can groundwater be managed to help adapt to climate change and increase water security? Firstly, it is important to know how much is being used and by whom. For e.g., recent research is showing that many urban dwellers in the world have access to groundwater as a backup for when a municipal system fails, but this groundwater use is rarely recorded. Then, 3D knowledge and mapping of aquifers, and monitoring of groundwater dynamics and trajectories helps identify where the opportunities for groundwater development are, and where boundaries are at threat of being exceeded, or may already have been surpassed. But this knowledge alone will not effect change. A deep and nuanced understanding of the science-policy-practice framework is required to help effect change that will be long lasting including an understanding of what makes groundwater knowledge useful, usable and accepted.

Keywords: *Water security, climate change, groundwater, aquifers, groundwater dynamics*

SOIL AQUIFER TREATMENT: PROCESS OPTIMIZATION AND ALTERNATIVE APPROACHES

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Sustainable irrigation with treated wastewater is a well-established solution for water scarcity in arid and semi-arid regions. Soil aquifer treatment (SAT) provides a solution for both the need for tertiary treatment of the wastewater to make it suitable for a wide range of crops and the seasonal storage of wastewater. However, stresses over land resources and the need to control the obtained water quality make the optimization of SAT of great importance. This study presents SAT activities at the SHAFDAN site in Israel and their advantages and limitations. The main focus is on hydraulic process optimization, which is conducted using a combination of laboratory experiments and a numerical model. In addition, several studies that look at different approaches to enhance the hydraulic efficiency and capacity of SAT facilities have also been explored. These include Ag-SAT, in which agricultural plots are considered a supplementary venue for the conventional infiltration ponds, and Air-SAT, in which air is actively injected into the subsurface to enhance aerobic processes and eliminate the needed drying time. The preliminary results of a pilot study are presented using Air-SAT. A long (6 m) column experiment was carried out to examine the effects of different flooding/drying period ratios on dissolved oxygen (DO) concentrations, oxidation-reduction potential (ORP), and outflow composition. Flooding periods were kept constant at 60 min for all experiments, while drying periods (DPs) were 2.5 and 4 times the duration of the flooding periods. The results show that the longer DPs had a significant advantage over the shorter periods in terms of DO concentrations and ORP in the upper parts of the column and the deeper parts, which indicates that larger volumes of the profile could maintain aerobic conditions. The experimental results were, then, used to calibrate a flow and transport model that considers many reactions using the ulti-Monod approach. Using the calibrated model, we have identified an optimal operation that maximizes water quality according to the system demand. While those results still need to be verified at full scale, they suggest that SAT can be treated as a pseudo-reactor that, to a great extent, could be manipulated hydraulically to achieve the desired water quality while increasing the recharge volumes. The Ag-SAT study presents a new approach to winter recharge through non-dormant orchards. The challenge here is triple viz. to maximize recharge while maintaining wastewater quality and preventing crop damage. In a preliminary experimental study, the satisfactory results are obtained for up to three concessive days of flooding in a month. The Ag-SAT approach can easily duplicate the recharge volumes in Israel. Nevertheless, a techno-economic analysis and significant regulations need to be developed before the approach can be applied on a larger scale. The Air-SAT study explored the ability to maintain high water quality over continuous infiltration using 1 hr per day. The experimental results suggest that not only is the water quality maintained, but the recharge quantity is doubled and even tripled. This is likely because the air streams mechanically cultivate the soil, practically preventing natural clogging of the soil surface. The most efficient SAT process can be further developed reaching higher hydraulic efficiency and water quality.

Keywords: *Ag-SAT, soil aquifer treatment, water conservation, water quality*

EMERGING APPROACHES TO PROTECT AND MANAGE COASTAL GROUNDWATER RESOURCES

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Groundwater resources along the coastline are vital for managing ecosystems, economic growth, and coastal populations. These resources are increasingly under threat due to rise in sea levels, challenges posed by growing populations and climate change-driven alterations in recharge patterns. The declining groundwater table caused by over-extraction of groundwater, coupled with rising sea levels, has led to the salinization of coastal groundwater resources. The problem not only impacts the fresh water availability, but also endangers coastal ecosystems. To address these pressing challenges and ensure the long-term sustainability of coastal groundwater resources, innovative scientific approaches and engineering solutions are crucial. Recent advancements in coastal groundwater management integrate numerical modeling approaches, real-time in-situ monitoring, and sustainable engineering interventions. This keynote talk explores the advancements in groundwater resource management driven by scientific research and different engineering innovations. Emerging techniques such as the characterization of submarine groundwater discharge (SGD) zones, numerical simulations for seawater intrusion behavior, hydrogeological investigations, and the implementation of managed aquifer recharge (MAR) with subsurface barriers to protect coastal aquifers are the focus of this talk.

For instance, accurate assessment of SGD zones provides valuable insights into the groundwater and seawater interface. Unmanaged extraction of groundwater resources in coastal areas may lead to the loss of these SGD zones, creating pathways for seawater intrusion. Therefore, characterization and monitoring of these zones are crucial for coastal groundwater management. SGD zones can act as conduits for contaminants reaching the sea, posing risks to coastal ecosystems. Continuous qualitative monitoring of these zones is crucial for protecting marine environments. Further, identifying high- and low-discharge zones aids in strategically allocating extraction and recharge wells to enhance freshwater availability. In recent times, MAR has emerged as a promising technique to enhance the sustainability of aquifers and to mitigate seawater ingress in coastal regions. The method involves the artificial replenishment of groundwater storage through approaches such as infiltration basins and injection wells. By increasing freshwater availability, MAR not only counters the effect of seawater intrusion but also improves groundwater quality and strengthens overall water security. Moreover, a key subset of MAR, aquifer storage and recovery (ASR), is particularly relevant for coastal regions, as it addresses water scarcity by storing surplus freshwater in underground aquifers for later use, especially during dry periods or peak demand. However, factors such as storage duration and the length of time for which water remains in the aquifer, must be carefully evaluated to minimize water loss due to mixing with saline groundwater, geochemical reactions, or potential leakage. Proper assessment of storage conditions ensures ASR effectiveness in maintaining water quality and optimizing recovery efficiency. Similarly, advanced modeling tools aid in the assessment of freshwater storage conditions in the coastal field by solving density dependent flow equations numerically. These tools are crucial in understanding and optimizing MAR techniques and enable researchers to simulate the behavior of stored freshwater within coastal aquifer systems. These help in assessing the impacts of various operational factors, such as groundwater flow dynamics and solute transport. Modeling helps predict the efficiency of freshwater recovery under different scenarios, optimizing MAR system performance. By selecting the relevant operational parameters like- the volume of water injected in each cycle, the frequency of recharge cycle, storage duration etc., the performance of MAR can be sustainably enhanced. Thorough multidimensional modeling and careful consideration of operational factors are key to the successful implementation of the MAR technique in the interacting fresh and saline water zones.

Apart from these technical approaches, the integration of multidisciplinary approaches, including policy frameworks and community-based conservation efforts, is essential for sustainable coastal groundwater management. To ensure long-term resilience, an integrated strategy must encompass regulatory measures, technological innovations, nature-based solutions and active community participation. Developing comprehensive water management policies, enforcing extraction limits, and implementing regulatory frameworks are critical steps in preventing groundwater overexploitation in coastal regions. Technological advancements, such as density dependent modeling of sea water intrusion, real-time monitoring of SGD quantity and quality, can further enhance predictive capabilities for optimizing coastal groundwater uses. Public awareness and community engagement are equally important, as educating locals about sustainable water practices and involving stakeholders in decision-making processes can lead to more effective management. Thus, by integrating these strategies, coastal groundwater management can become more resilient and adaptive, addressing the increasing pressures of climate change, population growth, and rising water demand. These advancements provide a sustainable roadmap for protecting coastal aquifers, ensuring long-term water security for densely polluted regions, and safeguarding ecosystems that rely on these critical freshwater resources.

Keywords: *Coastal aquifers, sea water intrusion, submarine groundwater discharge, numerical modeling, managed aquifer recharge*

ROADMAP OF HYDROLOGY RESEARCH FOR DEVELOPED INDIA: VISION 2047

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On top of the ongoing challenges in meeting ever increasing water demand for growing population and socio-economic prosperity of India, there is a more daunting challenge of dealing with uncertainties about hydrological response to ongoing climate change as well as, to the engineered interventions made by us over the past decades, and to the natural variability on which we have no control. To deal with the emerging hydrological disasters with increasing frequency of occurrence and magnitude of devastation, it is essential to have a well-informed planning, and resolute decision making, based on dependable scientific understanding about causalities of and consequences of adaptation strategies. The new scientific understanding is expected to arise through hydrology research, but how do we assure that the direction of current hydrology research is appropriate so as to generate the desired new scientific knowledge. For this, it is essential to have an updated framework to assess and calibrate our research endeavors, ongoing or proposed, and individual or collective. Using this framework of recent findings, one can independently evaluate significance of one's own research ideas. These recent findings also provide a catalogue of knowledge gaps for us to assess if particular research will be able to fill any of these gaps meaningfully, and if any revision of research objectives is needed.

There are enough recent research findings to convey that hydrological cycle is turning out to be increasingly more complex, as newer linkages and patterns are identified. These recent findings are actually counterintuitive and to a certain extent contrary to the understanding hitherto. Various components of coupled ocean-land-atmosphere system, forming the hydrological cycle, are amazingly interconnected in a manner that was not thought before. These recent findings have posed newer scientific questions and uncovered newer knowledge gaps for researchers to deal with.

Some of the most important research findings which have advanced the fundamental understanding about hydrological cycle in the recent past are: (1) Groundwater extraction contributes to the sea level rise, increasing the risk of groundwater inundation in coastal areas. Role of groundwater in the global water cycle is more dynamic and complex than thought so far, (2) Moisture transport from oceans to India has significantly increased during 1951–2020 due to strengthening of winds, and seven of India's ten most severe floods in the summer monsoon season with substantial mortality were associated with atmospheric rivers, (3) During 2000–2019, the glacier loss in High Mountain Area (HMA) of Asia accounted for about 19% of the global glacier mass loss of 267 ± 16 Gt per year, resulting in a decline in Terrestrial Water Storage in HMA, reducing water availability and exacerbating water stress in the Indus and Brahmaputra River basins, (4) Indian summer monsoon rainfall trend reversals are not uniform across space and time. North-South and East-West polarity in rainfall trend reversals is observed around 1930s, 1960s, and 1980s, (5) Southern Hemisphere has dominated the declining trend in global water availability from 2001 to 2020 while there is negligible trend in Northern Hemisphere due to regional increase balanced by decrease, (6) Forty-one high-altitude lakes appeared in the eastern Himalayan region alone, during the past 50 years and the existing lakes have undergone 50% expansion. The lake area in the eastern Himalayan region has rapidly expanded, at a rate of 14.44 km^2/yr between 1976 and 2018. This may lead to increase in the number, extent, and impacts of lake-breaching events in the Himalayas in the near future, (7) On an annual basis, ~41% (~ 2 BCM) of replenishable groundwater is estimated to be drained as SGD into the Arabian Sea along the coastal Kerala, (8) Sub-glacial groundwater below Antarctic ice-sheet affects the ice motion through “hard-bed” and “soft-bed” sliding, and controls the Antarctica’s ice-sheet dynamics and its contribution to sea level rise, (9) Total river runoff, glacier melt, and seasonality of flow are projected to increase in the Himalayan-Karakoram Region (HKR) until the 2050s and then decrease (with some exceptions and large uncertainties). With largest irrigated area (~577,000 km^2) and the largest installed hydropower capacity (~26,000 MW) worldwide in this region, the reversal of directionality of glacio-hydrological change and its uncertainty is a cause of concern, (10) Northern Hemisphere cooling by ice sheet albedo drives a monsoonal retreat across Africa and the Arabian Peninsula - a response that triggers a weakening of the Indian monsoon via cooling of the Arabian Sea and associated reductions in moisture supply, and (11) Indian monsoon is indeed expanding to the west, and mean rainfall over the semi-arid northwest parts of India and Pakistan has increased by 10%–50% during 1901–2015 and is expected to increase by 50%–200% under moderate greenhouse gas (GHG) scenarios of SSP2–4.5 (i.e. Shared Socio-economic Pathway with radiative forcing target of 4.5 w/m^2).

In line with the above scientific understanding, and taking cognizance of Indian water resource scenario, some of the representative hydrological problems have been identified to invite the attention of researchers of India, so that these can be addressed collaboratively in a concerted manner.

Keywords: *Hydrology, Vision 2047, coastal aquifers, submarine groundwater discharge, groundwater*

MACHINE LEARNING FOR GROUNDWATER LEVEL PREDICTION USING FIELD GRAVITY DATA: A NOVEL APPROACH

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Groundwater is a vital natural resource that plays a crucial role in drinking water supply, agriculture, and industrial applications. However, increasing pressure from over-extraction and climate change has highlighted the need for improved methods of predicting and managing groundwater levels (GWL). Traditional groundwater monitoring techniques rely on hydrological models that require extensive datasets and struggle to capture the non -linear dynamics governing groundwater systems. These models often require numerous input parameters, which may not always be readily available, especially in regions where data collection is sparse or challenging. In response to these limitations, this study explores the application of Machine Learning (ML) techniques for predicting groundwater levels using field gravity data, aiming to develop a more efficient and accurate approach to local groundwater evaluation.

Field gravity data measures changes in the Earth's gravitational field caused by fluctuations in groundwater storage, providing a novel dataset for GWL prediction. The research was conducted in Roorkee, Uttarakhand, India, where gravity data was collected alongside groundwater level measurements. This dataset was used to develop and train various machine learning models, including Random Forest (RF), XG-Boost, Regression Trees (RT), Artificial Neural Networks (ANN), and Support Vector Machine with Radial Basis Function (SVM-RBF). The models were evaluated for their accuracy in predicting groundwater levels, comparing their performance across different modeling approaches. The methodology for this research involved testing three distinct modeling approaches. The first objective was to assess the relationship between temporal gravity and GWL using linear regression analysis and then identify suitable AI techniques. The second objective focused on developing an ML-based gravimetric model for a single well, employing three different approaches. The first approach, known as the single-parameter model, utilized gravity data alone to predict GWL, based on the assumption that variations in gravitational acceleration directly correlate with groundwater fluctuations. The second approach, the double-parameter model, incorporated time as an additional input variable, acknowledging the influence of temporal variations, such as seasonal re charge and extraction cycles. The third approach, a multi-parameter model, integrated hydro-meteorological data, including temperature, precipitation, wind speed, and relative humidity, to assess whether these factors enhanced prediction accuracy. The third objective involved conducting a detailed linear regression analysis of the dataset, followed by the development of an ML-based groundwater simulation model to capture the response of field gravity under various well scenarios in Roorkee. The developed models were trained and tested using historical data, and their performance was evaluated using standard statistical metrics: The Coefficient of Determination (R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Nash-Sutcliffe Efficiency (NSE). These metrics provided a comprehensive assessment of the models' accuracy in both training and testing phases.

The results of this study yielded several key findings. Firstly, the relationship between field gravity data and groundwater levels was found to be non-linear, making traditional linear regression models inadequate for GWL prediction. Machine learning models, particularly ensemble methods such as Random Forest and XG-Boost, outperformed other models in capturing these complex relationships. Both Random Forest and XG-Boost demonstrated high R^2 and NSE values, indicating their superior ability to predict groundwater levels accurately. Among the three modeling approaches, the double-parameter model, which utilized gravity data and time, produced the most reliable predictions. Surprisingly, the inclusion of hydro-meteorological factors in the multi-parameter model did not lead to significant improvements in prediction accuracy. This finding suggests that, at least in the Roorkee region, gravity and time data alone capture the critical information necessary for groundwater level prediction. However, in regions where groundwater is more directly influenced by meteorological conditions, these additional factors might prove more useful. Furthermore, ensemble models, particularly Random Forest and XG-Boost, were found to be more robust and less prone to overfitting, making them more reliable for practical applications. The study's findings suggest that ML-based models can serve as an efficient alternative to traditional hydrological models for predicting groundwater levels. By capturing non -linear relationships between gravity data and groundwater levels without requiring extensive input parameters, these models offer a more flexible and scalable solution for groundwater management.

This study makes several significant contributions to the field of groundwater management. It demonstrates the potential of machine learning models, particularly Random Forest and XG-Boost, as powerful tools for GWL prediction. These models require fewer input parameters compared to traditional hydrological models, making them suitable for regions where data collection is challenging. Additionally, the study provides a replicable framework for integrating field gravity data into machine learning models for GWL prediction, which can be applied to other regions or adapted to incorporate additional datasets as necessary. Another important contribution of this study is its potential application in real-time groundwater monitoring systems. By integrating ML models with continuous gravity measurements from remote sensors or satellite data, real-time monitoring of groundwater levels can be achieved, improving groundwater management and decision-making. Such a system could provide valuable insights for policymakers and water resource managers, helping them implement more effective conservation and management strategies.

In conclusion, this research highlights the effectiveness of machine learning models in predicting groundwater levels using field gravity data. The study demonstrates that ensemble models such as Random Forest and XG-Boost outperform traditional methods by capturing non-linear relationships between gravity data and groundwater levels. The findings suggest that a double-parameter model, incorporating gravity and time, provides the most reliable predictions. While the inclusion of hydro-meteorological factors did not significantly enhance prediction accuracy in this study, their relevance may vary depending on regional conditions. The study's results underscore the potential of machine learning as a valuable tool in groundwater management, offering a scalable, data-driven approach for predicting and monitoring groundwater levels in real time.

Keywords: *Groundwater, aquifers, groundwater, AI techniques, machine learning*

IS SUPPLY SIDE INTERVENTIONS CAN EFFECTIVELY NEUTRALIZE GROUND WATER OVEREXPLOITATION IN INDIA

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Ground water as a resource is the lifeline of food and drinking water security for India, beside substantially supporting the industrial growth. As a country, the extraction of ground water is about 21% of total annually utilizable water resources in India. As per the Central Ground Water Board (CGWB) estimate made in 2024, about 11% of the geographical area is marked with ground water resource overexploitation, where extraction exceeds the recharge, and additionally in about 3% area the withdrawal is more than 90% of the recharge in an annual scale. The seed of rising dependence on ground water was sown during the green revolution initiated in 1960s, when rapidly expanding assured irrigation was supported by construction of lakhs of tube wells. During 1970s, as the sign of stress on ground water resource is has started surfacing in vulnerable geographies like north-western and western India, discussions were initiated on how to rejuvenate the depleting ground water resource. The policy initiative heavily relied on supply-side interventions like Rain Water Harvesting and Artificial Recharge. Though Rain Water Harvesting is applied since historical times, particularly in arid and semi-arid regions, artificial recharge as an upcoming technique caught the imagination of the scientist and technocrats. CGWB has initiated pilot-scale implementation of different types of artificial recharge structures in different aquifer topologists and climatic zones during the XIII Plan period. The objective of the project was to ascertain the suitability and efficacy of different types of interventions so as to arrive on suitable designs and optimum cost-benefit ratio. Govt of India also issued a Manual on Artificial Recharge in the year 1994 to facilitate pan India implementation by different State Governments, Union Territories and various other organizations.

Government of India has initiated a number of schemes on harvesting water and recharging aquifers. The frontrunner is the Mahatma Gandhi National Rural Employment Guarantee Act 2005 a rural poverty alleviation programme. Significant effort under this scheme is directed in creating village level assets to conserve water and facilitate recharge to local aquifers. Besides almost all State Govts and Union Territories has initiated innovative schemes by converging various ongoing schemes and funds. Civil Societies across India are also involved in watershed mapping and creating awareness and mobilizing communities to create monitor and maintain water harvesting and recharge structures. Such endeavors are funded primarily by private organizations and public sector undertakings under the Corporate Social Responsibility component.

As the groundwater exploitation continued to raze ahead in later decades, new thoughts started creeping in on adopting saving water by enhancing water use efficiency, which in turn release load on rising ground water extraction. The National Aquifer Mapping and Management (NAQUIM) Program launched by the CGWB in 2012, has created a wider understanding as it tries to develop a sustainable ground water management plan in 1:50,000 scale. Investigations revealed that the demand-side interventions like crop diversification, micro irrigation, proper agronomic practice, adhere to a monsoon aligned cropping calendar etc. create better impact in rejuvenating ground water resources than the supply side interventions. The State Govts has initiated no of activities in this direction like, subsidy on adopting micro-irrigation by farmers, incentives on cultivating replacing water guzzling crops with water efficient crops etc. Govt of India has initiated Atal Bhujal Yojana, in the year 2019-20 targeting the states of Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, and Uttar Pradesh, severely impacted by ground water overexploitation, by primarily relying on demand side interventions. Under this scheme water security plans are being prepared for every village with support and consent from the local community and the interventions are being adopted by aligning existing Govt schemes.

The two basic factors that hinders the effective and large-scale implementation of artificial recharge and rain water harvesting are (i) lack of space and (ii) dearth of source water. Space is often a constraint in a densely populated country like India, if surface methods for recharge are adopted. The water bodies, both in urban and rural areas, which are traditional source of recharging underlying aquifers, are under threat from encroachment, siltation and degradation. The "source water" is often remains inadequate, particularly for a large-scale recharge planning and implementation. Another issue is the overland flow often loaded with harmful chemical contaminants, which if used for direct recharge can degrade and even permanently spoil the aquifer Climate change induced spatio-temporal variation in rainfall is also imposing an uncertainty on source water availability. The other important factor is that the interventions targeting harvesting water on surface and recharge aquifers are often not in tune with the local hydrogeology, water level behavior, ground water quality and demand mapping. In such cases the types of structures and their designs are not aligned to local condition, leading the suboptimal gain from the investment.

In the country scale there is marginal improvement in Stage of Ground Water Extraction, as estimated by CGWB after 2017 when it reached to 63% to around 60% in the estimation of 2022, 2023 and 2024. Researches are required to delineate the impacts of various interventions and any change in rainfall pattern. However, it may be concluded that the supply and demand side interventions should be adopted in a coordinated manner in tune with the local hydrogeology, groundwater level regime and resource dynamics, taking the local community along.

Keywords: *Overexploitation, stage of ground water extraction, rain water harvesting, artificial recharge, supply side intervention, demand side intervention*

FROM SALINITY TO EMERGING CONTAMINANTS – GROUNDWATER QUALITY CHALLENGES AND THE NEED TO REDOUBLE EFFORTS TO IMPROVE GROUNDWATER QUALITY ASSESSMENTS

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Groundwater has a huge contribution to make to the security of future food production and drinking water resources globally and supports a vast range of different groundwater dependent ecosystems in rivers, wetlands and marine systems. However, there are a range of both legacy and new groundwater quality issues which can constrain the use of groundwater for potable supply, use in industry, for crop irrigation and may also have negative impacts on groundwater dependent ecosystems. Groundwater pumping can also enhance groundwater capture with potential impacts on environmental flows in rivers. The development of groundwater resources in the last century has been a catalyst for phenomenal economic growth, water and food security and improvements in drinking water supply and related health benefits for millions of users. India is a case in point, where groundwater abstraction in some regions underpinned the green revolution contributing to large increases in crop yields and enabled multiple crops cycles each year through a shift from a dependence on rain-fed agriculture to irrigation using canals and groundwater. Recent research has shown how distributed canal networks helped enhance recharge to groundwater and sustained a vast expansion of groundwater abstraction in parts of India over the last 6 decades.

While the majority of the Indo-Gangetic Basin has seen no or limited deterioration in groundwater stores, locally, high rates of groundwater depletion can be observed which challenge the continued exploitation of groundwater resources. In parallel, the acceleration in groundwater uses for food production, coupled with an increase in population has the potential to modify sources and pathways for natural and anthropogenic pollutants and can also modify the biogeochemical cycling of nutrients and contaminants along the land-ocean continuum. There is growing evidence that groundwater quality issues, such as salinity, nitrate, arsenic and uranium are now starting to constrain the use of groundwater resources, and across large regions provide a greater constraint on groundwater resources compared to groundwater storage.

There is growing evidence that globally we may be starting to approach and potentially exceed planetary boundaries for key pollutants. Until recently the challenge of groundwater quality has tended to take a back seat in the face of growing demand for increases in groundwater supply for irrigation and other uses. This keynote highlights some of the major current water quality challenges globally and explores their implications and draws on examples from recent studies within an Indian context. Some of the most pressing concerns include the widespread issues of groundwater salinity, geogenic sources of groundwater contamination, anthropogenic pollution as well as emerging threats from PFAS and microplastics. While the risks from key geogenic contaminants such as As, F and U and selected anthropogenic contaminants such as heavy metals and nitrate have been more widely investigated in India, and elsewhere globally, there are still major knowledge gaps for many legacy contaminants as well as contaminants of emerging concern, many of which can be categorized as persistent, mobile and toxic contaminants. There is an ongoing need to prioritize groundwater quality assessment in the face of growing water quality pressures, while remaining vigilant of new contaminants of concern.

If we are to ensure that groundwater can deliver potable drinking water today (and for future generations) and continue to provide clean inputs to rivers and other dependent ecosystems, it is crucial that water quality challenges are fully investigated, and sustainable solutions implemented to protect groundwater and water supplies which depend on this resource. Groundwater resources have been shown to buffer impacts of changing climate and provide secure water resources, but this is only realized and sustainable if we also consider groundwater quality constraints as well groundwater storage. There is a tendency for siloed research on aspects of water resources and water quality, as well as siloed research within hydrology - how often do we ignore key aspects such as surface-groundwater interactions for example, what about considering the wider drivers of contaminant emissions (agrochemical use, wastewater treatment, impacts of legacy and current mining etc.). It is easy to assume that models can provide insights for understanding risks and assessing potential solutions, but in many cases, there is not adequate conceptual understanding of key processes which drive contaminant transport, limited hypothesis testing or adequate evidence from monitoring data with which to assess and evaluate the performance of models to predict current status – never mind future scenarios. Similarly, AI tools have their place - they have been used for some time, but they should not be seen as a way to replace well designed monitoring programmes which are the foundation of improved understanding of groundwater quality and groundwater resources.

The issue of rising nitrogen stores in groundwater, salinity and geogenic contamination such as arsenic (and manganese more recently) in some regions have provided cautionary examples of how groundwater quality challenges can undermine the role of groundwater for safe and secure water supply if there is poor installation and inadequate monitoring and treatment solutions alongside resource development. For many regions globally water quality challenges continue to be poorly understood and may potentially undermine the role of groundwater resources to provide security in the long term. This requires difficult decisions in terms of reducing emissions at source, better groundwater source protection and design standards, increased funding for improved treatment solutions and the development of appropriate groundwater monitoring strategies to characterize a wide range of water quality threats to groundwater. It is a false economy to project a view that groundwater is somehow immune to groundwater quality issues and can provide limitless clean water without the need for adequate protection and maintenance of water points alongside treatment and robust monitoring. With ever growing competition for funding resources and we need to re-double efforts to make a strong case to funders and wider stakeholders for rapid and improved groundwater quality assessment globally, which in many regions is poorly characterized compared to surface water resources.

Keywords: *Salinity, emerging contaminants, groundwater*

IMPACT OF CLIMATE CHANGE ON COASTAL GROUNDWATER RESOURCES

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The coastal groundwaters are more vulnerable to climate change-induced stresses. Coastal groundwaters are affected by changes in rainfall patterns, urbanization, and rising sea levels. Climate change's adverse impacts on water quality are of emerging interest and importance. This study examines the effects of this on coastal regions of India. The study analysed the long-term groundwater level data and used numerical modelling to understand the impact of changes in rainfall and sea level rise. The study indicates that several parts of coastal aquifers in India are affected by seawater intrusion. The fresh coastal groundwater resources are diminishing due to rising sea levels and overuse. Downscaled climate prediction was carried out using the Regional Climate Model (RCM) with seven ensembles for the Chennai region. A numerical model for simulation of groundwater flow in the coastal aquifer of Chennai was formulated to understand the responses of the groundwater table and existing freshwater lens to downscaled predicted rainfall, sea level rise, and expected urbanization impact until the end of the year 2050. The rapid changes in the land use and land cover pattern inferred by change detection were extended and examined in the aquifer's future characteristics by increasing and decreasing groundwater pumping with RCM-predicted rainfall recharge and sea level rise.

The intricacy of the aquifer arises from the minimal ratio of width to the overall length of the study area, coupled with the sensitivity of the boundary to the mound-shaped phreatic groundwater table. Consequently, the FEFLOW saturated flow code has been selected for model development due to its precision in boundary impact analyses. A three-dimensional model has been constructed utilizing 25,455 six-node triangular elements. The vertical thickness incorporated in the model ranges from 10 to 24 m, comprising three distinct layers: sand, sandy clay, and clayey sand, which extend laterally and vertically at varying scales. Notably, the sandy clay layer predominates towards the western boundary, influenced by the presence of a canal. The model domain's boundary is clearly delineated at the surface due to the encirclement of saline water. Initially, a constant boundary condition is applied in all directions across all layers, with the exception of the western side at the bottom layer. The existing connection to the mainland in the west at the base of the aquifer facilitates regional flow towards the east into the Bay of Bengal after traversing the study area. A flux boundary is established along the western edge of the bottom layer, reflecting the estimated regional flow. This estimation is derived from the observed contrast in groundwater density and the pressure head differences between wells monitored on the mainland and those on the dune surface. This approach is particularly effective in addressing the barrier effect on the regional groundwater gradient caused by the Buckingham Canal.

Sea level rise supports the formation of the freshwater lens after overcoming the groundwater decline caused by predicted urbanization groundwater demand. The use of General Circulation Models (GCM) indicates that the Intergovernmental Panel on Climate Change

(IPCC) anticipates an increase in both temperature and rainfall intensity. However, the projections derived from PRECIS, a Regional Climate Model tailored for the study area, exhibit variability in quantity compared to those from GCM. The application of the Mann-Kendall statistical analysis on historical and future predicted data reveals a reduction in annual rainfall by 6.398 mm per year. Additionally, there is a noted decline in seasonal rainfall. This study underscores the importance of downscaled analyses in forecasting climate change through Regional Climate Models (RCM). Furthermore, the research demonstrates that local hydrogeological conditions influence the effects of sea level rise. The intricate aquifer system in the study area allows freshwater retention as a lens, which is heavily relied upon by the local population. This situation has led to seawater intrusion, particularly in the densely populated northern region. The rainfall predictions made using PRECIS may exacerbate groundwater quality issues due to reduced replenishment in this shallow, over-extracted aquifer. The developed groundwater model forecasts a maximum decline of 0.08 meters in groundwater levels by the year 2050. However, this decline is moderated by sea level rise, which is another natural factor contributing to climate change. Variations in groundwater table elevation can significantly alter the thickness of the freshwater lens. Increases in the groundwater table of 0.1 m, 0.15 m, and 0.25 m have been observed as a result of sea level rises of 1 mm, 2 mm, and 5 mm per year, respectively.

The anthropogenic impact in this region, located south of Chennai metropolitan city, is particularly pronounced. Rapid changes in land use and land cover are evident, and the dense population coupled with the swift expansion of built-up areas may lead to increased groundwater extraction. Conversely, the government's establishment of a desalination plant with a capacity of 400 million litres per day may help mitigate some of these challenges. The analysis of aquifer behaviour in relation to different levels of groundwater extraction suggests that a reduction of 10% in groundwater pumping is necessary to preserve the freshwater resources at their current levels, assuming no rise in sea level occurs. However, the research indicates that a sea level rise of just 1 mm per year is sufficient to keep the freshwater resources stable, even with a 10% increase in groundwater extraction. This study offers an in-depth examination of aquifer responses to various future climate and discharge scenarios, demonstrating that the effects of sea level rise can be advantageous for the region under consideration. Also, reduced outflow against various ranges of sea level rises confirms that the sea level rise in the study area will reduce the volume of freshwater storage. Improving recharge and reducing the pumping are some of the mitigation measures to overcome this problem.

Keywords: *climate change, groundwater, RCM, GCM, coastal aquifers*

DEVELOPMENTS IN MESHLESS NUMERICAL METHODS AND ITS APPLICATIONS IN GROUNDWATER MANAGEMENT

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Numerical simulations play a crucial role in modeling the various groundwater processes, including flow, contaminant transport, and multi-species reactive transport. Recently, numerical simulators combined with metaheuristic algorithms have gained popularity in groundwater studies, such as management, remediation, and source identification. Traditional numerical methods like the Finite Difference Method (FDM) and Finite Element Method (FEM) are commonly applied to groundwater problems. However, these methods have limitations, including the need for extensive preprocessing, limited automatic meshing and remeshing capabilities, and potential inaccuracies in representing complex geometries. To address these challenges, meshless methods have emerged as popular alternatives for groundwater modeling. Unlike traditional methods, meshless techniques discretize the domain using only nodes, with little to no reliance on meshes. The use of support domains for interpolation enhances stability. Depending on the formulation of the governing equations, meshless methods are categorized into strong, weak, and hybrid weak-strong forms. Strong form methods directly discretize the equations, while weak form methods integrate the equations before formulation. The integration in weak form methods imparts higher stability and accuracy at the expense of increased computational cost. On the other hand, strong form methods are computationally efficient but can be unstable at derivative boundaries. Hybrid forms aim to combine the strengths of both weak and strong forms. The strong form Radial Point Collocation Method (RPCM), the global weak form Element Free Galerkin Method (EFGM), the local weak form Meshless Local Petrov Galerkin (MLPG), the Local Radial Point Interpolation Method (LRPIM), and the hybrid Meshless Weak Strong (MWS) method are some of the commonly used meshless methods successfully applied in groundwater modeling. In this study, considering the numerous advantages of meshless methods, groundwater management modelling is demonstrated using different meshless simulators for groundwater flow and contaminant transport modelling. The results indicate close match between meshless methods and the commonly used groundwater models such as MODFLOW/MT3DMS, and effective planning and design of management schemes. Further, the meshless models are coupled with latest optimization tools such as meta heuristic algorithms to have efficient simulation optimizations models and applied to various groundwater management problems such as groundwater remediation designs, parameter estimation, and source identification. Therefore, the meshless methods can serve as alternatives to the existing simulators, with advantages of low preprocessing and simpler adaptive analysis.

Keywords: *Meshless methods, groundwater management, meshless weak strong, simulation optimization models*

WATER SECURITY IN THE AGE OF EXTREMES: GROUNDWATER SOLUTIONS FOR CLIMATE-RESILIENT GROWTH

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Groundwater serves as a vital buffer against climate variability, providing a critical source of freshwater for agriculture, drinking water, and industrial use. However, its sustainable management faces mounting challenges in the context of rising global water demand, prolonged droughts, and extreme weather events driven by climate change. As the frequency and intensity of these climate extremes increase, so does the urgency to adopt innovative and integrated approaches that ensure groundwater remains a reliable resource for current and future generations. The abstract summarizes transformative solutions that leverage cutting-edge technologies, nature-based approaches, and policy innovations to enhance water security and build climate resilience.

Groundwater constitutes nearly 30% of the world's freshwater resources and supports the livelihoods of billions of people globally. It is especially critical in arid and semi-arid regions where surface water resources are limited or highly variable. As climate change exacerbates water scarcity through increased evapotranspiration, altered precipitation patterns, and more frequent droughts, groundwater will play an even more pivotal role in ensuring water security. Despite its importance, groundwater is often poorly understood, under-monitored, and inadequately managed. Over-extraction, pollution, and the lack of effective governance frameworks have led to declining groundwater levels in many regions. To address these challenges, a shift towards integrated groundwater management is required—one that combines scientific knowledge, technological innovation, and participatory governance. Managed aquifer recharge (MAR) is a proven strategy to enhance groundwater storage by intentionally infiltrating excess surface water into aquifers during periods of water surplus. This technique helps mitigate the impacts of droughts by creating strategic water reserves and stabilizing groundwater levels. MAR can be implemented through various methods, such as infiltration basins, recharge wells, and induced bank filtration. The success of MAR relies on understanding local hydrogeological conditions, water quality management, and community engagement.

Underground Transfer of Floods for Irrigation (UTFI) is an innovative approach that addresses both flood and drought risks by capturing excess floodwaters and storing them underground for later use in irrigation. This method not only reduces flood damage but also recharges depleted aquifers, providing a sustainable water source during dry periods. UTFI has shown promising results in South Asia, where it has helped improve water availability for agriculture while reducing groundwater depletion.

Effective groundwater management requires accurate data on water availability, usage, and recharge rates. Water accounting tools, combined with agricultural water management practices, can enhance water use efficiency and promote sustainable extraction. Techniques such as deficit irrigation, crop diversification, and the use of drought-resistant crop varieties help optimize water use in agriculture, which is the largest consumer of groundwater globally. Drought-proofing involves a combination of proactive measures designed to reduce the vulnerability of communities and ecosystems to drought. This includes the development of early warning systems, drought contingency planning, and the promotion of water conservation practices. Integrating groundwater management into drought-proofing strategies ensures that aquifers can serve as reliable buffers during prolonged dry spells. The adoption of solar-powered irrigation systems offers a sustainable alternative to diesel and electric pumps, reducing greenhouse gas emissions and operational costs. However, it is crucial to couple solar irrigation with strong groundwater governance measures to prevent over-extraction. Smart metering, water pricing, and user regulations can help balance the benefits of solar technology with the need for sustainable groundwater management. Advancements in digital technologies are revolutionizing groundwater monitoring and management. Remote sensing, GIS and real-time data analytics provide critical insights into groundwater dynamics, enabling more informed decision-making.

South Asia and Africa offer valuable lessons in adaptive groundwater management, given their diverse climatic conditions, agricultural practices, and governance structures. In South Asia, countries like India have pioneered large-scale groundwater monitoring networks and community-based water management programs. The India Drought Management System (India DMS), for instance, provides real-time data to support early warning systems and drought preparedness. In Africa, initiatives such as the Digital Innovation for Water Secure Africa project have demonstrated the potential of digital tools to enhance water security. By leveraging remote sensing, hydrological modeling tools, and participatory mapping, these projects have improved water resource planning and management at both local and regional scales.

Addressing the complex challenges of groundwater management requires a holistic approach that integrates scientific research, technological innovation, and robust governance frameworks. Effective groundwater management involves diverse stakeholders, including government agencies, local communities, the private sector, and research institutions. Collaborative platforms facilitate knowledge exchange, capacity building, and coordinated action. Sound groundwater governance is underpinned by clear policies, regulatory frameworks, and enforcement mechanisms. Policies that promote sustainable extraction, protect recharge zones, and incentivize water conservation are critical for long-term groundwater security. Empowering communities with knowledge, tools, and resources fosters local stewardship of groundwater resources. Participatory approaches ensure that management strategies are context-specific and socially acceptable. Groundwater is more than just a resource; it is a cornerstone of climate resilience, food security, and sustainable development. In the face of escalating climate extremes, the need for innovative, integrated, and inclusive groundwater management has never been greater. By harnessing the power of technology, embracing nature-based solutions, and fostering multi-stakeholder collaboration, we can ensure that groundwater remains a reliable foundation for resilient growth in a rapidly changing world.

Keywords: *Water security, climate change, groundwater, managed aquifer recharge*

GEOSPATIAL TECHNOLOGY FOR WATER RESOURCES MANAGEMENT

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Water resources management has become increasingly complex due to factors such as climate change, population growth, urbanization, and rising water demand. Effective management strategies require advanced tools and methodologies to ensure water availability, quality, and sustainability. Geospatial technology, which encompasses remote sensing, GIS and geospatial artificial intelligence (GeoAI), has emerged as a powerful approach to addressing these challenges. By integrating spatial data with AI-driven analytics, decision-makers can improve water resource allocation, enhance monitoring, and optimize predictive modelling. This paper explores the synergy between geospatial technology and AI in water resources management, highlighting their transformative potential for sustainable water security.

Remote sensing plays a crucial role in monitoring and analysing water resources on a large scale. Satellite-based sensors provide invaluable data on surface water bodies, groundwater fluctuations, precipitation patterns, and hydrological changes over time. High-resolution satellite imagery from platforms such as Landsat, Sentinel, and MODIS enables continuous observation of rivers, lakes, reservoirs, and wetlands. Additionally, microwave remote sensing techniques, such as Synthetic Aperture Radar (SAR), allow for the detection of soil moisture levels and groundwater depletion, even under cloud cover. These datasets help researchers and policymakers assess water availability, detect drought conditions, and monitor changes in land use that impact hydrological cycles. The integration of remote sensing with hydrological models provides better insights into water balance, runoff estimation, and watershed management.

GIS serves as a fundamental tool for analyzing and visualizing spatial data related to water resources. GIS facilitates watershed delineation, flood risk mapping, and water quality assessment by integrating multi-source datasets. For instance, GIS-based hydrological modeling enables the identification of critical recharge areas, pollution hotspots, and areas vulnerable to water stress. By analyzing topographic, climatic, and land-use data, decision-makers can develop more effective water conservation strategies. Additionally, GIS is essential for real-time monitoring of water distribution networks, enabling rapid response to leaks, contamination, and inefficiencies in water supply systems. One of the key applications of GIS in water management is the assessment of groundwater potential. By integrating geological, hydrological, and climatic parameters, GIS-based models can predict areas suitable for groundwater extraction while minimizing environmental impacts. Moreover, GIS is used in urban planning to design sustainable water management infrastructure, such as rainwater harvesting systems and green stormwater solutions.

GeoAI represents the convergence of AI and geospatial technology, leveraging machine learning (ML) and deep learning (DL) techniques for enhanced decision-making in water resources management. GeoAI enables predictive modelling, anomaly detection, and automated feature extraction from satellite imagery and sensor data. AI-driven models can predict future water availability based on historical climate patterns, hydrological data, and socio-economic factors. Machine learning algorithms analyze large datasets to forecast drought occurrences, seasonal water demand, and the impact of climate change on water resources. Deep learning models, such as convolutional neural networks (CNNs), are used to identify surface water changes from remote sensing images, improving early warning systems for droughts and floods. Maintaining water quality is crucial for public health and ecosystem sustainability. AI-powered systems analyze water quality indicators such as turbidity, dissolved oxygen levels, and pollutant concentrations using satellite imagery and in-situ measurements. Anomaly detection algorithms identify deviations from normal patterns, enabling timely interventions in case of contamination events or pollution spills. Additionally, AI enhances the management of water distribution networks by detecting leaks and inefficiencies. Smart sensors deployed in pipelines transmit real-time data, which AI models analyze to pinpoint anomalies, optimize water flow, and reduce losses. These systems significantly improve water conservation efforts in urban and rural areas.

Flooding is one of the most devastating natural disasters, causing extensive damage to infrastructure, agriculture, and human settlements. AI-driven flood forecasting models integrate satellite imagery, meteorological data, and hydrological simulations to predict flood occurrences and intensity. By training ML algorithms on historical flood patterns, GeoAI systems can provide early warnings, allowing authorities to implement evacuation plans and mitigate damages. Furthermore, AI-powered flood susceptibility mapping identifies high-risk zones based on topography, land cover, and hydrodynamic models. These insights aid urban planners and policymakers in designing resilient flood mitigation infrastructure.

Groundwater recharge plays a vital role in sustaining freshwater supplies. Traditional methods for estimating recharge rates rely on field measurements, which can be time-consuming and spatially limited. AI models offer a scalable solution by analyzing climate variables, land use changes, and soil moisture levels to estimate groundwater recharge potential. This approach supports sustainable groundwater management by identifying areas suitable for artificial recharge and conservation initiatives.

Water contamination poses significant risks to human health and the environment. AI models integrate satellite-based observations with hydrological simulations to assess contamination risks from industrial discharge, agricultural runoff, and natural pollutants. Machine learning classifiers analyze spatial patterns of contamination sources and predict areas susceptible to waterborne diseases. In addition, AI-powered remote sensing techniques enable real-time monitoring of harmful algal blooms (HABs) in lakes and coastal waters. These models detect changes in chlorophyll-a concentrations and surface temperatures, providing early warnings to prevent adverse ecological impacts. The integration of geospatial technology and AI in water resources management presents a transformative approach to addressing contemporary water challenges. Remote sensing, GIS and GeoAI collectively enhance hydrological monitoring, predictive modelling, and resource optimization. By leveraging AI-driven insights, policymakers and water managers can make informed decisions to ensure sustainable water security in the face of climate change and increasing demand. While challenges remain in data accessibility, computational complexity, and policy integration, continued advancements in geospatial AI promise significant improvements in water resource management, benefiting both society and the environment.

Keywords: *GeoAI, machine learning, GIS, Geospatial technology, water resources*

RIVERBANK FILTRATION FOR IRRIGATION AT A WASTEWATER-IMPACTED RIVER IN AN ARID REGION

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Managed aquifer recharge (MAR) holds promise to offset the impacts of a decrease in groundwater (GW) resources and a deterioration of the GW quality, as well as provides a buffer against saltwater intrusion and land subsidence from unsustainable abstractions in the water-stressed eastern Mediterranean region of the Middle East. In Jordan, drinking water production and irrigation water supply compete for scarce GW resources. There, the MAR technique of riverbank filtration (RBF) could be an alternative to the direct abstraction of wastewater-impacted surface water for irrigation of fodder and food crops, thereby contributing to the conservation of GW resources and providing a barrier to the propagation of human and plant pathogens into the food chain. While RBF is used at many sites worldwide for producing drinking water, only a few studies have investigated RBF as an alternative to direct surface water abstraction for irrigation, especially for food crops in water scarce regions and/or grown by surface waters with considerable fecal contamination. The objective was to obtain an initial assessment for the application of RBF for irrigation at a site by the Zarqa River in Jordan with the overarching aim of improving the quality of water by RBF for irrigation of food crops and builds upon previously reported results within the framework of this study.

The suitability of sites for RBF was mapped and evaluated along the Zarqa River in Jordan using multi-criteria decision analyses (MCDA) that considered different parameters such as the geology, presence of fluvial deposits, landcover and slope of the catchment in the upper course of the Zarqa. Subsequently, geo-hydraulic, water quality and numerical GW flow and transport modelling investigations were conducted at a site located around 35–40 km north of Amman within a bend of the Zarqa River. The Zarqa River flows through hills in its middle/upper course and at this particular site it passes through cemented Pleistocene sediments (conglomerates), with visible fluvial deposits on the inner bank within the bend indicating the presence of a potential site for RBF with medium to coarse alluvial sediments.

Water sampling from an angled large-diameter (1 m) caisson well on the right bank and from the Zarqa River commenced in September 2023. Two monitoring wells (MW2 and MW3) were constructed on the left bank in January 2024, which were subsequently monitored for water quality parameters and GW levels. Since then, water samples were collected from the Zarqa River, MW2, MW3 and from an irrigation pond located to the landward side of the monitoring wells. The water samples were analyzed for total coliforms and E. coli, major cations and anions, metals, dissolved organic carbon (DOC), selected organic micropollutants and standard on-site parameters such as temperature, pH, dissolved oxygen and electrical conductivity (EC).

The MCDA identified 9 of 24 potential sites as having highly suitable geo-hydraulic conditions, while another 9 sites, including the selected location, demonstrated moderate suitability. Suitability mapping indicated that most suitable sites are situated upstream along the Zarqa River, between the As Samra wastewater treatment plant and the King Talal Dam. The similarity in EC between the river water and MW2 and MW3 suggests a strong hydraulic connection between the river and the adjacent fluvial aquifer. During flood events, a significant decrease in river water EC is observed, with a corresponding decrease in EC in MW3 on the left bank and the irrigation well on the right bank, further confirming the hydraulic linkage. Conversely, the elevated EC observed in the irrigation pond water is likely attributable to evaporation effects. Steady-state calibrated 3D numerical groundwater flow models estimated a travel time of 1–2 weeks for water to flow from the Zarqa River to MW2 and MW3 under baseflow conditions. Under natural infiltration (non-pumping conditions), RBF demonstrated high efficiency, achieving a log10 removal value (LRV) of 3–5 for total coliforms and a median LRV of 3 for E. coli following the estimated residence time along the river-MW transect. The Zarqa River consistently exhibits high DOC concentrations (median 10.2 mg/L). Attenuation of approximately 50% was recorded for DOC in MW2 and MW3, indicating effective reduction of organic pollution. In addition, specific organic micropollutants, e.g. diclofenac, exhibited attenuation rates between 70% and 90%.

The study conducted at Jordan's Zarqa River confirms that RBF is an effective strategy for mitigating waterborne pathogen risks, offering a sustainable alternative to directly pumping river water for irrigation. The results highlight the importance of the hydraulic connection between the river and the adjacent fluvial aquifer, as well as the influence of travel time and flow path length on contaminant attenuation. Specifically, water quality improvements, including the removal of coliforms were significantly greater along the natural gradient of the river-MW transect on the left bank of the Zarqa River compared to the subsurface flow to the irrigation well on the opposite bank. Furthermore, a significant reduction in DOC as well as specific organic micropollutants was further underscoring the potential of RBF for water quality improvement. In addition to validating the effectiveness of RBF, the research identified other potential sites suitable for implementing RBF systems in similar alluvial settings, contributing to sustainable water quality management in the Zarqa River region. The integration of geo-hydraulic data into numerical models enabled the optimization of RBF well siting at the investigated site, taken into account the observed hydrochemical and microbiological data. Additionally, various well designs were numerically evaluated, offering adaptable solutions to ensure sufficient irrigation water supply while preserving groundwater resources.

Keywords: *Jordan, Zarqa, riverbank filtration, water quality, water nexus*

EFFECT OF SALINITY ON CROP GROWTH AND SOIL MOISTURE DYNAMICS: A STUDY WITH ROOT WATER UPTAKE MODEL

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Salinity is a major constraint affecting agricultural productivity, particularly in arid and semi-arid regions where irrigation is essential for crop cultivation. The present study investigates the adverse effects of irrigation water salinity on crop growth, root water uptake (RWU), and soil moisture dynamics in the root zone. A field-scale experiment was conducted to evaluate the response of paddy (Oryza sativa L. Basmati variety) under varying salinity conditions (0.5, 5, 10, 15, 20, and 25 dS/m). A numerical RWU model was developed and validated to simulate soil moisture movement, incorporating osmotic stress developed due to salinity. The study presents a comprehensive analysis of effect of salinity on leaf area index (LAI), root depth, soil moisture retention, and crop evapotranspiration. The findings highlight the necessity of effective salinity management strategies to sustain agricultural productivity. Soil salinity, arising from natural processes and anthropogenic activities, poses a significant challenge to global food security. The accumulation of salts in the root zone disrupts plant water uptake mechanisms, leading to osmotic stress, ion toxicity, and nutrient imbalances. Salinity affects soil structure, reducing hydraulic conductivity and altering soil moisture retention properties. Paddy, a staple crop in many regions, is particularly sensitive to salinity stress, which impairs its growth and yield. This study aims to quantify the effect of irrigation salinity on paddy growth and develop a reliable RWU model that integrates soil moisture dynamics under salinity stress.

A controlled field experiment was conducted at the Indian Institute of Technology Roorkee to study the effects of irrigation salinity on paddy crop growth. Six experimental plots, each measuring 1.5 × 1.5 m, were irrigated with water of different salinity levels (0.5, 5, 10, 15, 20, and 25 dS/m). Crop growth parameters such as LAI and root depth were monitored throughout the 101-day growth period. Soil moisture measurements were taken at six depths up to 1m to assess moisture dynamics under different salinity conditions. A numerical model based on the Richards equation, incorporating a nonlinear RWU function, was developed to simulate soil moisture movement. The model was calibrated using observed data and validated against field measurements. The RWU model used in this study integrates the effects of both matric and osmotic stresses to evaluate plant water uptake under different salinity conditions. The governing equations were solved numerically, employing finite difference methods for soil water flow simulation. The osmotic stress function was incorporated based on empirical relationships defining the threshold salinity concentration beyond which plant transpiration declines significantly. The model also accounted for soil hydraulic properties such as retention curves, hydraulic conductivity variations, and soil texture properties derived from laboratory experiments.

The experimental findings indicate a significant decline in crop growth parameters with increasing salinity. The maximum LAI during the growth period decreased from 5.19 m^2/m^2 at 0.5 dS/m to 2.01 m^2/m^2 at 25 dS/m, reflecting a 61% reduction. Root depth also declined substantially, from 69.5 cm at 0.5 dS/m to 44.5 cm at 25 dS/m, a decrease of 36%. These reductions are attributed to the osmotic stress caused by high salinity levels, which restricts water absorption and nutrient uptake. The RWU model simulations reveal that root water uptake is significantly impaired under saline conditions. The RWU rate exhibited an approximate decrease of 81% as salinity increased from 0.5 to 25 dS/m. The model accurately captured the declining trend of soil moisture content with increasing salinity, aligning well with field observations. Soil moisture retention at depths of 20 cm and 40 cm showed a progressive reduction, indicating enhanced drainage due to the altered hydraulic properties of saline soils. Moreover, the reduction in soil moisture retention under saline conditions is primarily due to the increased osmotic pressure of the soil solution, which reduces the availability of water for root absorption. The Richards equation simulation indicated that soil water content at deeper layers was less affected than surface layers due to capillary movement and reduced evaporation losses. The study also demonstrates that salinity stress leads to a nonlinear reduction in transpiration rates, further impacting crop water use efficiency. The model's performance was evaluated by comparing simulated RWU with observed values. The results indicated an acceptable level of accuracy, with minor discrepancies attributed to variability in soil heterogeneity and root distribution patterns. The findings suggest that the RWU model can be effectively used for assessing the effect of salinity stress on different crop species and soil types under variable climatic conditions. This research underscores the detrimental effects of irrigation salinity on paddy crop growth, RWU, and soil moisture dynamics. The numerical RWU model developed in this study provides a robust tool for simulating moisture movement and plant water uptake under saline conditions, aiding in the development of sustainable irrigation strategies.

Keywords: *Salinity, soil moisture, irrigation, root water uptake*

STATUS OF GROUNDWATER RESOURCES IN NEPAL: IS IT SUSTAINABLE TO FULFIL SUSTAINABLE DEVELOPMENT GOALS?

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Nepal is a mountainous country located at the center of Himalaya region its altitudinal variation ranges from 64 m to 8848.86 m within 150 km of aerial distance north-south section. Nepal is considered one of the richest countries in water resources but its unique physiographic setting and hydro-meteorological condition makes it, a country situated in the region of too little and too much water availability. Groundwater resources of Nepal is distributed in different types of aquifers in Terai, Siwalik, Lesser Himalaya and Higher Himalaya regions. Groundwater in Nepal is available in the form of thousands of springs in the Middle hill regions and abstracted groundwater by pumping from drilled dug well, shallow tube well and deep tube well in in Terai region and intermountain basins. Groundwater is one of the major sources of water, which is being used for drinking, sanitation, irrigation and cultural purposes. Not only these direct uses, groundwater in form of springs are lifelines for rivers originating from non-snowfed parts of Nepal Himalaya and plays a key role by providing base flow, especially in dry season. The rivers originating from the Middle hill region has a significant role for providing water for irrigation, aquatic ecosystem as well as for hydropower. This research consolidates current status of groundwater resources in Nepal and its linkages with sustainable development goals (SDGs) through review of existing data and the author's own research findings in Nepal Himalaya. In addition, this research tries to address research gaps for sustainable management of groundwater resources in groundwater research and institutional void for groundwater governance in Nepal.

According to Department of Water Supply and Sewerage Management, Nepal, there are about 1,050,000 shallow wells installed in Terai to extract groundwater for daily domestic water uses, whereas most of municipal and community water supply schemes also abstract groundwater from deep tube well but information about these wells are not available. Similarly, for groundwater irrigation uses, 1050 deep wells and 129,000 shallow tube wells were drilled. It is estimated that a total amount of groundwater extraction for irrigation from both types of groundwater wells is about 1312 MCM/year and groundwater extracted for domestic uses shallow wells are 462 MCM/year. Similarly, extraction of groundwater for industrial uses in Terai is about 131 MCM/year. Spring water in the Middle hill are being used through community supply, individual household supply and also for municipal water supply. The amount of discharge of springs and their water quality data are available in different cluster mostly in central Nepal. Many springs are drying rapidly and many villages are migrated out from their traditional villages due to drinking water scarcity caused by drying of springs. Kathmandu, the capital city of Nepal, also mainly depends on groundwater sources for drinking water supply and facing tremendous stress to fulfil water depends for increasing populations.

The 2030 Agenda for Sustainable Development, are adopted by all United Nations Member States in 2015, for prosperity for people and the planet and are categorized into seventeen

Sustainable Development Goals (SDGs). The 14th Plan (2016/17–2018/19) was the first periodic plan of Nepal to mainstream and internalize the 2030 SDGs Agenda. The 15th Plan sets out 10 national goals, each contributing towards SDGs progress: The 15th Plan (2019/20-2023/24) has continued to mainstream the SDGs and also to align SDGs related targets. In terms of practical progress, Nepal has been reasonably successful to date in making headway across the 17 SDGs and their respective indicators. Out of seventeen SDGs, three are 'on track', six are in the line of moderately improving', four are installing state', or one 'decreasing' and insufficient data exist in remaining three goals.

Out of seventeen SDGs, eight SDGs are related with groundwater resources in Nepal. Among the direct related SDGs, the goal six, goal two and goal fifteen, which are respectively related to water and sanitation, food security and sustainable agriculture, promoting and restoring terrestrial ecosystems as well as protection of biodiversity are major groundwater-related goals. Additionally, SDGs one, goal seven and thirteen are well connected to groundwater resources in Nepal. The indirectly related SDGs with groundwater resources are goal three and goal seventeen, which, respectively, focuses on healthy life and promoting well-being, developing global partnership for sustainable development. Therefore, we can clearly elaborate how groundwater resources are well connected with multiple SDGs and availability and sustainability of groundwater resources depends to achieve these SDGs.

Though, a smooth but slow progress has been made to achieve targets related with all SDGs. But the groundwater resources management is very often neglected topic when many springs are drying in Middle hill and groundwater level in Kathmandu including some parts of Terai are showing continuously decreasing water levels. An intensification of groundwater uses has led the additional stress on groundwater resources and has caused its over-exploitation during recent years, especially when climate change in exacerbating the situations by extending seasonal drought and changing monsoon trend. As water demand in the season of too little surface availability is increasing, groundwater remains only the source to fulfil water for drinking, household uses and irrigation. However, there is no any institution for groundwater governance in Nepal, Therefore, the aforementioned SGDs which are directly and indirectly linked with groundwater resources in Nepal fully depends on the proper management of groundwater resources of Nepal. According to United Nations sustainable development framework 2023-2027 for Nepal, among groundwater related SDGs; SDGs six, one and seventeen are under 'significant challenges' category; SDGs fifteen, three and seven are in 'major challenges remain' category; whereas SDG thirteen has placed in 'achievable' category. There is an urgent need for a suitable groundwater management framework for sustainability of groundwater resources to ensure the achievement of groundwater dependent SDGs. For this, it is required to address institution gaps to manage groundwater resources in Nepal through a proper groundwater governance mechanism by establishing a new and powerful institution under the current federal government system of Nepal.

Keywords: *Groundwater, sustainable development goals, groundwater governance, spring and groundwater nexus, water security*

GROUNDWATER RESEARCH: A BRIEF HISTORY, FUTURE CHALLENGES AND TRENDS

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Utilization of groundwater has been known since prehistoric times. Over time, groundwater has become recognized for its widespread distribution, stable water quantity, and excellent water quality. Despite that, it faces unprecedented challenges in attaining the UN Sustainable Development Goal on Clean Water, mainly because of: increasingly severe climate change impacts, resource constraints, financial instability, religious conflict, inequalities within and between countries, environmental degradation, etc. These aspects have emerged as the future frontier areas of groundwater research using innovative technologies. Future research cannot be delinked from the history and progression of groundwater research. The paper thus addresses a few lookouts on: (i) a brief history of groundwater research, (ii) a brief of future challenges, and (ii) a likely trend in groundwater research.

Although groundwater uses date back to 8000 years ago; the quantitative approach to modern groundwater hydrology began with the experimental work by Henry Darcy in 1856, which brought out the famous Darcy's law. Over the years since then, groundwater research focal areas have evolved, shifted, and expanded to meet societal demands. Important themes included: the development of groundwater flow theory, well hydraulics, geostatistical analysis of aquifer systems, numerical modelling, contaminant transport and remediation, stream-aquifer interactions, and groundwater sustainability to name a few. Numerous researchers contributed to the development of those approaches and the list is very extensive. A few important ones are mentioned here.

Based on Darcy's law, Dupuit (1863) studied the groundwater flow under steady-state conditions, while Thiem (1906) derived a solution to the steady-state groundwater flow equation. Before Thiem (1906), Slichter (1899) developed the potential theory for quantitively describing the steady-state flow field to a discharge well. Until Theis's (1935) time-dependent (transient flow) quantitative analysis of a pumping well, groundwater research was limited to steady-state or equilibrium conditions. Theis's (1935) contribution enabled hydrologists to do quantitative calculations for the understanding and management of resources. The USGS has made significant contributions to the analysis of flow to wells based on Theis's transient flow equation. Generally, the period 1850-1950 is considered the golden period of Groundwater Hydrology. After 1950, the revolution of Computers led to a new development of hydrogeological sciences.

The USGS works on the development of simulation models for quantitative groundwater analysis first for the two-dimensional case, and later, for the 3D case brought out the popular 3D hydrologic processes model MODFLOW. Since then, the period of simulation models started for the modelling and management of groundwater resources. Until 2018, the potential of numerical simulation methods in groundwater science expanded covering areas of groundwater recharge, karst water, geothermal water migration, seawater intrusion, variable-density flow, contaminant and solute transport, pollution remediation, and land subsidence. Uses of geostatistical methods, GRACE and Satellite data, application of RS and GIS witnessed the development of effective Simulation-Optimization models for groundwater management together with developing precision in estimating groundwater hydraulic parameters.

A changing and uncertain future climate, together with a rapidly growing population and changing demands and supplies, presents a future challenge to increased social and economic development, globalization, and urbanization. These underline the major frontier areas for research: Groundwater hydrological dynamics and climate change impacts covering areas of groundwater flow, river dynamics, evapotranspiration, and how these processes are affected by temperature, climate conditions, and soil conditions; Climate change and water resource adaptability. These frontier areas emphasize the trends for groundwater research: “Climate change”, “groundwater”, and “model” are the top three key topics, and “flow” and “variability” are the key two inclusive topics. Artificial intelligence, Machine learning, Deep learning, Data science and analytics, and remote-sensing technology are emerging as the new innovative technologies for the micro and macro analysis, modelling, and management of groundwater resources.

Keywords: *Groundwater modelling, challenges, MODFLOW, groundwater hydrology*

SCALING WATER SAFETY IN SOUTH ASIA: A MODEL FOR POLICY INTERVENTIONS, GROUNDWATER MONITORING, DRILLER ENGAGEMENT AND DIGITAL INTERVENTIONS FOR SUSTAINABLE ARSENIC MITIGATION IN BANGLADESH

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Access to safe drinking water continues to be a critical challenge in South Asia, particularly in rural areas where the population largely depends on groundwater sourced from privately drilled tube wells. Although groundwater typically offers protection from microbial contamination, it presents significant risks due to long-term exposure to arsenic and other naturally occurring contaminants, impacting millions of people across the region. In the Ganges-Brahmaputra-Meghna (GBM) basin in Bangladesh and the Indo-Gangetic Basin (IGB) in India, shallow groundwater is frequently laden with elevated arsenic concentrations. In Bangladesh, over 17 million people, mostly in rural communities are exposed to arsenic levels exceeding the national drinking water standard of 50 µg/L. Arsenic contamination in groundwater exhibits spatial heterogeneity, and the long-term safety of arsenic-safe aquifer sections remains uncertain.

Sustainable arsenic mitigation in Bangladesh faces significant challenges, including unregulated private water source installations and drilling by untrained drillers, with no frameworks for registration or groundwater abstraction. Efforts are fragmented, lacking an integrated approach and a centralized digital platform for transparent, evidence-based decision-making. Additionally, the absence of comprehensive groundwater monitoring hinders tracking of water quality and levels. Addressing these issues requires policy reform, driller training, regulatory frameworks, and digital tools to ensure sustainable and safe water access. In partnership with UNICEF and the Department of Public Health Engineering, Government of Bangladesh (DPHE-GoB), an integrated protocol for sustainable arsenic mitigation has been developed, focusing on four key components including policy interventions, comprehensive groundwater monitoring, driller engagement and capacity building, and the adoption of digital technologies. This model aims to provide a scalable approach to ensure safe drinking water access, particularly in rural areas where reliance on groundwater is high.

To safeguard rural drinking water supplies, a comprehensive groundwater monitoring network with a centralized protocol for the capture of quality-assured data collection is essential. The Department of Public Health Engineering (DPHE), responsible for ensuring safe drinking water, is installing monitoring wells to track groundwater levels and quality variations following the guideline and framework for planning, prioritizing and site selection for the installation of these wells. Key factors for a sustainable monitoring system include securing land ownership (preferably at union headquarters), engaging local government institutions, modifying DPHE's institutional framework, and building driller capacity to select appropriate aquifer depths for tubewell installation.

More than 80% of drinking water wells in Bangladesh are privately drilled, with most tubewell drillers in rural areas lacking formal training in geology or hydrogeology yet playing a critical role in water source installation. Engaging these local drillers requires identifying them, assessing their knowledge, and training and certification for safe tubewell installation. In Bangladesh, as well as in much of South Asia, local hardware shops at the Upazila/union level serve as community hubs, connecting all drillers within a region. Empowered though the Sediment Color Tool (SCT) and ASMITAS, which link groundwater arsenic concentrations to sediment color, this approach offers the local tube well drillers as well as the technocrats a practical and scalable way for the identification of arsenic-safe aquifers for mitigation. The ASMITAS digital platform provides a centralized system to collect and analyze real-time groundwater data from piezometers, supporting informed decision-making for water supply interventions. By combining policy interventions with monitoring and tubewell installations by training and certification of tubewell drillers, the installation of arsenic-safe wells has been significantly improved, reducing the risks for arsenic exposure and ensure the long-term sustainability of safe drinking water supplies in Bangladesh. This approach, with its focus on policy interventions, strengthening monitoring networks, driller training and certification as well as use of digital tools, holds great potential for scalability across South Asia, where similar challenges with arsenic contamination are prevailing.

Keywords: *Policy interventions, sustainable arsenic mitigation, groundwater monitoring, drinking water safety, digital technology, driller engagement, South Asia, Bangladesh.*

ISOTOPE HYDROLOGY APPLICATIONS IN THE ASIA-PACIFIC REGION: A FEW RECENT CASE STUDIES

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Helium (He) in groundwater helps to understand the sources of recharge, the age and process of migration. Groundwater samples were collected from Kuwait and Dammam aquifers in Kuwait at different depths and analysed for ^{4}He, $^{3}He/^{4}He$, ^{20}Ne and major ions. It was determined that He decreased with Cl concentration and $d^{18}O$ with a few exceptions, and the distribution of He was inferred to be influenced by geological structures. He fluxes increased with age, but more significantly during Last Glacial Maxima. R_A (air normalized helium ratio) values indicated that most of the samples of north Kuwait, aging from 1650 to 348 y BP, had tritiogenic component similar to the present atmospheric condition, which was inferred to be due to the decay of tritium derived from meteoric impact. The epicenters of the earthquakes with magnitudes 2 to 4 were frequent in the regions with relatively lower R_A values. The variation of R_A values with depth of sampling indicated the dominance of lateral flow with insitu (He derived from rock matrix along the flow) and external sources (vertical upward cross formational flow, atmospheric input and from hydrocarbon reservoirs). The groundwater samples adjoining the oil fields observed to have more terrigenic He, possibly migrated to the shallow waters through weaker planes. Higher He in saline groundwater at shallow depth could indicate the probability of an abundant source beneath. The inferences from He Excess (He_{ex}) and air corrected He excess $\Delta He\%$, indicate the additional terrigenic He sources, apart from neuclogenic and radiogenic, like the exsolution from adjoining hydrocarbon fields, through the geological structures.

The domestic and irrigation needs of the country are primarily achieved by the surface water resources in the South, Southeast, and East Asian regions, in addition to groundwater. Recharge from the surface and the rainwater is the key source for groundwater. The river system dynamics are generally associated with climate and their environmental interaction. The Asian rivers travel through varied climatic conditions, are influenced by monsoonal precipitations, and are prone to anthropogenic contaminations. Studies have focused on the isotope signatures to unravel the environmental interaction and dynamics of the riverine system. Globally, detailed long-term observation of the river water isotopes prevails for many countries, but those of Asian rivers are still lacking. The current review focuses on understanding the dynamics of rivers in a few Asian countries based on the availability of the data. Stable isotope signatures ($\delta^{18}O$ and δD) of the surface waters from selected rivers of South, Southeast, and East Asia representing China, India, Nepal, Pakistan, Thailand, and Vietnam were assessed. A South Asian River water line was derived reflecting the linear relationship of the stable isotopes of oxygen and hydrogen ($\delta D = 7.3\ \delta^{18}O + 6.2$), and it was compared to the existing river water lines of other countries. The study also attempts to analyze the long-term data set in the countries depending on the data availability. It is interesting to note that a significant pattern and the variation in the isotopic signature are noted with respect to time and space and are predominantly dependent on monsoonal vapor sources.

Precipitation represents the input to the hydrological system, and it is the source or recharge for surface water reservoirs and groundwater aquifers. Stable isotopes (^{2}H and ^{18}O) were measured for the period from 2011 to 2020 for 240 precipitation samples in all 16 Iraqi provinces distributed throughout the country. These isotopic results of the precipitation were adopted to produce for the first time a unified Iraqi Local Meteoric Water Line (LMWL), ($\delta^{2}H= 7.66\ \delta^{18}O + 14.19$). The d-excess values (14.19) fall between the value of the global meteoric water line (GMWL) (10) and the east Mediterranean meteoric water line (22). This is due to the continental effect with less humidity and higher temperature than the Mediterranean area. The study showed a weak positive correlation between the stable isotope values and the ambient air temperature and a weak negative correlation between relative humidity and the precipitation amount. This is mainly due to the variation in moisture sources and the amount of precipitation. The effect of altitude was reflected in the isotope signatures of precipitation. The altitude gradient of $\delta^{18}O$ in precipitation was estimated to be -0.5‰ per 100 m elevation. The results indicated the influence of ambient temperature, spatial deviation of the precipitation amount, and relative humidity levels. Additionally, the sources of moisture for the rainfall events were also deduced using the HYSPLIT backward trajectory model. The Mediterranean Sea and the Caspian Black Sea moistures have been identified as the two major moisture source regions.

Keywords: *Noble gases and isotopes, hydrocarbon fields, cross formational flow, meteoritic impacts, stable isotopes, River, HYSPLIT backward trajectory model, moisture sources*

THE IMPACT OF HYDROMETEOROLOGICAL EXTREMES ON CONTAMINANT FATE AND TRANSPORT ACROSS URBAN TERRESTRIAL-AQUATIC INTERFACES

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The drivers and controls of biogeochemical cycling across the terrestrial-aquatic continuum of urban systems are still poorly understood. While there is increasing understanding of the efficiency of biogeochemical turnover of nutrients and organic carbon largely being controlled by the temporally dynamic activation of different sources of reactants and their connectivity as well as mixing and residence time distributions, rather little is known of the spatio-temporal organization of the natural and anthropogenic drivers of source activations and mixing in complex urban systems. We here present results of extended high-frequency in-situ water quality monitoring at the Birmingham Urban Observatory, covering a range of low- to mid-order streams across an urban / peri-urban gradient. The analysis of the distinct concentration – discharge relationships of different nutrients and functional organic matter fractions reveal the existence of diverse, compound specific activation mechanisms that are responsible for establishing connectivity and mixing between different terrestrial and aquatic sources. The combination of multiple functional concentration-discharge metrics highlights the impact of pre-event conditions not only for the initiation of different transport mechanisms but also for the preconditioning and activation of variable organic matter sources of different bioavailability. Our results indicate that events of dramatic water quality decline such as freshwater hypoxia during summer storms are largely driven by anthropogenic disturbances and the activation of wastewater based labile organic matter sources, with variable and scale-dependent impacts across the observatory. These insights, only possible through continuous high-frequency in-situ monitoring of nutrients and diverse functional organic matter groups enable the identification of the trigger conditions of compound specific source activations as a prerequisite for designing efficient pollution control, management and mitigation measures.

Keywords: *Hydro-meteorological extremes, water quality, contaminant transport*

GEOENVIRONMENTAL APPRAISAL OF GROUNDWATER RESOURCES FROM DECCAN BASALTIC REGIONS, MAHARASHTRA, INDIA

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The Deccan Plateau, covering much of Maharashtra, is dominated by vast basaltic formations, known as the Deccan Traps, which were formed by ancient volcanic eruptions. These formations shape the region's topography and influence groundwater systems. Basaltic terrains in Maharashtra, characterized by low porosity but high fracture density, provide groundwater storage primarily through weathered zones and fractures. While these aquifers offer water for irrigation and domestic use, their low porosity and recharge rates make groundwater sustainability a challenge. In contrast, alluvial areas, particularly along river valleys, feature more porous and water-retentive soils, offering significant potential for groundwater storage. A geoenvironmental approach is crucial in this context as it integrates geological, hydrological, and environmental factors to assess groundwater resources comprehensively. This approach, which has been employed in recent studies in the different Basin, enables a better understanding of how human activities, land use, and climatic conditions impact groundwater systems. For instance, recent literature reviews and progress reports, including the use of techniques like AHP fuzzy logic for potential mapping, indicate the importance of adaptive management practices. By considering both the quantity and quality of groundwater alongside environmental health, the geoenvironmental approach supports sustainable management strategies for this critical resource in Maharashtra’s diverse terrains.

Maharashtra, known for its diverse geological terrains, has implemented various groundwater management strategies across different regions, with significant focus on both basaltic and alluvial aquifers. Two key case studies from the state – Vel River in Pune (basaltic terrain) and Mor River in Jalgaon (alluvial terrain) – provide valuable insights into the effectiveness of groundwater management practices. In the Vel River basin, located in the Deccan Plateau's basaltic region of Pune, groundwater management has been a critical concern due to the slow recharge rates and limited storage capacity of basaltic aquifers. Over-extraction for irrigation purposes has led to declining water levels in many areas. However, a successful strategy implemented here has been community-based water management, which involves the active participation of local farmers, NGOs, and government bodies. A key component of this strategy has been rainwater harvesting through the construction of small check dams, percolation tanks, and recharge wells. These structures help increase the infiltration of rainwater into the fractured basaltic rock, enhancing recharge during the monsoon season. The government has also promoted watershed management programs, aiming to reduce surface runoff and increase water retention in the catchment areas. Furthermore, the community has been engaged in water budgeting, where water use is monitored, and practices like drip irrigation have been encouraged to minimize wastage. While these efforts have resulted in a modest increase in groundwater levels, challenges remain in scaling these practices across the region, especially with the variability in rainfall patterns and the slow recovery of deeper aquifers.

In contrast, the Mor River basin in Jalgaon, situated in an alluvial region, faces challenges related to high groundwater extraction, primarily for irrigation in the region's vast agricultural fields. The alluvial aquifers in this area are more productive, but over-extraction has led to concerns about groundwater depletion and contamination. The local authorities and farmers in the region have adopted integrated water resource management strategies, with a focus on sustainable agricultural practices, efficient irrigation techniques, and community-driven initiatives. One of the most successful interventions has been the implementation of water-efficient irrigation systems such as drip and sprinkler irrigation, which have significantly reduced water wastage and improved crop yield. Additionally, artificial recharge techniques such as the construction of recharge ponds and recharge wells have been used to enhance groundwater replenishment during the monsoon season. The state government has also supported the construction of small-scale water storage systems and promoted rainwater harvesting at the household level. The community's involvement in water management has been crucial in raising awareness about groundwater conservation and ensuring the sustainable use of water resources. However, challenges such as contamination from agrochemicals and industrial effluents, as well as the risk of saline intrusion in some areas, remain persistent concerns.

In both regions, government policies play a pivotal role in facilitating groundwater management. Maharashtra's state policies, such as the Maharashtra Groundwater (Development and Management) Act, 2009, encourage sustainable water use practices and emphasize groundwater recharge. The government has also supported initiatives to enhance groundwater data collection and monitoring, which allows for better decision-making. Despite these efforts, both regions face ongoing challenges such as insufficient funding for large-scale implementation, resistance to new water management practices, and the need for greater coordination between local communities, government bodies, and private stakeholders. Advances in technology have significantly enhanced the ability to assess and manage groundwater resources in diverse terrains, including both basaltic and alluvial regions. In Maharashtra, modern techniques such as remote sensing, GIS mapping, hydrogeological modeling, and isotopic analysis have proven instrumental in improving groundwater management practices, particularly in understanding the complex groundwater dynamics of different geological formations. The integration of remote sensing, GIS, hydrogeological modeling, and isotopic analysis has revolutionized groundwater management practices, enabling more precise and efficient water resource management. These technologies provide a comprehensive understanding of groundwater systems, allowing for better monitoring of groundwater levels, recharge rates, and water quality.

In conclusion, understanding the geological and environmental factors that influence groundwater resources in both basaltic and alluvial terrains is crucial for ensuring sustainable water management in Maharashtra. The Deccan Plateau's basaltic formations, with their unique fracture systems, and the porous, unconsolidated sediments of the alluvial regions, both present distinct challenges and opportunities for groundwater management. Through the application of advanced technologies, hydrogeological modeling, and isotopic analysis, significant progress has been made in assessing groundwater resources, enhancing recharge, and improving water quality monitoring. Additionally, community-based management practices, government policies, and adaptive strategies to address climate change impacts have proven essential in maintaining groundwater sustainability in both terrains.

Keywords: *Groundwater, Deccan Plateau, Basaltic aquifers, Maharashtra*

GROUNDWATER USE UNDER INTENSIVE AGRICULTURE

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Fresh groundwater is rapidly becoming one of our planet's most valuable strategic resources, particularly in semi-arid, agriculturally intensive regions where surface water inflows are increasingly uncertain. Roughly 3% of the world's water supply is considered fresh; of this portion, approximately one-third is available as groundwater. Water is a key resource for human existence, and despite technological advances, established freshwater supplies worldwide are increasingly in crisis because of unmanaged consumption and lack of protection. Uncertainty in annual precipitation, subject to climate change, creates new vulnerabilities in water-scarce regions such as using local groundwater for various purposes, thus driving increased consumption of our planet's most valuable strategic resource. According to recent estimates, the intensity of worldwide groundwater use has increased by 23% globally since 1950, from approximately 124 m^3 to 152 m^3 per capita in 2021, and use is projected to exceed 1500 km^3 annually by 2050 if the present trend continues. We must work harder to manage and protect this resource.

While agriculture is the most prominent user of freshwater, agricultural production is the most significant driver of groundwater pollution. Evidence for contamination from agricultural production began to be noticed in rural areas approximately 75 years ago and agricultural pollution has recently overtaken contamination from industry and municipal pollutant sources worldwide. Sustainable use of this valuable strategic resource for agriculture must carefully evaluate not only the quantities used and potential for depletion, but also the vulnerability of these reserves to contamination. Aquifers supplying safe drinking water, irrigation, and industrial uses are increasingly stressed, depleted in areas with low recharge, and contaminated where groundwater lies near the surface. Depleted aquifers and contaminated groundwater are expected to impact food production, and economic and social well-being in the coming years. Planning for sustainable groundwater use thus will require better management of groundwater quantity and quality particularly in agriculturally intensive regions.

In examining the literature, we find many instances where the loss of this resource through groundwater level declines and reserves alone have severely impacted the local economy. For example, it has been estimated that the average loss of revenue in the High Plains aquifer region of the United States will result in a total reduction of $127 million by 2050 and $266 million by 2100. Groundwater depletion requires adjustment in cropping practices, followed by resource use restrictions leading to income loss. At the same time, continued use of the resource contributes to a severe and effectively permanent reduction in the quality of the resource, impeding its use for drinking and habitat. For example, in the Nebraska part of the High Plains aquifer system, a strong correlation was found between corn production area, crop prices, and groundwater nitrate concentrations. Comparing areas of the High Plains aquifer with the most significant declines in the water table, we also find a high probability for elevated nitrate concentrations. If we look at areas of the same system with a high density of irrigation wells, sandy soils, and shallow water tables, we see an even closer correlation.

Nitrogen fertilizer losses to groundwater are highest on sandy, irrigated soils, which are shallow water tables. The cost for small public drinking water treatment ranges from $3.5-4.0 million for nitrate treatment alone and up to $15-20 million for moderately sized communities faced with nitrate and other contaminant sources.

Nitrate is now recognized as the most common groundwater pollutant worldwide, and contamination is directly associated with irrigated row crop agriculture. Even parts of India, where agriculture is intensive, are affected by groundwater pollution. A recent report by the Central Ground Water Board reveals that 440 districts across India have high nitrate levels in their groundwater, with 20% of the samples exceeding the permissible limit for drinking water. The Northern Indo-Gangetic Plain groundwater resource, which supports about 500 million people, is severely contaminated with nitrate (>200 mg-N/L), posing health risks to 27% of the children. In another study, 46.4% of dug wells and 51.3% of tube wells in several districts of Central India, including parts of Maharashtra, exceeded the nitrate permissible limit in drinking water. Other contaminants, such as geogenic uranium and arsenic, are also linked to nitrate contamination, groundwater pumping, and excess fertilizer use. While nitrate concentrations above safe drinking water levels alone may concern many, there is increasing evidence that a mixture of contaminants will result from continuing practices. Each contaminant is associated with different health effects and treatment requirements, thus complicating our ability to use groundwater safely for human consumption and irrigation. Mitigating groundwater pollution is quite expensive, and treatment technologies must match water use, chemical composition, and contaminants to be treated. Reduction of contaminant inputs from land use through better management of fertilizers and water use in irrigated landscapes should continue to be widely promoted, but even so our continued use of strategic groundwater supplies more monitoring and more expensive treatment.

Keywords: *Groundwater, agriculture, pollution, contaminations*

USE OF REGIONAL SCALE MODELS FOR WATER RESOURCES ASSESSMENT, PLANNING, AND MANAGEMENT

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Most states in the United States have created laws and policies to manage groundwater withdrawals. These laws provide a legal foundation for the government to ensure that responsible agencies manage their groundwater resources sustainably. For example, Arizona passed the Groundwater Management Act in 1980 and more recently California enacted the Sustainable Groundwater Management Act in 2014. These laws provide a legislative framework for long-term sustainable groundwater management in these states. Large amounts of data are collected, organized, and disseminated by the government and private entities for stakeholders to use in a variety of different ways. These data include, but are not limited to, precipitation, meteorological data to support the estimation of evapotranspiration (ET), streamflow, groundwater elevation, and aquifer data such as pumping test estimates, well log texture data, and geophysical survey data. The measured or estimated data provide valuable resources that enable the formation of a scientific basis for making objective decisions and come up with quantifiable metrics to monitor progress. The large amounts of continuous data form the basis of analyses and modeling of water resources that drive decision-making. This talk presents real world applications of modeling in southwestern United States, particularly in California and Arizona. Southwestern states share common water supply challenges. As surface water supplies dwindle with increased water demands and changing climate, users turn to groundwater during droughts, withdrawing from aquifer systems that are already under stress. Tough choices have to be made when managing the limited water supplies that provide for agricultural, municipal, domestic, and environmental uses. Recurring and prolonged droughts have accentuated the crises. Integrated surface water-groundwater management, therefore, is key to sustainable development. Regional scale modeling performed in Sacramento Valley, California and Phoenix Active Management Area (AMA) in Arizona will be presented.

The Sacramento Valley Model (SVSim) is an integrated surface-water and groundwater model. The primary objectives of SVSim include the estimation of regional water budgets and to estimate stream depletion caused by groundwater pumping. SVSim was developed using the Integrated Water Flow Model (IWFM) code. It incorporated precipitation derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), ET estimates available for agricultural, urban, and native land uses, geological information derived from well and boring logs, groundwater pumping derived from water demand calculations, and additional data and information needed by the model. Model calibration was supported by streamflow measurements, groundwater elevation measurements, estimates of agricultural water supply requirements, and additional observations such as independently estimated aquifer parameters that provided constraints on water budgets. Achieving a plausible water balance was critical to SVSim calibration to ensure it provided reliable calculations for numerous current and long-term predictive groundwater management applications, which will impact stakeholders in the Sacramento Valley.

The Phoenix AMA model was developed to determine whether future development is sustainable in the Phoenix AMA. A MODFLOW model was developed and calibrated. A variety of input data for model development and observation data for model calibration were used. Achieving a reliable water budget and estimating plausible aquifer properties was essential in developing reliable predictive capabilities of the model. These predictions had real world repercussions on development decisions in the Phoenix area. The need for a legislative framework, data collection, and scientific decision-making is imminent in India. Lessons can be learned from groundwater management in the US and adapted for Indian conditions. The social challenges presented by development and enforcement of laws, and technical challenges such as fractured bedrock geology, and limited data availability should be addressed sooner rather than later. Social issues need to be met with the development of reasonable legislation, together with education and outreach to encourage coordination at a local level with farmers and other stakeholders. The technical challenges can be met with data collection and the development of reliable water resources estimates based on data analyses and modeling for making informed decisions.

Keywords: *Regional scale modeling, data analysis, data collection, legislation, groundwater management, water resource management, water resources*

CHALLENGES AND STRATEGIES TO IMPROVE GROUNDWATER AVAILABILITY

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Water availability is going to be one of the most challenging issues for the 21st century, around the world. The challenges are intensifying due to increased populations needing both water and foodstuffs and being dramatically compounded by climate change. Some of the issues becoming evident in Canada in particular are presented, and some of the strategies that have the potential to improve the future circumstances but not without significant effort. For e.g. For the ‘breadbasket’ portion of Canada (the prairie provinces), climate is changing from snowfall to rain. The results are showing that significant runoff is occurring earlier, making the runoff less available for agricultural use and water supplies to some cities. The total precipitation is basically constant over time, the amount of rain that is occurring since about 1970 has been increasing, whereas the snowfall rates are decreasing (due to warmer temperatures from climate change) are decreasing. The net result is that the high runoff periods are occurring earlier, leaving much less to follow in the periods where water is needed for supplies to cities and for irrigation purposes. Climate change is resulting in more intense storms, causing increased levels of flooding of cities. While an array of natural disasters is increasing (e.g., forest fires) in frequency and severity, but flooding is now the most common and costly occurring natural hazard in Canada, causing over $1 billion in direct damage to dwellings, properties and infrastructure and affecting thousands of dollars in damage. The Canadian government is moving forward with a number of measures to help Canadians reduce their financial and physical vulnerability to flooding. Assessments of intense storms are showing that what was a 500-year event is being projected to become a 100-year event, and hence resulting in frequencies that are exacerbating flood potential. Land glaciers in Canada (and elsewhere) are rapidly being depleted, translating to less water will be available for downstream use to cities. This issue is also highly relevant to countries such as India, Bangladesh, and Pakistan, and for many other locations such as Amu Darya and the Mekong and many more.

In Ontario, Canada, heavier rains are occurring earlier, resulting in soil erosion before the vegetation has fully developed. In recent studies, an assessment showed that heavy storms (the types of storms that occur ~8 times per year, are changing the times within a year as to occurrence). The heavy storms are moving earlier during the year by about 45 days. The result is that heavier storms were occurring in August but now, instead, the heavy storms are now occurring now in June, with the result that for Ontario’s agriculture timeframes, in June, the agricultural growth is not yet established. hence, when the heavier rains occur, the vegetation is not fully established so that we are getting severe damage to the soils being washed off and slumping into nearby rivers or streams. Historically (approximately 40 years ago), the heavy storms in a year were occurring during the substantial agricultural growth, so minimal erosion was evident. Instead, what is happening now is that more erosion and slumping of soils. Since recharge of groundwater involves very significant time to occur, that it takes. For every meter drop in groundwater level, this translates to ~3.3 cm of subsidence that is not recoverable. Some options are being evaluated as a means to enhance infiltration to

both replenish groundwater as well as to decrease flooding, through use of porous pipes and underground storage. The situation has reached the point where much planning needs to be done, to protect the availability of water for useful purposes, and to avoid both flooding and drought, both of which are the convincing factors that water will become one of the most challenging concerns to the human race.

Keywords: *Water availability, floods, soil erosion, Canada*

UNRAVELLING LONG-TERM CONTRIBUTIONS TO RECHARGE IN THE INDUS BASIN

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The Indus basin is vital for food production in South Asia and as a result has become a global hotspot of groundwater exploitation. The region has a long history of major surface and, more recently, groundwater development for irrigation and is the largest contiguous tract of irrigated land in the world. The Gravity Recovery and Climate Experiment (GRACE) satellites, launched in 2002, provided early evidence of the scale of groundwater depletion in the region. More recently, a number of studies have shown that groundwater depletion is more nuanced and regionally heterogenous, and is influenced by a combination of human and climatic factors, including changes in monsoon precipitation and recharge from the regions vast canal network. The areas of most concern for the long-term sustainability of the transboundary aquifer are within the states of Punjab and Haryana in India and Punjab Province in Pakistan. Here groundwater levels can be 20 – 50 m below ground level and are falling at rates of 0.5 – 1 m per year.

Recent groundwater depletion is set within a much longer history of groundwater level variation spanning the last 150 years. Using a unique long-term dataset, we investigated groundwater level change throughout the 20th century and the first decade of the 21st. The dataset contains time-series from 3827 observation wells and includes 110 years of groundwater level data from 1900 to 2010. Our aim was to: 1) examine changes in post-monsoon groundwater levels during the 20th century and; 2) unravel the influence of canal construction, tubewell development and precipitation on long-term groundwater storage in northwest India and central Pakistan.

We found that for the majority of the 20th century groundwater levels were rising and estimated net groundwater accumulation of 350 km^3 (estimated range: 150-450 km^3). Large scale irrigation development via canal construction played a defining role in groundwater accumulation during the early twentieth century. Between 1900 and 1960 approximately 150,000 km^2 of canal command area was constructed. The groundwater depletion that occurred in the first decade of the 21st century, and which we estimate at 75 km^3(estimated range: 25-100 km^3), was driven by the superimposed effects of low rainfall and large-scale tubewell development. Between 1970 and 2010 almost six million tubewells were constructed. However, between 1970–2000, when large increases in tubewell irrigation began, groundwater levels stabilized because of higher-than-average rainfall.

More recently we have attempted to estimate the contribution of different sources of groundwater recharge in the western Indus basin. To achieve this, we developed a spatially correlated linear model for the daily rate of groundwater level change using a higher temporal resolution dataset across the period from 1979 – 2009 from 2,968 observation wells in

Pakistan Punjab. Across Punjab mean recharge from canals and rivers is approximately 1.5 mm/day, and precipitation is approximately 2 mm/day. However, we find that recharge contributions vary temporally and spatially, precipitation provides a larger and more consistent source of recharge in the north-western areas of Punjab, while canal and river contributions are more significant in the south. We find that canals provide a consistent baseline level of groundwater recharge, even during periods of low precipitation and river flow. We also find evidence of enhanced capture from 2000 to 2010 of around 1 mm/day, as groundwater pumping increased during this period. As groundwater levels are lowered the aquifer has more capacity to accommodate additional recharge.

Our study clearly demonstrates that human activity in the early 20th century increased the total volume of groundwater available prior to the large-scale exploitation that began in the late 20th century. The two dominant human interventions during this period, canal irrigation during the 20th century and groundwater development for irrigation during the late 20th and early 21st centuries, continue to play an important role in groundwater recharge and storage dynamics in this critically important region. Our results have implications for conjunctive use of groundwater and surface water in the region and on the debate in managing recent groundwater level decline in the region.

Keywords: *Indus Basin, groundwater, water availability, irrigation*

ARSENIC CONTAMINATION AND GROUNDWATER HYDRODYNAMICS: GEOSCIENTIFIC INSIGHTS FROM THE GANGA BASIN, NORTHERN INDIA

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The Middle Ganga Plains (MGP) in Northern India, one of the world's most densely populated regions, faces critical water resources, primarily groundwater depletion and arsenic (As) contamination. These issues are closely interlinked with the over-exploitation of groundwater for drinking and irrigation purposes. It causes significant environmental and public health problems. The depletion of shallow aquifers coupled with the increasing dependence on deeper often As-free aquifers, intensified the risk of contamination. To effectively manage this problem, a comprehensive understanding of the region's complex groundwater hydrodynamic is essential particularly in relation to the As-migration from shallow to deeper aquifers by developing a groundwater flow model with geoscientific knowledge. In this MGP region, groundwater depletion is primarily driven by unsustainable extraction for irrigation and domestic consumption. As the shallow aquifers are drained, there is a growing dependency on the deeper aquifers, which are largely uncontaminated by arsenic. However, this over-extraction increases the risk of mixing As-contaminated groundwater from shallow aquifers to deeper, which are not contaminated sources. The presence of arsenic in groundwater is attributed to natural geochemical processes that mobilize arsenic from sedimentary layers often enhanced by the over-exploitation of groundwater, and sometimes, it comes from anthropogenic sources. Consequently, certain areas in the basin experience arsenic concentrations exceeding the WHO's safe limit (50 ppm), threatening both human health and agricultural productivity.

There are several issues that contribute to the worsening As-contamination in groundwater at the shallow aquifer of the MGP region. They are mainly the excess and unregulated pumping of groundwater disrupts the natural equilibrium of the aquifer system. This disturbance can lead to pressure imbalance that causes the migration of arsenic-contaminated water from shallow aquifers to deeper, previously not contaminated layers. The confining lay layers that separate mainly two principal aquifers act as barriers to prevent the mixing of groundwater. However, under the stress of excessive pumping, these layers may be compromised to allow contaminated groundwater to move downwards from shallow aquifers into deeper layers. This inter-aquifer leakage presents a significant threat to groundwater quality, particularly when the thickness and strength of clay layers are reduced. Geophysical surveys such as electrical method and heliborne survey have revealed multi-layered aquifer disposition along with paleochannels, and faults within the aquifer system. These geological features can act as conduits and enable to migration the As-contaminated water from shallow to deeper aquifers as in dynamic. Understanding these geophysical features is crucial for assessing contamination risks and developing mitigation strategies.

To understand the groundwater dynamics and the risks of inter-aquifer leakage, a regional groundwater flow model was developed taking the consideration of natural boundaries, and also micro-scales. This model simulates the interactions between two aquifers (both shallow and deeper) under varying stress conditions to assess the potential for contamination of multi-aquifer system. The simulated model results have shown that increased pumping leads to groundwater depletion. The depletion of shallow aquifers exacerbates the situation, as deeper aquifers become more susceptible to contamination. The model has demonstrated that under stress conditions inter-aquifer leakage could reverse with arsenic laden water moving downwards into deeper aquifers. This reversal represents a significant threat to groundwater quality as it can contaminate previously safe groundwater reserves with toxic levels of arsenic. The model identified specific regions within the MGP that are particularly susceptible to inter-aquifer leakage. These areas are characterized by thinner clay layers that are more prone to the migration of contaminated efforts.

In the view of implication for groundwater management in the MGP, the safe pumping rates for marginal farmers are suggested. The model provides the guidelines for safe pumping rates that ensure sustainable extraction from deeper aquifers without risking contamination. By adopting these guidelines, marginal farmers can avoid over-extraction, reducing the likelihood of arsenic contamination and ensuring the long-term availability of clean water. Alternative water supply sources are also identified. The study revealed the areas with uncontaminated groundwater that can be used as alternative sources for groundwater extraction. By prioritizing these areas, decision-makers can reduce pressure on vulnerable aquifers and ensure a sustainable water supply for agricultural and domestic use. In addition, the regulated pumping practices are suggested. This model has shown the importance of implementing controlled and sustainable groundwater extraction practices. It is essential to enforce regulations that the limited pumping rates, and prevented over-extraction to safeguard groundwater quality. This can help mitigate the risk of arsenic contamination and ensure the long-term sustainability of groundwater resources. The combined challenges of arsenic contamination and groundwater depletion in the MGP regions pose significant risks to public health, agriculture, and the region’s overall water security. The integration of advance groundwater modeling and geophysical data provide a detailed understanding of the region’s multi-layered aquifer system and the complex dynamics driving contamination. Addressing these challenges requires sustainable groundwater management strategies that balance water extraction with the need to protect groundwater quality. Implementing controlled pumping, identifying alternative water sources, and prioritizing region’s vulnerable to contamination are the key steps in ensuring a safe and reliable groundwater supply for millions of people in the MGP. The sustainable management will be crucial for mitigating the long-tern effects of arsenic contamination and safeguarding groundwater resources for future generations.

Keywords: *Multi-layered aquifer system, groundwater modelling, hydrodynamics, reversal leakages, arsenic threats, Ganga basin, Northern India*

VANISHING GROUNDWATER - SEEKING PATHWAYS FOR WATER SECURITY IN THE NCT OF DELHI

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Groundwater depletion in the Indian National Capital Territory (NCT) of Delhi has emerged as a critical environmental and socio-economic issue, driven by rapid urbanization, shifting rainfall patterns, and escalating reliance on groundwater resources. As Delhi's population has expanded rapidly over the past few decades, so has the pressure on natural water resources, with groundwater becoming the primary source for both residential and commercial consumption. The increasing demand, coupled with erratic rainfall and insufficient recharge mechanisms, has resulted in significant spatial variations in groundwater availability and heightened the risk of long-term depletion. This study investigates the spatio-temporal dynamics of groundwater levels between 2013 and 2023, examining the interplay between groundwater extraction patterns and urban expansion across the NCT. It highlights how the heterogeneity in landforms influences groundwater recharge processes, resulting in uneven abstraction and availability throughout the city.

Using secondary data provided by the CGWB, this research adopts a GIS-based methodology to capture intra-annual, seasonal, and decadal trends in groundwater levels. The study emphasizes the importance of understanding the spatial variability across different regions of Delhi, recognizing that groundwater depletion is not uniform and requires a targeted approach. While some areas exhibit minimal declines, others are experiencing significant depletion, posing serious risks to long-term water security. As the demand for water intensifies, the identification of spatial patterns through advanced geospatial techniques becomes essential to guide sustainable management practices. This study utilizes multiple geospatial techniques and statistical methods to comprehensively analyse groundwater trends and urbanization impacts. The research employs Getis-Ord Gi* hotspot analysis to identify significant clusters of groundwater depletion and to detect spatial mismatches, such as areas with unexpectedly high or low extraction rates. These spatial clusters provide insights into regions requiring urgent policy intervention. In addition, Bivariate Local Moran's I is applied to explore the spatial correlation between groundwater levels and urbanization patterns, revealing areas where urban sprawl and extraction rates exhibit a strong interrelationship. To further investigate the temporal dimension, the study applies the Mann-Kendall trend test and Sen's Slope estimator to identify statistically significant trends in groundwater levels over the 10-year period. This trend analysis allows for the detection of emerging hotspots and forecasts localized risks of depletion. The results from these statistical analyses are particularly relevant for decision-making, as they help policymakers identify regions where groundwater levels are declining rapidly, necessitating immediate action to prevent future crises. Seasonal variations are also analysed, with a focus on pre-monsoon and post-monsoon groundwater levels, reflecting the impact of rainfall variability on natural recharge processes.

The results of this study reveal that densely populated areas in Delhi exhibit accelerated groundwater depletion, driven by the growing water demands of urban settlements. Southern parts of Delhi, which include high-density residential and commercial zones, have witnessed significant declines in groundwater levels over the past decade. Shahdara and the New Delhi districts reflect the most critical levels of depletion, with groundwater levels falling by 2 to 4 m. The situation in these regions is particularly alarming as groundwater serves as a critical buffer against water shortages during dry seasons. The seasonal analysis shows predictable fluctuations, with groundwater levels rising during the post-monsoon period due to rainfall recharge and declining sharply in the pre-monsoon months as extraction increases. However, the variability in seasonal recharge indicates that changing rainfall patterns are disrupting natural replenishment cycles, making certain areas more vulnerable to long-term depletion. This trend is particularly evident in the southern and central parts of the city, where high water consumption and poor recharge mechanisms exacerbate the problem. The spatial analyses using Getis-Ord Gi* reveal clusters of groundwater depletion concentrated in urban centres, highlighting the area's most at risk. Conversely, some peripheral areas show relatively stable groundwater levels, indicating that land-use patterns play a critical role in recharge dynamics. Bivariate Local Moran's I further confirm a strong positive spatial correlation between groundwater depletion and urbanization, particularly in regions where unplanned urban growth has occurred without adequate infrastructure to manage water resources. The findings of this research underscore the need for spatially explicit governance frameworks that take into account the heterogeneity of groundwater dynamics. Current water management policies often treat the city as a homogenous unit, overlooking the localized variations in depletion and recharge. This study suggests that the development of region-specific strategies based on the identified hotspots and spatial outliers is essential to ensure sustainable groundwater management. The GIS-based approach adopted in this study offers a valuable framework for identifying areas at high risk of groundwater depletion and can be replicated in other urban regions facing similar pressures. By combining spatial and statistical analyses, the methodology provides actionable insights that can support the design of targeted interventions, such as artificial recharge structures, stricter extraction regulations, and incentives for rainwater harvesting. The study emphasizes the importance of strengthening local institutions to monitor groundwater usage more effectively and recommends integrating urban planning with water management policies to mitigate future risks.

The study concludes that groundwater depletion in the NCT of Delhi reflects the complex interplay between urbanization, rainfall variability, and land-use patterns. As urban growth continues unabated, the pressure on groundwater resources will only intensify, making it imperative to adopt sustainable practices at both the local and city-wide levels. The research highlights the need for data-driven policies that leverage spatial insights to inform decision-making processes and calls for greater collaboration between urban planners, hydrologists, and policymakers. Future research could focus on integrating groundwater models with climate change projections to assess the long-term impacts of changing rainfall patterns on groundwater availability. Additionally, expanding the temporal scope of the analysis to include more recent data could offer deeper insights into how recent policy interventions and rainfall trends have influenced groundwater dynamics. This study provides a replicable model for addressing groundwater challenges in other urban contexts and serves as a crucial step towards sustainable water resource management in Delhi.

Keywords: *Groundwater governance, Delhi, urbanization, GIS, spatio-temporal analysis*

URBAN GROUND WATER PROBLEMS AND PROSPECTS – A CASE STUDY OF UPPER MUSI BASIN HYDERABAD, INDIA

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India is presently witnessing fast urbanization. According to 2011 census 31% of India's population are living in cities and it is going to be increased by 50% by the year 2050. As the cities are expanding, traditional drinking water sources are sinking either due to pollution or due to unsustainability. Hence distance from the source is increasing putting pressure on the investments. On the other hand, as the large-scale water is pumped to the city, traditional ground water sources are getting polluted due to lack of treatment of sewerage and solid wastes and their disposal on the land and water bodies. In this context, governments should plan for proper and sufficient treatment plants and discharge the sewerage only after treating it to tertiary level. Same is the case with the industrial pollution, flouting all the norms of state and central pollution control boards, they are disposing their wastes spoiling land water and air. Latest investigations of the ground water reveals that the presence of heavy metals, pharmaceuticals, microplastics and many carcinogenic elements are found in the ground water. Once ground water is polluted it is very difficult to remediate and take decades to clean. Moreover, ground water is the only nearby source when drought occurs and surface water supply ceases.

The rainfall, ground water levels, and the surface and ground water quality investigation in the upper Musi basin including the catchments of Osmansagar and Himayatsagar, and Hyderabad city over the last three decade forms the data base for the present study. Water levels from both digital water level recorders and traditional water levels from open wells were collected from the state ground water department and directly from the field. Rainfall was collected from bureau of economics and statistics department of the state. Ground water samples and surface water samples from lakes and rivers were collected and analysed for various hadrochemical and hydrogeochemical parameters including emerging pollutants and heavy metals. Time series graphs and contour maps, for water level variations and chemical parameters were prepared and analysed. From surface to ground water pollution pathways were established

In spite of normal rainfall, ground water levels have declined over the years though recovery of ground water levels is achieved in good monsoon years. The general decline is due to overexploitation of groundwater in the rural areas due to intensive agriculture owing to the demand for the agriculture produce in the nearby city Hyderabad. In fact, the more the ground water is withdrawn in the catchments, the lesser is the inflows to the reservoirs. It is the ground water levels which are influencing the recharge more, rather than the actual rainfall. The deeper the ground water levels the more is the recharge from the rainfall. With in the Hyderabad city, reduction of recharge areas due to concretization of surface and heavy pumping of ground water is the main reason for ground water levels decline. It has been observed in the city clearly that the pollutants dumped on the surface are reaching the groundwater which includes heavy metals such as lead, Zinc and Arsenic There is a clearcut deterioration of water quality as we run the TDS profile from rural to urban areas.

Rain water harvesting and its recharge to ground water in urban areas is still in its infant stage as the implementation of laws governing the recharge is hardly complied with. With the advent of climate change coupled with urbanization, the cities are more prone to floods and the urban flood should be wisely directed to storage treatment and recharge facilities. In this context the civil society has great role to play by popularizing recharge pits in the individual houses and community recharge pits in their residential areas. Artificial recharge of ground water not only improves quantity but also ground water quality. Treatment of sewerage water and recirculating it back to the city for gardening purposes will reduce the demand on the city water supply.

Conservation Protection and maintaining of fresh water in the lakes and rivers surrounding in our environment is the key component to our water security. Residential Welfare Associations (RWAs) must take initiative not to pollute water bodies and educate the residents not to throw garbage and other liquid and solid wastes in the water bodies. It is highly essential to form lake/river conservation committees from the civil society with all the RWAs surrounding the lake/river as members of it and become a strong force to represent the government. Since these lakes and rivers are the natural recharging structures, if we maintain them as fresh water bodies our ground water will not be polluted and we can safely use ground water in our residential localities surrounding the water body. Local governments must implement the laws governing the water in letter and spirit. In case no such law is existing, it is highly essential to enact a comprehensive law governing the urban water including the ground water.

***Key words**: Urban ground water, pollution, ground water recharge, ground water laws*

HARNESSING MACHINE LEARNING AND DECISION SCIENCE FOR CLIMATE CHANGE ADAPTATION IN GROUNDWATER

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Groundwater plays a vital role in drinking water supply and agricultural production. It is also becoming a driving factor for several industries because of the dependence of industrial water supply on groundwater resources. The overreliance on groundwater coupled with adverse hydrological manifestations resulting from climate change and reduced groundwater recharge particularly in urban environments has gone up considerably has led to a significant decline in water level which is posing serious challenge for water sustainability and food security. The traditional hydrological assessment methods involving empirical formula, adhoc norms, or process based hydrological models are lacking in deciphering intricate interactions between various hydrological processes and external forcings that influence groundwater dynamics and thereby affect groundwater recharge, groundwater level and groundwater availability. A knowledge gap persists in understanding the precise effects of changing climate conditions on groundwater, as well as the efficacy of advanced modelling approaches that could address this challenge.

Machine Learning (ML) and Remote Sensing (RS) techniques provide potential new ways to address these issues. ML algorithms can process large, varied datasets to uncover patterns in aquifer behavior that might not be visible using standard statistical or physics-based models. They can incorporate different inputs such as precipitation, soil type, pumping records and land surface temperature. Meanwhile, RS technologies have advanced considerably, offering real-time data on variables like terrestrial water storage, land surface temperature, vegetation indices, and soil moisture content. These platforms reveal changes in groundwater storage over large areas and often fill data gaps where traditional monitoring wells are unavailable. When ML models combine these RS inputs with local weather data and extraction rates, they can generate more accurate and flexible forecasts of groundwater levels. Despite their potential, the integration of these advanced techniques for groundwater management under climate change scenarios remains less explored.

The objective of the study is to present an integrated framework of a multi-dimensional approach, combining ML algorithms (random forests, neural networks), RS data (satellite-based landscape, soil moisture and precipitation measurements or estimates), and optimization techniques (linear and nonlinear programming algorithms with multiple conflicting and non-commensurate objectives capturing diverse stakeholders' viewpoints and operational and site specific restrictions and constraints) to investigate groundwater dynamics under various climate scenarios. The key findings include enhanced predictive accuracy, with ML models trained on RS data significantly improving groundwater level predictions compared to conventional climate models. By incorporating RS inputs, the ML models achieve higher predictive accuracy for groundwater levels than the traditional climate models. Integrating these techniques also reduces forecast uncertainty, yielding more reliable information for resource planning. RS data highlights critical spatial and temporal patterns in groundwater recharge and depletion, informing targeted management measures. Finally, the optimization models offer actionable strategies for sustainable groundwater extraction, ensuring a balance between sustainable and ecological requirements and human demands under changing climate conditions.

This study explores and demonstrates various techniques employed for sustainable groundwater management and policymaking under the stress of climate change. More specifically, the study examines robust ML models for groundwater level prediction by incorporating meteorological data, land-use patterns, and anthropogenic stressors. It explores advanced RS techniques to capture large-scale spatial and temporal variations in groundwater storage and associated environmental factors such as soil moisture, vegetation indices, and land surface characteristics. It discusses the formulation of optimization strategies that consider conflicting demands, including municipal water supply, agriculture, and industry to ensure equitable and sustainable groundwater allocation. The study also assesses model uncertainty and reliability by comparing ML driven forecasts with traditional climate model outputs and in-situ observations. Furthermore, it fills a critical gap in the literature by demonstrating the efficacy of integrating advanced techniques for groundwater management, paving the way for future research. The applicability of the developed framework is also demonstrated with a case study by employing machine learning to predict groundwater variations in Delhi using an Artificial Neural Network (ANN) model. The model employs historical data and considers influencing parameters, namely, precipitation, soil permeability, and satellite derived changes in land use/land cover to provide accurate predictions and practical insights. The results demonstrate the effectiveness of machine learning in identifying spatiotemporal variations in groundwater levels as evident from the significant predicted accuracy achieved from such models. It is capable of handling complex non-linear relationships that provides big boost over the conventional models for examining groundwater dynamics in changing climate.

The integrated framework developed in this study addresses the limitations of conventional climate models and offers a scalable, adaptable solution for managing groundwater in diverse regions, such as semi-arid areas and rapidly growing urban environments. By combining RS data with in-situ measurements, ML models significantly improve the accuracy of groundwater predictions, particularly during extreme weather events like droughts or heavy rainfall. This enhanced adaptability is critical in regions where limited field data can make traditional models less effective. Additionally, multi-objective optimization techniques, supported by these improved predictions, help decision-makers design optimal strategies for groundwater extraction and recharge. Early analyses show that aligning well locations, managing pumping schedules, and implementing artificial recharge projects based on these optimized strategies can extend the life of aquifers by preventing excessive drawdowns while helping maintain essential baseflows. This not only minimizes the risk of land subsidence but also protects ecosystems from degradation. This study offers a thorough framework for groundwater assessment, providing essential insights to aid policymakers and water resource managers in implementing focused and effective methods to mitigate groundwater depletion and foster sustainable resource planning. The proposed framework is adaptable to different geographic and climatic conditions, making it a valuable tool for evolving climate adaptation strategies, global groundwater management and policymaking.

Keywords: *Machine learning, optimization, remote sensing, groundwater management, climate change adaptation*

A NEW GEOPHYSICAL APPROACH TO ASCERTAIN RISK OF GROUNDWATER CONTAMINATION IN UNCONFINED ALLUVIAL AQUIFERS: A REVIEW

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In India, through the construction of millions of private wells, there has been a phenomenal growth in the exploitation of groundwater during the last 150 years. In part, this is due to the absence of a systematic registration of wells. Widespread groundwater pollution has a potential of further rendering the resource useless before it is exhausted. This poses a big challenge to the agencies responsible for groundwater development and governance in the country. Many cities in such regions have also witnessed development of significant industrial activities where large quantities of waste/effluents are disposed off directly into the local drainage systems. The exploitation of groundwater through shallow wells and handpumps constructed in these areas for meeting drinking water requirements of the large populace is often found to be contaminated from the hazardous, often toxic, chemicals drawn from the wastes/effluents percolating with the infiltrating runoff directly into the unconfined aquifer(s) of the region. Arising from earlier studies, the magnitude of 'total longitudinal conductance's of the unsaturated zone overlying an unconfined aquifer can be used for estimating degree of its protection from the pollutants infiltrating and percolating into the aquifer. The ability of the overburden to retard and filter percolating waste effluents is a measure of its protective capacity. Therefore, a new technique is proposed for evaluating the risk of groundwater contamination in alluvial aquifers. A geoelectrical parameter widely known as 'Total Longitudinal Conductance' of the unsaturated overburden, computed from the data of electrical resistivity soundings, is utilized to evaluate the degree of groundwater protection of the unconfined aquifers. Such aquifers are common in occurrence in many urban areas of north India, as well as in the coastal regions, where large no of water wells (dug or bored) are often constructed indiscriminately to meet the increasing water demands of the burgeoning human population. In urban areas, municipal and industrial waste effluents from local industries are mostly discharged directly into the drainage network of the areas, thus polluting the unconfined aquifers occurring beneath the unsaturated overburden. The 'Total Longitudinal Conductance' approach was tested in Saharanpur town of Uttar Pradesh where resistivity soundings were recorded during geophysical exploration. In this town, effluents from municipal wastes and industrial activities often find direct entry into the drainage system of the area which infiltrates into the shallow unconfined aquifer. Many groundwater samples were collected from hand pumps tapping this aquifer and analysed for determining the quality of groundwater including selected trace metals, nitrate and faecal coliform. The spatial variation of the hazardous chemicals presents in the groundwater yielded a Potentially Hazardous Activities Map (PHAM) of the area. Interpretation of the resistivity soundings yielded data of total longitudinal conductance of the unsaturated sedimentary overburden which ranged between 0.03 to 0.74 mho. The perusal of the total longitudinal conductance map of the area and its comparison with the PHAM of the area was found to match quite well indicating the effectiveness of the technique in finding degree of protection of the unconfined aquifer at various localities vis-a-vis the hazardous chemicals percolating downwards with the infiltrating runoff in the area. The approach when used in

combination with groundwater vulnerability estimates can prove to be of considerable help in planning groundwater protection and governance issues in alluvial and coastal areas of the country. There are many notable industrial units in the area such as a large paper mill, a tobacco company, distilleries, besides several cardboard manufacturing units, electroplating, meat products and chemical units. Lithologically, the water bearing formations in Saharanpur town are composed of fine to medium grained sands separated by clay horizons. Based on lithological logs of tube wells and available water level data, two types of aquifers have been delineated. The upper one is a shallow unconfined aquifer which generally extends down to depth of about 15 m below ground level (bgl). The deeper aquifers, are confined to semi confined in nature, occurring in depth range of 15 to 115 m (bgl) largely separated by three to four aquitards in the depth ranges of 15-36, 54-60, 80-90 and 95-120 m bgl, respectively. Based on the hydrogeological setting of the study area, Drastic method of aquifer vulnerability assessment was applied to find out its risk of pollution in different parts of the Saharanpur Town. The parameters considered in this analysis included Depth to Water table, Net groundwater recharge, Nature of aquifer media, Nature of soils, Topographic zonation, Impact of unsaturated zone and Hydraulic conductivity of the aquifer. The calculation of the Drastic Index (DI) values indicated that some central and southern localities of Saharanpur city are in medium risk (D.I.: 160-179) and high-risk zones (D.I. >180). A Potentially Hazardous Activities map (PHAM) was generated using ArcGIS software for the town for comparison with the Groundwater vulnerability map. It is suspected that the localities inferred to be hydro-geologically more vulnerable for ground water pollution are more prone to contamination by hazardous pollutants in ground water, and thus stand greater risk of pollution than the areas with lower vulnerability. Data of 32 vertical electrical resistivity/ Induced Polarization soundings recorded in the Study area was interpreted by curve matching techniques as well as by available software for generating geoelectrical sections for evaluating the total longitudinal conductance of the overburden over the unconfined aquifer of the area. It was observed from the data interpretation that the total longitudinal conductance of the unsaturated overburden using the relevant equation varied between 0.03 mho to over 0.7 mho Figure showing the contours of total longitudinal conductance of the unsaturated overburden for the Saharanpur town, indicated that area towards central, western and NW parts possessed highest longitudinal conductance. This implied that these parts of the town offered relatively higher protection to the underlying aquifer; on the other hand, the localities towards south and southeast and the north-eastern parts offered relatively lesser degree of protection to the unconfined aquifers from infiltrating pollutants. Such differentiation of the area on the basis of the total longitudinal conductance can prove to be of immense value in the groundwater management. It could be concluded from the above study that the Total longitudinal conductance Map of Saharanpur town was found to match quite well with the PHAM map showing spatial distribution of hazardous parameters of the area indicating the efficacy of the above technique in ascertaining the degree of protection of the unconfined aquifer in the study area.

Keywords: *Groundwater protection, unconfined aquifers, total longitudinal conductance*

PARTICIPATORY APPROACH FOR SUSTAINING GROUNDWATER AND IMPROVING LIVELIHOOD: LESSONS FROM THE MARVI PROJECT IN RURAL INDIA

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Groundwater resources in India are facing a critical threat due to both water stress and the exacerbating impacts of climate change. This alarming trend of groundwater depletion has far-reaching consequences, particularly in rural communities, where it hampers food production, disrupts farmers' incomes, fuels urban migration, and strains community cohesion. Moreover, the scarcity of groundwater places an additional burden on rural women and girls, who must expend more time and energy in fetching water. Further, lowering groundwater levels leads to higher pumping costs, reducing the baseflow to local streams, and degradation of water quality. This paper focuses on the valuable insights and experiences gained from the 'Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention (MARVI)' project, which sought to address these pressing challenges. MARVI adopted a participatory and transdisciplinary approach that involved engaging and training local villagers. Implemented over a decade in two watersheds in Rajasthan and Gujarat, the MARVI approach is now being expanded to other parts of India and beyond. The approach developed through MARVI offers a promising strategy to actively involve local communities in combating the impacts of climate change and working towards the sustainable management of groundwater resources. This work underscores the critical importance of community participation, monitoring, and shared management in ensuring the availability of groundwater resources for both today and the future amid growing environmental and climatic pressures.

Keywords: *Participatory approach, livelihoods, groundwater management, MARVI*

AEM SIGNATURE OF PALEOCHANNELS: IMPLICATIONS TOWARDS GROUNDWATER SECURITY UNDER CHANGING CLIMATE

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The paper provides a detailed analysis of paleochannel mapping across various hydrogeological environments in India, utilizing heliborne geophysical techniques complemented by ground-based geophysical observations and drilling data. An integrated study consists of dual moment transient electromagnetic and magnetic methods were carried out using helicopter over diverse hydrogeological settings of the country under aquifer mapping program by CSIR-NGRI and funded by Ministry of Jal Shakti, Government of India. The results were supported by ground geophysical and borehole results for ground truthing at varied scales. The study highlights the geophysical characteristics of paleochannels and aquifers are the same except difference in their dimensionality. Therefore, scale and data density of geophysical investigation become crucial to resolve dimensionality aspects of paleochannel research. The study includes examples such as: i) paleo river capture in the coastal aquifer near Cuddalore, ii) alluvial deposits over a Proterozoic basement that illustrate the effects of neotectonics activity on river course alterations in the Aravali region, iii) changes in river pathways in arsenic-affected areas of the Ganga plain, and iv) the identification of a buried paleo river close to Prayagraj, Uttar Pradesh including the hydrogeological linkages of the present and paleo rivers with the underlying aquifer system. The knowledge will be useful for groundwater sustainability and security.

A thorough investigation of AEM imaging, combined with ground and borehole data across diverse hydrogeological settings in India, has led to the discovery of concealed paleo river courses with widths ranging from approximately one hundred meters to several kilometres. The extensive dataset gathered over a considerable area has allowed AEM to effectively differentiate the dimensional attributes of subsurface features, which can be categorized as either paleo river courses or alluvial aquifers. The resistivity profiles of alluvial aquifers and paleochannels exhibits similarities. It is essential to comprehend the subsurface characteristics, including connectivity and continuity, when examining paleochannels. Alluvial aquifers are generally composed of water-saturated, porous and permeable sediments that take on irregular shapes and sizes, while paleochannels are defined by river channel deposits of coarse-grained sediments arranged in linear to curvilinear patterns. Therefore, distinguishing between linear and curvilinear features is crucial for the accurate identification of paleochannels. Study further reveals connectivity of soil to the deep aquifer including recharge pathways for planning of managed aquifer recharge to ensure water security.

Keywords: *AEM, heliborne geophysics, aquifer, paleochannel, and resistivity*

UNDERSTANDING ENABLERS FOR SCALING SPRINGSHED MANAGEMENT AS NATURE-BASED SOLUTION

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The IPCC's Sixth Assessment Report underscores the urgent need for swift and decisive actions to tackle the interconnected challenges of climate change, biodiversity loss and environmental pollution. The AR6 Working Group II highlights the importance of nature-based solutions (NbS), particularly for "water-based adaptation." Springshed management emerges as a promising approach, addressing water insecurity, restoring degraded lands and conserving biodiversity by revitalising springs, which in turn enhances the resilience of mountain communities to climate change and variability and reduces the drudgery of women. Springs sustain life and the livelihoods of millions of people in the Hindu Kush Himalaya (HKH). They are the primary source of water for most people residing in the hills and mountains, and the lifeblood of many terrestrial and aquatic ecosystems. Water supplies for many peri-urban and urban centres in the HKH are also from springs. Springs are not only a vital source of water for drinking, domestic use, and minor irrigation, they also serve important hydrological functions by sustaining the stream flows of non-glaciated catchments. Almost every river in India has at least partially fed by springs, studies from other regions of the world show that while springs are small habitats, they are hotspots of biological diversity and sources of water for wildlife. In the HKH, springs have great cultural significance as well. Springs can therefore be seen as key social, economic, cultural, and ecological pillars of sustainable mountain development in the HKH.

There is increasing evidence that spring discharge in the HKH is decreasing, or in some cases, ceasing altogether. Assessment and understanding of the impacts of land degradation, land use/land cover change, and climate variability on spring ecosystems in the HKH is only now emerging. Nearly 50% of the perennial springs in the Indian Himalayan Region have dried or become seasonal, according to NITI Aayog. Springs are also reported to be drying in Bhutan and Nepal, causing much hardship to local people and greater drudgery for women and children, who are traditionally responsible for fetching water for household use. A survey in mid-hill districts of Nepal has revealed that nearly 80% of those who fetch water from springs are women. A 2017 study of a Nepal watershed records decreased flow in 73% of springs used as water sources, and the drying of 12% of springs over the past decade. An assessment of springs by the Himalayan Resilience Enabling Action Programme (HI-REAP) of ICIMOD seven municipalities of Kavre district, Nepal has revealed that out of the nearly 5000 springs mapped, about 25% have dried. As a result, many people have started excavating wells to tap water from already stressed aquifers. In Lholing village of Bhutan, the drying up of springs resulted in acute water scarcity, forcing people to migrate. In addition to quantity, water quality of springs in terms of total coliform and E. coli contamination, nitrate content and total dissolved solids is also degrading in many places due to unsustainable land management practices in the springshed area.

According to the HKH Assessment Report, climate change in the form of erratic rainfall, changes in rainfall and snowfall patterns, and prolonged dry spells seems to be a major driver of spring depletion in the region. The observed warming trend in the HKH will also continue

throughout the twenty-first century, with a slight increase in precipitation. This will have direct implications on water resources across the HKH. The other drivers include increasing water demand due to population growth and tourism pressure, improper land use and land cover change, haphazard construction of roads and buildings without proper environmental impact assessments, abandonment of traditional ponds, increased groundwater pumping, earthquakes and lack of governance systems. If the current situation of spring depletion persists, achieving the Sustainable Development Goals in the HKH– especially those concerning water security, gender, land degradation neutralization and poverty reduction will be very challenging.

The majority of water resource management programs in the HKH apply the “ridge to valley” watershed management concept. However, this concept only accounts for surface water movement. Springsheds differ from watersheds because the source of spring water is determined by aquifer characteristics and not just surface topography. A springshed is a set of watersheds and aquifers that integrate into a system that supplies water to a group of springs. Therefore, to revitalize springs and ensure the flow of multiple services from springs and enhance resilience of people and ecosystems in the HKH, springshed and not watershed should be the organising framework for water resource planning. In the HKH region, numerous spring revival initiatives are going on and showing positive outcomes, especially in enhancing water security. However, scaling and adapting current practices to integrate NbS elements remains critical, given the reliance of nearly 100 million people on rapidly drying springs. This paper explores springshed management as NbS, identifying key enablers for scaling the solution, which including knowledge sharing, local stewardship, policy integration, institutional capacity building, robust monitoring and evaluation for evidence, financial partnerships and embedding gender equality and social inclusion (GESI).

Keywords: *Springshed management, Hindu Kush Himalaya, Nature-based Solution, Scaling, Enablers*

EMERGING CONTAMINANTS AND MICROBIAL INDICATORS IN SURFACE WATERS AND GROUNDWATERS IN BENGALURU CITY, KARNATAKA, INDIA

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The rapidly growing and industrialized city of Bengaluru, Karnataka, faces significant challenges concerning drinking water supplies. However, water quality issues in urbanised areas also often pose a challenge for safe water supply and wider environmental protection. However, groundwater quality assessment of Indian cities with regards to emerging organic contaminants (EOCs) and antimicrobial resistance (AMR) are scarce in India. This study provides a joint assessment of EOCs and AMR-related risks in multiple water sources within Bengaluru, evaluating the presence of over 1,499 EOCs and the AMR gene marker *intI1* across various water sources. By incorporating a multi-faceted approach that includes groundwater, surface waters, and tap water, this research highlights the intensity, and implications of EOCs and AMR contamination in one of India’s major urban centres. To capture a representative overview of contamination, 25 water samples were collected from different water sources, such as rivers, tanks, groundwater and three households supplied with tap water. The sampling process included key locations within and around the Bengaluru metropolitan area, covering regions with varied exposure to untreated wastewater and industrial discharge. Organic contaminants were isolated in the field using Solid Phase Extraction (SPE). A broad-screening of 1,499 EOCs was conducted at the National Laboratory Service (NLS) at Starcross near Exeter, UK using an Agilent 6540 Ultra- High-Definition Accurate-Mass Quadrupole Time-of-Flight LC/MS system. DNA quantity and quality were assessed using the NanoDropTM 8000 Spectrophotometer and integron-integrase gene, intI1, was chosen. To determine the prevalence of intI1 in the water samples, a hydrolysis probe-based qPCR approach was used to quantify absolute copy number of both the 16S rRNA and intI1 genes.

The broad-screening for EOCs revealed the presence of 125 distinct compounds across the sampled sites. These compounds, representing pharmaceuticals, pesticides, personal care products, and industrial chemicals, were detected in varying concentrations. Maximum concentrations for individual EOCs were found to reach up to 314 µg/L, a level that exceeds concentrations reported in a number of previously published studies assessing EOCS in Indian groundwaters. Among the contaminants of particular concern, PFAS were identified in high concentrations, with levels of up to 1.8 µg/L detected in surface water and 0.9 µg/L in groundwater samples. PFAS, known for their persistence and bioaccumulation, represent a significant concern due to their links with adverse health effects. The detection of PFAS compounds at such levels raises important questions regarding potential sources, pathways, and accumulation in the local water cycle, as well as implications for human exposure through drinking water sources. Additionally, the widespread detection of artificial sweeteners, such as sucralose an indicator of recent wastewater contamination reveals the relatively short timescale of aquifer recharge and its interaction with surface water and underscores the extent to which treated or untreated waste waters have permeated the subsurface, altering the natural chemistry of groundwater reserves.

The study also highlights a critical connection between EOCs and AMR development. Specifically, the presence of common antimicrobials, including azithromycin, fluconazole, and sulfanilamide, was notable in surface water bodies that are frequently exposed to untreated sewage inflows. The elevated concentrations of these antimicrobials in urban surface waters, reaching levels with high risk for selective pressure, were assessed using risk quotients that quantify AMR selection potential. Results from this analysis indicate that specific compounds present in wastewater-exposed environments exert selective pressures that foster AMR. The AMR marker gene *intI1*, a proxy for anthropogenic pollution and horizontal gene transfer, was detected consistently in highly impacted water bodies, underscoring the role of contaminated urban waters as reservoirs and transmission routes for resistance genes. Recent restoration efforts involved interventions in specific tanks, were also evaluated to assess their effectiveness in reducing EOC contamination and AMR risk. Restoration activities, including silt removal, encroachment management, and improved protections against wastewater inflows, were observed to correlate with lower concentrations of specific contaminants and reduced AMR selection potential. These findings emphasize the effectiveness of some environmental management measures in mitigating pollution sources. This illustrates that targeted restoration of urban water bodies can yield measurable benefits for groundwater and surface water quality. However, the persistence of certain contaminants, particularly PFAS, even in restored areas, suggests that ongoing monitoring and further protective measures are necessary to address specific contamination issues & protect water quality over the long term. This research represents one of the first in-depth studies to simultaneously address EOC and AMR presence across multiple water sources and the findings carry significant implications for water resource management, public health, and policy. First, the high concentrations of EOCs and AMR indicators suggest a need for monitoring of these emerging contaminants, particularly in urban areas where wastewater and industrial effluents interact closely with natural water systems. Second, the results highlight the role of restoration and environmental intervention in moderating contamination levels, supporting the implementation of similar initiatives across other urban water bodies. This study illustrates the complex interactions between surface water sources, piped mains water and groundwater within urban systems. The infiltration of surface water contaminants into groundwater systems suggests that holistic monitoring and management approaches are needed to address water quality challenges. In conclusion, the study provides critical insights into the prevalence, distribution, and risks associated with EOCs and AMR in an urban Indian context. The findings not only reveal significant contamination in Bengaluru’s water resources but also underscore the potential health and ecological risks posed by these contaminants. This research lays a foundation for future studies and policy discussions aimed at safeguarding water quality and public health in rapidly growing urban environments.

Keywords: *Water quality, Emerging contaminants, AMR, PFAS, intl1*

IMPLEMENTATION OF ATAL BHUJAL YOJANA FOR SUSTAINABLE GROUND WATER RESOURCES MANAGEMENT IN GUJARAT

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Groundwater has played an important role in increasing food and agricultural production, providing safe drinking water and facilitating industrial development in Gujarat. It contributes fresh water to meet the requirement of nearly 51% of total irrigated area, in addition to the rural drinking water supply and the urban drinking water needs of the state. Over the last three decades, the rapid expansion in the use of groundwater, primarily for irrigation, has contributed significantly to its agricultural production and overall economic development. Therefore, sustainable groundwater management, aimed at ensuring sufficient groundwater for the future generations is essential to mitigate the adverse effects of decline in the storage and availability of groundwater.

The Atal Bhujal Yojana (2019-2026) is a major step in this direction and its goal is to demonstrate community-led sustainable groundwater management which can be taken to scale. The scheme is World Bank aided Central Sector Scheme of the Govt. of India with a total outlay of Rs.6000 Cr. The scheme has been designed as a pilot with the principal objective of strengthening the institutional framework for participatory groundwater management and bringing about behavioural change at the community level through awareness programs and capacity building for fostering sustainable groundwater management in the in the selected water stressed areas in seven participating states viz. Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan and Uttar Pradesh.

Atal Bhujal Yojana in Gujarat is targeted at sustainable groundwater management, mainly through convergence among various on-going schemes with the active involvement of local communities and stakeholders in the Scheme area comprising 1873 GP's falling in 36 water stressed Blocks of six districts namely Gandhinagar,Patan,Banaskantha,Mehsana Sabarkantha and Kachchh, and to ensure the funds allocated by the Central and concerned State government are spent judiciously to ensure long term sustainability of groundwater resources .

Atal Jal Project implementation cost for Gujarat is Rs. 741.23 Cr. comprising (i) Rs. 202.12 Cr. for Institutional Strengthening & Capacity Building and (ii) Rs.624.48 Cr. Incentive component (totally fungible).

For precise measurement of various parameters all the GP's have been provided with Analog water level recorder for measurement of depth to ground water level and kit for water quality testing to measure 5 selected chemical constituents. In addition, one piezometer in each GP has been provided with DWLR for closely observing the water level behaviour. About 11500 water flow meters have been installed on selected tube wells fitted with electric pumps in different GP's for measurement of ground water draft from. Services of NGO's have been taken as District Implementation Partners for working at the grass root level. For institutional strengthening services of domain experts have been hired for the District and State Project Implementation units. Water Budgets and Water Security Plans identifying the required interventions for implementation have been prepared in participatory mode by Village Water Committees and are being updated every year. For the data disclosure, the data recorded in each GP is placed on a display board in each GP and also on the website of GWRDC and Atal Jal as well as through Taluka wise Hydrogeological reports.

Analysis of the efforts made so far in implementation of various interventions in Gujarat during 2019-2024, indicate that the emphasis has been more on measures aimed at reducing the demand (demand side measures) supported by increasing the availability of groundwater (supply side measures) along with IEC and training programmes for behavioural change of communities.

The Gujarat Govt. provides financial subsidy of 70 to 90% of unit cost for installation of drip and sprinkler irrigation to the farmers. For encouraging behavioural change amongst the farmers for adoption of drip and sprinkler irrigation special financial incentive of 15% unit cost of the system along with GST has been also provided from the incentive component of Atal Jal Scheme. This has accelerated the pace of adoption by the farmers by marginal and small farmer’s also.

On demand side management adoption of efficient water use practices (Drip, sprinkler etc.) has been achieved in more than 67,500 ha area in addition to millet kit distribution for encouraging sowing of less water intensive crops. On the supply side more than 300 scientifically designed recharge tube wells have been constructed targeting the aquifers exhibiting declining trend in ground water levels in addition to more than 4000 water conservation structures like check dams (new/repairing/deepening), percolation tanks, recharge pits and shafts, existing dug well/tube well recharge, pond desilting etc. have been constructed at a cost of about Rs.750 Cr. Nearly 24,170 IEC/training programmes have also been conducted at GP/Block/district/State level for sensitisation of the members of public on sustainable ground water management with emphasis on demand side management.

Evaluation of the impact of implementation of the various interventions by the Quality Council of India has indicated that as compared to base level data (2015-19) of ground water levels, the year wise no. of blocks and GP’s showing distinct rise in both pre- monsoon and post- monsoon ground water levels: (a) 2023 - 8 Blocks and 114 GP’s and (b) 2024- 12 Blocks and 130 GP’s.

Positive indications of the sustainable ground water management have already started emerging and with completion of ongoing supply and demand side interventions, we are anticipating more number of Blocks and GP’s to become sustainable models of ground water management in the years to come.

Keywords: *Sustainable, indiscriminate, unregulated, demand side intervention, behavioural change*

CHALLENGES FOR MOUNTAIN HYDROLOGY AND ITS IMPACT ON SPRINGSHED MANAGEMENT

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Mountain hydrology has undergone significant changes within the last decades due to climate and land use change as well as altered water consumption patterns. Climate change influences both the characteristics of droughts and floods as well as evapotranspiration, sublimation, snow-rainfall ratios, snow seasonality, and water reserves locked in glaciers. Land use changes and altered water use may strongly outweigh these impacts, through industrialization, urbanization, and tourism. Extreme hydrological situations such as new flood types have evolved from combined land-use and climate change and new types of water scarcity in association with accelerated and seasonally shifted water abstraction. Related water quality and pollution issues are of growing concern especially in seasonally highly populated areas.

Main challenges for mountain hydrology include keeping pace with recent hydrological changes, such as global warming, altered water inputs, water abstraction, and water quality. These changes have put significant impact within the total water cycle as these may have major impacts on floods, water scarcity, and general livelihood. It is generally agreed that the hydrological cycle has intensified in response to an alternating, stepwise change in global warming. As temperatures are increasing strongly over the Himalayan region, there is a general decline in both duration and total accumulation of snow, especially at altitudes below 1500 m. Simultaneously, there is a decreasing trend of the snowfall rainfall ratio, snow water equivalent, and snow depth during the melt season.

As mountain water resources can become seasonally scarce, water quality may suffer. Still, water quality and water pollution are not frequently associated with mountain hydrology. Due to the vulnerable and episodic nature of water resources in many mountain catchments, water pollution is becoming a rising issue when impacted by land-use change, such as urbanization, road infrastructural development and tourism.

A major challenge remains understanding the impacts of landuse change such as bridges, roads, canalization, rectification and damming of rivers on the natural springs. Many new constructions on the landscape influence surface runoff and spring recharge. The drying up of springs and the factors responsible for the reduction in their discharges in the mountain ranges has been highlighted during the last three decades through isolated studies. Some of the studies have generated baseline data and provided opportunities for assessment of factors responsible for the reduction in spring discharges. Most of the observations are based on limited data, qualitative assessment and observations, particularly on a temporal scale. Drying up of springs has resulted due to the collective impact of activities related to indiscriminate exploitation of mountain resources, enhancement of climate variability, increase in temperature and at substantial negligence of springs as a vital water resource. This dwindling resource of the mountain region requires more focused in-depth studies to identify the vulnerable spring hydrogeological processes.

Rejuvenation of the springs is the need of the hour and requires planning based on scientific studies that augment folk knowledge of this precious resource. Reviewing most of the spring revival programme implemented in mountain regions, different springshed development methodology can be adopted. These comprises spring and springshed mapping, monitoring and creation of databases, identifying vulnerable spring, development of adaptive strategy through large scale afforestation in the catchment.

The general lack of higher altitude hydrological and meteorological data at the basin scale in mountains and the lack of experience with new hydrological phenomena will require an analytical approach directed more strongly toward interactions between scientists, stakeholders and decision makers. Local stakeholder knowledge and historical evidence will need to be systematically categorized using a scientific methodology based on intensive mutual exchange between scientists and mountain stakeholders. Water management should be recognized as a necessity encompassing all water uses regardless of their political and economic influence.

Keywords: *Mountain hydrology, springshed management, springs, rejuvenation*

TOWARDS THE FUTURE OF GROUNDWATER MODELLING: FROM CONCEPTUALIZATION TO UNCERTAINTY QUANTIFICATION

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Significant work has been carried out in the last decade to quantify the uncertainty of the model predictions in the groundwater field. The uncertainty quantification is typically focused on parameter variability. This includes methodologies such as sensitivity analysis, Monte Carlo analysis up to ensemble smoother techniques. However, today’s industry practice still assumes a strong link between the groundwater model and one single 3D geological structural model. The fundamental reason of such as limitation is that the current modelling technology does not allow us to iterate programmatically between a 3D geological model and 3D groundwater numerical model, or vice-versa without passing a tedious workflow of reconstructing both models entirely. Some attends have been done to overcome this limitation; however, the studies are purely based on simple geometries (box-like domains) and cannot be applicable to complex 3D geological settings.

The current study presents on-going research, which facilitates the bridge between 3D geology and 3D groundwater modelling. Common 3D geological tools (open-source and/or commercial) are based on implicit modelling techniques such as radial basis functions, co-kriging, etc. DHI has been working extensively in the last years to close the gap between implicit modelling, 3D meshing and model parametrization. The goal is to have all together within one single workflow from geological boreholes up to an entire 3D groundwater model. The implicit modelling is based on typical geological information such as boreholes, stratigraphical stack and/or fault constraints. Results of the implication are the 3D geological contacts within the user-defined domain. Geological contacts are passed forward to FEFLOW’s meshing algorithm to create a tetrahedral mesh acknowledging the geological constraints. The workflow is scriptable through Python and allows the user to combine existing open-source packages for uncertainty quantification such as PEST or PEST++. In this scientific contribution, the new methodology will be demonstrated and tested against typical groundwater applications.

Keywords: *Groundwater modelling, uncertainty analysis, Sensitivity, FEFLOW*

GROUNDWATER MANAGEMENT STRATEGIES TOWARDS SUSTAINABLE WATER SUPPLIES TO CHANDIGARH

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Chandigarh is a highly urbanized city having an area of 114 km^2. It needs about 500 million litres per day (MLD) at present which is likely to go up to 555 MLD in 2031. Water available is only 330 MLD. The shortfall of availability of water is likely to be about 225 MLD in the year 2031. Presently, major part of water requirement, to the tune of 253 MLD, is met by canal water. Ground water, through about 200 deep tubewells, contributes about 77 MLD. The water demand scenario described above requires smart planning of water resources of the 'City Beautiful' and more so of the groundwater resources that can be used more fruitfully. Chandigarh is occupied by semi-consolidated formations of upper Siwalik system that are exposed in north-eastern fringe whereas the rest of the area is occupied by alluvium of Pleistocene age. The piedmont deposits at the foot of Siwalik hills comprise cobble, pebble and boulder, associated with sand, silt and clay and are followed by alluvial plain comprised of clay, silt and sand. Chandigarh has two different sets of hydro-geological settings. Whereas in northern part it has four distinct promising aquifer systems, in the southern there are only two. Deeper aquifers in the southern part have predominantly fine-grained sediments and are not as promising as in the north that has relatively coarser sediments. The yields of the deeper aquifers are also lesser as compared to the shallower ones.

Ground water in the area occurs under water table, confined as well as semi-confined conditions. Good, confined aquifers occur around central and northern parts while leaky are encountered towards east. The depth of the shallow aquifer system is less than 30m below ground level (mbgl) whereas the depth of the deeper aquifer system ranges from 40 to 450 mbgl of explored depth. Groundwater behavior in the city has been studied based on its occurrence separately in the shallow aquifer and deeper aquifer system. During the pre-monsoon period in the year 2020 depth to water level in the shallow aquifer system varied between less than 5 to more than 22mbgl. In the south-western part of the city the water level is shallow (<5m). This is due to finer nature of sediments and lithological boundaries. In the western parts and southern sectors, the water levels are in the range of 5 to 15 mbgl. In the deep aquifer system, the water level lies between 16 and 37mbgl. In the south and southwestern part of the city the water level of deep aquifer system is shallower as compared to north-eastern and northern part, where water level is more than 37 mbgl.

Long term water level fluctuation data for shallow as well as deep aquifer systems has been assessed for 30 years for the period May 1991 to May 2020 to understand the water level behaviour in different time periods. The data of the shallow aquifer system reveals that over a 30-year time (1991-2020), the water levels have declined by an average of 3.11 m all over the city. The water levels did not show much change during the decade of 1991-2001 but registered an average decline of 3.05 m during 2001-2010, and again a rise of 0.98 m during 2010 to 2020. For a 15-year period, the water levels declined by 3.45 m during 1991-2006 and 0.61 m during 2006 to 2020. Thus, there has been no set pattern of decline of water levels except that the water levels are declining in the shallow aquifers at a rate of approximately 10 cm/year. A very interesting observation made is that there was no appreciable change in water levels during the period of 11 years from the year 1991 to 2001 in the shallow aquifer, which is attributed to negligible withdrawal of ground water from the shallow system. However, there is a sudden decline in the water levels in five years from 2001 to 2006 in the shallow aquifers of sector 10 and 21 and slight fall in sector 12. This can be attributed to the fact that in these years pumping has increased from the shallow aquifers in the central parts, which was hitherto banned in Chandigarh city. The long-term water level fluctuation of the deep aquifer system (May 91-May 2020) shows that in all parts of the city there is a decline in water levels. The most pronounced water level decline is in the northern parts where a fall of almost 31.2 meters has been registered in the last 30 years. In major parts of the city, it ranged between 6 to 13 m. The average fall in the water levels in the last 30 years has been 12.95 m at the rate of nearly 43 cms/year. This is more than 4 times the rate of fall of the water levels of the shallow aquifer system. This fall in water levels is attributed to heavy pumping from the deep aquifers underlying the city.

As per the Dynamic Ground Water Resources assessment for the year 2023, the Stage of GW extraction for the city is 75.41% and it falls in the 'Semi Critical' category. It has further been estimated that after allowing for an annual allocation of GW for domestic use amounting to 26.07 MCM up to the year 2025, the Net GW availability left for future use is only 11.91 MCM. CGWB has also assessed Total Fresh Ground Water Resources for the year 2017 down to 400 m depth under its NAQUIM studies. These have been estimated as 680.73 MCM out of which total dynamic resources down to 400 m depth are 15.67 MCM and in-storage are 665.04 MCM. In the present paper an attempt has been made to emphasize the need for decreasing the withdrawal from deep aquifers to the tune of about 5.5 MCM per annum and start withdrawing 15 MCM from the shallow aquifers, especially in southern sectors having shallow water levels to augment drinking water supplies. It has also been estimated that 42.6 million cum of rainfall runoff is available annually that can be used for recharge of the deeper aquifers in the city. Since Chandigarh has a capacity to treat 210 MLD wastewater, it is proposed that the entire demand for horticulture may be met from recycled water treated to standards set by Central Pollution Control Board for discharge of treated water on land for irrigation. This will reduce the water deficit to 35 MLD from 170 MLD presently and from 225.58 MLD to 91.68 MLD in 2031. It is equally important to reduce the 28% non-revenue water losses which are mostly due to various leakages. These measures will check further exploitation of deeper aquifers that are already under great stress and will also go a long way in sustainable management of the ground water environment including drinking water supplies in the "City Beautiful".

***Keywords**: Chandigarh, water requirement, dynamic ground water resources, confined aquifer, water level fluctuation*

THE ROLE OF GROUNDWATER FOR WATER SECURITY IN THE AUSTRALIAN MURRAY DARLING BASIN AND THE INDIAN GANGA BASIN

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Groundwater plays crucial and distinctive roles for water security in large basins like the Murray-Darling Basin (MDB) and the Indian Ganga Basin. In these two basins, groundwater contributes significantly for irrigated agriculture, regional water supply and serves a wide range of ecosystem services, yet faces increasing pressures due to over-extraction, climate variability, and land use changes. In the MDB, groundwater resources are heavily utilized for irrigation in a semi-arid climate, contributing to declining water tables, salt accumulation, and ecosystem degradation. Similarly, the Ganga Basin, home to millions of people and vast agricultural areas, is also experiencing groundwater depletion and contamination, exacerbated by industrial pollution and urbanization. Regulatory mechanisms and policy intervention for sustainable management of groundwater are in different stages of development and implementation in India and Australia. One of the key challenges is the incomplete understanding of the groundwater resource and the role it serves owing to limited data availability and limited adoption of scientific approaches for the monitoring and assessment of groundwater resources. In this study, we demonstrate the use of the available evidence base complemented with statistical analysis and modelling approaches for developing improved understanding of groundwater resources at the basin scale to support improved management.

Groundwater and other supporting data obtained from public sources in India and Australia were used for the analyses conducted in this study. This included groundwater level data obtained from the National Groundwater Information System (NGIS) of Australia and the Water Resource Information System (India-WRIS) of India. Robust analysis of trends and spatiotemporal patterns in groundwater level data of 910 observation bores in the alluvial aquifers of the MDB was undertaken for the period from 1971 to 2021. Similar analysis was undertaken for groundwater level data from 2851 monitoring wells in the alluvial aquifers of the Ganga Basin for the period 1996 to 2017. Complementary analysis was undertaken using GRACE data and numerical modelling with a regional scale MODFLOW model to understand the overall water balance in the regional aquifer. Based on these analyses, trends in groundwater storage changes in the aquifer was comprehensively evaluated. Trends, spatiotemporal patterns and water balance were evaluated in the context of groundwater availability, demand and management.

Trend analysis of groundwater level data revealed that groundwater levels are declining in the alluvial aquifers of the Murray Darling and Ganga basins. In both basins, declining groundwater storage is driven largely by groundwater extraction and changes in recharge from rainfall. While hotspots of large-scale groundwater depletion exist in parts of the basins, opportunities exist for improved use of groundwater in both basins. Monitoring of groundwater levels have progressively improved in both the basins. Regulatory arrangements including groundwater licensing has enabled improved monitoring of use including metering of irrigation water use in the MDB. While such arrangements are currently difficult in the context of the Indian Ganga Basin where groundwater extraction occurs through millions of small holders, availability of remote sensing and other secondary data sets enable development of an improved understanding of groundwater balance at the basin scale to support management measures and policy for sustainable management.

Keywords: *Ganga basin, Murray Darling Basin, trend analysis, modelling, groundwater management*

ATTAINING WATER SECURITY 2047: AI, NATURE-BASED, AND SMARTER HYDROLOGY-DRIVEN HIDDEN BLUE NEXUS FOR A CLIMATE-RESILIENT FUTURE

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Water security is emerging as one of the most pressing global challenges of the 21st century, exacerbated by climate change, rapid urbanization, and unsustainable resource extraction. With nearly two-thirds of the global population expected to experience water scarcity by 2025, the urgency for innovative and sustainable solutions has never been greater. India, home to 18% of the world's population but possessing only 4% of its freshwater resources, faces an acute water crisis, with groundwater levels declining at an alarming rate of 0.4 m per year in several regions. As the nation envisions a self-reliant and technologically empowered future—'Viksit Bharat 2047'—water security must become a fundamental pillar of this transformation. This keynote address explores how Artificial Intelligence (AI), Nature-Based Solutions (NbS), and Smart Hydrology can synergize to create a resilient and sustainable water future. Integrating hydroinformatics, digital water governance, and ecosystem-based hydrological interventions, India is pioneering next-generation water resilience models that can set global benchmarks. The discourse also highlights case studies from successful water conservation programs like the Atal Bhujal Yojana, which has led to a 15-20% improvement in aquifer recharge across critical districts. This address is drawn from author's four decades of multifaceted experience spanning water, watersheds, food security, farming, forests, grasslands, and hydrological land use systems.

In an era where water security is both a challenge and a necessity, AI and Hydroinformatics are revolutionizing the way we manage and govern water resources. The convergence of AI, big data analytics, and real-time hydrological modeling is revolutionizing water governance. It altogether is enabling smarter, more resilient, and adaptive water systems. AI-powered models trained on vast datasets from satellites, IoT sensors, and hydroclimatic records enhance precision in forecasting groundwater fluctuations, water demand patterns, and extreme climate events with over 90% accuracy in some predictive models. AI-driven remote sensing and real-time analytics allow for proactive contamination tracking, aiding in the mitigation of pollutants like arsenic, fluoride, and industrial waste, which affect over 50 million people in India alone. AI-powered leakage detection systems, self-optimizing water grids, and digital aquifers ensure equitable resource distribution, particularly in water-stressed regions, potentially reducing non-revenue water losses by up to 35%.

As the world grapples with escalating water crises, NbS are emerging as a game-changing approach to achieving water security, resilience, sustainability etc. They offer a transformative approach to water security by leveraging natural ecosystems to regulate water cycles, improve aquifer recharge, and enhance resilience. Few sample key applications may include constructed wetlands, sponge cities, and regenerative hydrology mitigate floods, purify groundwater, and optimize water retention. These solutions have been observed to enhance groundwater recharge rates by up to 30%. Enhancing soil conservation, stabilizing streambanks, and improving groundwater recharge. Studies indicate that bamboo-root systems can increase infiltration capacity by up to 60% compared to barren land. Urban Water Resilience: The sponge city model integrates urban forests, permeable pavements, and rooftop gardens to address urban flooding and decentralized water management, with case studies from China showing a 70% reduction in urban runoff.

The interdependence of surface and groundwater systems plays a crucial role in water security. AI-enhanced hydrological models are unlocking new insights into rainfall-runoff dynamics, land-use impacts, and water productivity. Some of the sample notable advancements may include *AI-Powered Hydrologic Parameterization, Hydroinformatics and Data-Driven Policy Innovation* and *Digital Twins for River Health.* In the face of climate change, traditional rainfall-runoff dynamics are being disrupted, necessitating AI-driven real-time modeling to forecast flood risks, optimize stormwater harvesting, and enhance catchment resilience. Simultaneously, rapid land-use changes—deforestation, urbanization, and industrial expansion are accelerating surface runoff and aquifer depletion, requiring AI-based impact assessments for proactive hydrological management. In agriculture, smart precision irrigation and climate-responsive agri-hydrology are optimizing water productivity, ensuring higher crop yields while conserving groundwater reserves. To address groundwater depletion, AI-powered Managed Aquifer Recharge (MAR) and eco-engineering solutions are transforming exhausted aquifers into climate-resilient reservoirs. Additionally, advanced hydrodynamic models guide bioengineered streambank stabilization strategies, curbing erosion and reinforcing riverine ecosystems. The integration of digital twins real-time AI simulations of river systems—is revolutionizing water quality management by enabling precision monitoring of pollution loads, sediment transport, and aquatic biodiversity, ensuring sustainable river health. Achieving Water Security 2047 necessitates a strategic policy framework integrating AI, NbS, and smart hydrology. Key policy imperatives include *AI-Driven Water Regulation*, *Cross-Sectoral Partnerships* and *Climate-Smart Water Policies*.

Water security is no longer a distant ambition but an urgent necessity. By integrating AI-driven hydroinformatics, nature-based solutions, and smart hydrology, we can transform the Hidden Blue Nexus into a cornerstone of global water resilience. The vision for 2047 calls for bold policies, cross-disciplinary collaboration, and next-generation technologies to ensure that water security becomes a reality for future generations. The adoption of AI-powered decision-making, eco-engineering, and digital governance models has the potential to reshape global water security paradigms. By leveraging these advancements, India can lead the world in sustainable water management. Scaling up successful interventions, fostering community participation, and aligning efforts with the SDGs will pave the way for a water-secure future. A forward-looking, innovation-driven, and sustainability-focused approach will not only safeguard water resources but also ensure that economic growth and human well-being remain intrinsically linked to environmental stewardship.

Keywords: *Water security, resilience, hydroinformatics, groundwater, Nature-Based Solutions*

SCARCITY OF WATER OR SCARCITY OF MANAGEMENT IN INDIA

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The concept of water security has progressed from a narrow emphasis on water supply infrastructure, primarily viewed through an engineering lens, to a comprehensive perspective encompassing technological, economic, environmental, and governance dimensions. The evolution of the water security concept signifies a noteworthy shift toward a more comprehensive consideration of diverse values, stakeholders, and viewpoints by representing in an equitable manner as possible human-centric and ecosystem-based priorities. It also emphasizes the pressing need for transdisciplinary and more integrated approaches, as the challenges in representing the water security notion more effectively continue to mount. In response to these pressing challenges, it is essential to employ interdisciplinary approaches comprising optimal dynamic combinations of technologies, economic analysis, and policies to devise national and regional water security strategies through inclusive approaches with relevant actors and stakeholders.

Clearly a major cause of water scarcity is mismanagement, and unfortunately this abounds across the world. Everyone appreciates that water security is an important issue for India. However, water management has been on an unsustainable path in India for centuries. Water security has progressively deteriorated over the years for many reasons. Unfortunately, inadequate planning, lack of awareness and non-implementation of best and established practices, have created a difficult-to-manage situation. Hence, an alarming scenario of water scarcity and environmental degradation is gradually unfolding in India. First is population growth. In 1947, total population of undivided India was 390 million. By 2050, it is estimated to reach 2206 million, a 5.66-fold increase in around 100 years. Second is rapid urbanization. In late 1980, India did not have a single megacity with more than 10 million people. Today it has five: Delhi, Mumbai, Kolkata, Bengaluru and Chennai. Soon Hyderabad and Ahmedabad will join them. Third is India’s economic growth. As the country has industrialized, its industrial water requirements have gone up significantly. Between 2000 and 2025 it is expected to increase three-fold. Intense competition for water among different sectors is depleting raw water sources. Widespread pollution of surface and groundwater is degrading the quality of these. In a nutshell, the root causes of the water crisis in India are: Highly uneven availability of water, both in space and time, often leading to floods and droughts; Diverse hydrogeological conditions; Underutilization of created irrigation potential; overexploitation and virtual water export; over-population and, Widespread pollution mainly by the agricultural, industrial and municipal sources.

Much of the water use in India is dominated by agriculture sector (~85%). The domestic sector uses a minimal share (~8%), followed by the industrial sector (~6%) with somewhat less water use. Although indirect evidence indicates that in India, like in most other developing countries, the share of agricultural water is gradually declining and industrial water is increasing. Thus, if India has to become water-secure, the share of water for agriculture must be efficiently managed and reduced. Agricultural water use has always been inefficient.

Currently capacity of the wastewater treatment plants is only about 40% of India's wastewater generation in urban areas for collection, treatment and safe discharge into environment. There is virtually no effort by any state to control or manage agricultural non-point pollution arising from fertilizers, pesticides and their derivatives. Hence, several water bodies, including rivers, lakes and aquifers, within and near urban centres as well as in irrigated and industrial areas are now heavily contaminated with all types of pollutants. The situation is getting progressively worse as appropriate and timely actions by the administration are still unsatisfactory. Social and economic costs of not treating all heavily contaminated wastewaters generated are already quite high and growing progressively with time. While Central and State Governments always focused on increasing water supply to meet higher demands, no serious effort has ever been made to manage efficiencies of water uses in domestic, agricultural and industrial sectors, which can be significantly improved through better management practices, including the use of economic instruments, adoption of new technologies and instilling a conservation attitude amongst the population to value, preserve and protect water resources and their quality.

The keynote pinpoints broad contours of a few important management strategies to address the so called ''scarcity of water" are: i) Closing the huge IPC-IPU gap is also a "low hanging fruit" which can be picked by investing in CAD works, ERM projects and irrigation management reforms. ii) Aggressive Promotion and incentivization of sprinkler and drip irrigation on a massive scale in general and over-exploited and critical areas in particular can be the most important demand side management strategy to over consumption, and iii) Managed Aquifer Recharge (MAR), intelligent management of the energy-irrigation nexus and participatory ground water management offers a major opportunity for water secure and resilient India. MAR is the most economic, most benign, most resilient and most socially acceptable solution, but has not been due importance in the past out of lack of awareness, inadequate knowledge of aquifers, immature perception of risk and inadequate policies for integrated water management, including linking MAR with demand management. iv) Mandating progressively increased use of recycled/treated waste water. This has huge potential for substitution of fresh ground water used in Industrial, domestic and agriculture sectors. v) Encouraging the Use of brackish/saline water for selected agricultural crops in western and north-western India, where huge unutilized potential exists. vi) In the country conjunctive management of rain, surface water, treated wastewater and groundwater is the big hitherto under-exploited opportunity for supply-side management. vii) Enabling Legislation for sustainable water management and Institutions for water governance needs to be established in the states for enforcing effective governance. It is estimated that effective implementation of strategies, ii) and iii) itself, shall provide for more than 300 BCM of fresh water, besides creating an additional 26 Mha of irrigation potential by closing the GAP between IPC and IPU, which is more than adequate to comfortably meet the projected water requirements of all sectors in the country by 2050.

In fact, we don't have a scarcity of water, but a scarcity of management in our country. There is plenty of water, and plenty of financial resources. The question is whether we are adequately managing our financial, human, and natural resources so that water flows to the places it is most needed. The country has enough expertise to solve its water problems. It has access to technology and investment funds to ensure a sustainable water future.

Keywords: *Water scarcity, groundwater, water management*

Theme 1
Vision 2047

IMPACT OF CLIMATE CHANGE ON GROUNDWATER AND ADAPTATION MEASURES

IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES OF HAROHAR BASIN, LOWER GANGA PLAIN, INDIA

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Groundwater is a crucial resource that fulfills essential needs such as drinking, industrial and agricultural purposes. In recent years, reliance on groundwater has surged, driven largely by the pollution of surface-water sources. Consequently, the quality and quantity of groundwater are deteriorating, primarily due to the population growth, which has propelled humanity into the Anthropocene era and exacerbated climate change. This transformation represents an undeniable reality, significantly affecting the availability of water resources worldwide. Climate change alters the physio-chemical characteristics of groundwater, making it imperative to understand these influences for effective management of global water markets. For India, home to over 1.37 billion people, the management of groundwater is vital for achieving the Sustainable Development Goals (SDGs), particularly in ensuring universal access to safe and clean water. Systematic evaluation and assessment of groundwater resources at the regional level are essential for sustainable management practices. These efforts are pivotal to achieving SDGs targets by 2030, fostering resilience in water systems and promoting equitable access. As the world faces increasing water challenges, prioritizing groundwater resource management will be crucial for sustaining communities and ecosystem. Therefore, In the present study, the impact of climate change on the Kiul-Harohar river basin in lower Ganga plain has been carried out to understand the effect of climate change on groundwater resources of the basin using satellite data, hydro-meteorological and hydro-geological data.

The basin is a tributary of Ganga River basin and covering a total area of around 17157 km^2 of Bihar and Jharkhand. The basin receives an average annual rainfall of 1,104 mm, which plays a critical role in shaping its hydrological dynamics. However, the Kiul-Harohar basin faces significant challenges related to groundwater availability and sustainability, exacerbated by over-exploitation of groundwater resources, increasing agricultural demands and irregular precipitation patterns. Kiul-Harohar river basin characterized by its unique geological formation comprises of Quaternary alluvium, underlain by Proterozoic Chotanagpur Gneissic Complex, the Bihar Mica Belt (Paleo-Mesoproterozoic), Neoproterozoic intrusive granites, Mesoproterozoic rocks of the Munger Group, Archean-Paleoproterozoic metamorphic rocks, and Lower Gondwana formations (Late Carboniferous to Permian). Geomorphologically the basin has diversified geomorphological features including alluvial plains, floodplains, denudational hills and plateaus, structural hills, along with many natural lakes and surface water bodies. The region is particularly vulnerable to drought and flooding, resulting in recurring water shortages that threaten both agricultural and domestic water supplies.

The study employs GIS tools and satellite data to analyze various factors affecting the groundwater resources of the basin including vegetation patterns, altered precipitation, changes in land surface temperatures and shifting evapotranspiration rates. The study results reveals that the rising surface temperature are intensifying evapotranspiration (ET) rates

while decreasing groundwater recharge. Simultaneously, unpredictable rainfall patterns are accelerating aquifer depletion and lowering groundwater levels. The increasing frequency and severity of droughts and other extreme weather events further exacerbate pressure on groundwater reserves, compelling unsustainable extraction practices to meet rising agricultural and domestic water demands. To assess the impact of climate change on groundwater resources of the basin, the important climatic variables such as precipitation (PT), land surface temperature (LST), ET and vegetation patterns along with groundwater level have been analyzed from 2004 to 2023. The spatial and temporal relation with various parameters such as LST, ET, PT, NDVI and groundwater have been carried out to understand the impact on water resources of the basin for the year 2004, 2013 and 2023. All the factors have been mapped using the data collected from various sources including groundwater levels, precipitation from the IMD and LST, ET, and Normalized Difference Vegetation Index (NDVI) data from NASA's MODIS products. The LST, ET, and NDVI data for the basin have been extracted through rescaling and reprojecting raster images using ArcGIS 10.8.2 software. In the first decade from 2004 to 2013, the average NDVI values have been found decline from 0.31 to 0.28. The mean annual LST also showed increasing trend. The change in temperature is closely associated with precipitation and groundwater levels changes over the years. The NDVI values, LST, ET, PT and groundwater level have positive relation. Based on the groundwater dynamic and interaction among temperature, vegetation health, and groundwater resources underscores positive relationships governing the groundwater availability in the Kiul-Harohar basin. Understanding these interactions is essential for developing effective strategies for sustainable groundwater management under changing climatic conditions. To ensure responsible groundwater use, implementing integrated groundwater resource management strategies is crucial. Policymakers and stakeholders must collaborate to create adaptive approaches that address climate variability, while advancing the Sustainable Development Goals.

Keywords: *Groundwater, climate change, Kiul-Harohar basin, NDVI, LST, remote sensing & GIS*

INSIGHT INTO GROUNDWATER VARIABILITY IN NORTH INDIA USING GRACE OBSERVATIONS: ROLE OF CLIMATIC AND SOCIO-ECONOMIC FACTORS

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Groundwater depletion is a global concern due to the large dependency of domestic and agricultural use of it. Between 1950 and 2000, annual groundwater extraction in North India increased dramatically from 25 to 200 km^3/year, making it one of the leading countries in terms of extraction rates. Recent studies indicate that human activities are contributing to groundwater depletion in northern India, especially in the states of Rajasthan, Punjab, Haryana, and Uttar Pradesh. The studies suggested that if current trends persist, 60% of aquifers could reach critical levels within the next two decades. Regular monitoring of changes in groundwater storage is essential for effective sustainable management of groundwater resources. In this study, we have investigated the spatiotemporal changes in groundwater storage in northern India from 2002 to 2023 by analyzing GRACE/FO RL06 mascon solutions for terrestrial water storage (TWS), GLDAS datasets, groundwater levels, rainfall, surface air temperature, population statistics, tubewell data and agricultural information. We reconstructed the TWS time series using singular spectrum analysis (SSA) to fill the gaps and apply the Mann-Kendall (MK) test with the Sen slope estimator, along with Standardized Precipitation Index (SPI) and change point analyses. The goals of this study are: i) to quantify the variability of groundwater storage over the past two decades at different scales, ii) to examine how these changes are related to climatic factors like rainfall and temperature, as well as human activities such as population growth, tubewell distribution, and the extent of irrigated areas, and iii) to evaluate the influence of aquifer heterogeneity on spatial trends. We have performed a spatiotemporal trend analysis of groundwater storage (GWS), groundwater levels (GWL), rainfall, surface air temperature, and tubewell distribution. To assess the variations in groundwater storage, we have employed several methods such as addressing gaps in the GRACE TWS data using singular spectrum analysis (SSA), calculating groundwater storage anomalies (GWSA) with the filled TWSA and GLDAS model, performed trend analysis of hydrological and climatic variables using the MK test and Sen's slope estimator, and utilized SPI and change point analyses to identify dry and wet periods and determine resilience phases. The estimated spatial variation of the GWS trends indicate a specific area centered in Haryana experiencing significant groundwater decline, with a maximum rate of around -6.6 cm/year. Our spatiotemporal analysis of CGWB GWL data from 1,798 monitoring wells across the study area reveals three distinct zones based on climate and aquifer characteristics: Z1 (northeast Rajasthan), Z2 (Punjab and Haryana), and Z3 (western and central Uttar Pradesh). In Z1, trends have shown severe groundwater depletion, with a maximum decline of about -300 cm/year. The north Indo-Gangetic plain, showing a moderate declining trend, is divided into zones Z2 and Z3. The average GWL time series for these zones indicates declining trends of approximately -61, -17, and -9 cm/year, respectively. Notably, Z3 exhibits clear seasonal variations. The GWL anomalies in Z1 are influenced by deeper aquifers (approximately 35 to 70 m), while Z2 and Z3 anomalies are primarily affected by shallower aquifers (less than 35 m). The average of annual rainfall and surface air temperature in the study area reveals that northern Punjab, northern Haryana and Uttar Pradesh receive moderate rainfall, while other regions have lower levels. The trend analysis of climatic factors shows a significant increase in rainfall in northern Rajasthan, while Haryana and western-central Uttar Pradesh experience declines. The surface air temperature increases toward the south, with the highest trend observed in central Haryana. Further, we have performed 12-month SPI analysis across different zones (Z1, Z2 and Z3) and we identified a pattern from 2002 to mid-2010, marked by alternating short-duration droughts and wet spells. This was followed by wet years from mid-2010 to mid-2014, a prolonged drought from mid-2014 to mid-2018, and a brief wet period from mid-2021 to 2022. We analyzed time series data for GWL, GWS, rainfall, SPI, and tubewells to assess temporal variations in GWS across different zones. Z3 exhibited the most pronounced seasonal variation in GWL anomalies, while GWS anomalies showed similar patterns across all zones. Change point analysis revealed five key episodes of GWS trends, including a prolonged decline from 2002 to 2011 and a steep decline from 2015 to 2017, followed by replenishment until mid-2020 and a mixed trend thereafter. The GWS stabilization during the wet period from 2011 to mid-2015 was significantly impacted by climatic conditions, especially in Z2 and Z3. Spatial analysis indicated that GWS trends are influenced by alternating dry and wet patterns. Additionally, the rise in tubewells, particularly deep and medium tubewells in Z1 and Z2, correlates with GWS changes, highlighting the combined effects of climatic and human factors. The GRACE-GWS anomaly exhibits noteworthy variability in north India, indicating a discernible decreasing trend with the highest value of approximately -6.7 cm/year. This trend is especially pronounced in the regions of NCT-Delhi, Haryana, north Rajasthan, and west central Uttar Pradesh and centered in Haryana. This well-established GWS depletion zone relates to the threatening declining rates of GWL in three zones of the study region. The current trajectory of groundwater storage shows a combined impact of temperature, rainfall, and groundwater pumping by tubewells for irrigation. These climatic and anthropogenic factors are influenced by climate change and rising crop water demand. Our SPI and change point analysis of rainfall and GWS demonstrates that successive dry spells in the periods from 2002 to mid-2010 and mid-2014 to mid-2018 govern the high declining rates of GWS. However, the wet periods from mid-2010 to mid-2014 and 2018 to mid-2020 relieve the subsurface groundwater stress. Over the past five years, the resurgence of groundwater in GWS likely corresponds to favorable government policies promoting recharge since the corresponding moderate wet period is short and not sufficient for changes alone. The rapid rise in the number of tubewells increases anthropogenic extraction of the groundwater and leads to the declining groundwater well-level trends in severely declining zones of Punjab, adjoining Haryana, and northeast Rajasthan. Our change point analysis reveals five main episodes of decline and replenishment of GWS due to the combined effects of the rainfall (climatic) and tubewell extraction (anthropogenic) effect. The spatial variation of GWS trend, SPI, and changes in tubewell numbers for different episodes exhibits that the Uttar Pradesh state shows high dependency on irrigation on shallow tubewells due to consistent dry spells and low rainfall.

Keywords: *Groundwater variability, GRACE, North India, socioeconomic factors, dry & wet periods*

GROUNDWATER MODELLING TO UNDERSTAND THE IMPACTS OF CLIMATE CHANGE IN THE CHENNAI BASIN, SOUTH INDIA

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Groundwater is a crucial resource for maintaining ecological balance and supporting the socio-economic needs of communities. The Chennai basin, a densely populated area in southern India, relies heavily on groundwater to meet its various demands. Over recent decades, rapid urbanization, industrial development, and climate variability have stressed the basin's groundwater resources. Climate change compounds these pressures by altering precipitation, temperatures, and extreme weather events. Given the basin's susceptibility to both natural and anthropogenic factors, it is essential to forecast future groundwater levels. Numerical modelling offers a powerful approach to simulate groundwater system responses under these variables, enabling water resource managers to make informed decisions about groundwater sustainability. This study aims to evaluate the impact of climate change on groundwater heads in the Chennai basin by integrating projected land use changes and population dynamics into a numerical model. This study integrates several datasets, including historical precipitation records, land use projections, and population growth data, into a numerical model developed using Visual MODFLOW. Precipitation data for the historical period (1995-2020) was obtained from the Tamil Nadu State Groundwater Department, and future precipitation projections from the NorESM2-MM climate model, downscaled and bias-corrected to suit the Chennai basin. The projected land use dataset, covering decadal changes from 1990 to 2040, reflects anticipated expansion in urban areas and corresponding reductions in agricultural land. Population growth data was sourced from the UN World Population Prospects, with estimates scaled to project urban and rural population changes within the basin. The groundwater model's conceptual framework comprises geological and hydrogeological units, recharge, extraction, and boundary conditions. The basin was spatially discretized into a 1 km size grid, with two distinct aquifer layers. Each aquifer's hydraulic properties were derived from the basin aquifer mapping dataset, which included lithological, stratigraphic, and transmissivity data from exploratory wells and Vertical Electrical Sounding (VES) surveys. Recharge calculations used the Curve Number method, correlating Thiessen polygons of rainfall distribution with land use and soil hydrology maps to estimate infiltration losses and adequate runoff per unit area. Land use classes were further divided by hydrological soil groups (C&D), representing low to moderate infiltration areas, which were especially important for simulating runoff in urbanized and agricultural areas. For future projections, precipitation estimates from climate models SSP126, SSP245, SSP370, and SSP585 were applied across various land use classes. Extraction rates were estimated by analyzing groundwater consumption across urban and rural areas, adjusted annually for population growth. Urban extraction rates were calculated based on domestic and industrial demands, with 40% of total urban water demand estimated as groundwater use. Conversely, rural extraction rates considered agricultural and domestic demands, with an estimated 80% reliance on groundwater. These projections were inputted as time-dependent parameters in the numerical model to simulate fluctuating extraction pressures across urban, suburban, and rural zones. Calibration and validation matched simulated groundwater levels with observed head data from 14 wells across the basin for both steady (1995) and transient states (1996-2020). Calibration focused on refining hydraulic conductivity values, while validation ensured the model could replicate observed conditions, resulting in a mean root square error of 3.87 m. With calibration complete, the model predicted groundwater head changes across the basin under each climate scenario from 2021 to 2050.

The model results indicate that climate change, urban expansion, and population growth are projected to impact groundwater levels across the Chennai basin significantly. Historical simulations show that groundwater levels fluctuate based on precipitation variability, particularly affecting rural regions dependent on agricultural recharge. Urban areas with limited recharge capacity experienced steady declines due to intensive extraction. Future projections suggest a gradual decrease in groundwater heads across the basin, with the most significant declines observed under the SSP585 scenario, where a predicted 1.25 to 2.0 m reduction in groundwater levels was noted at multiple wells by 2050. Urban expansion exacerbates the decline, as built-up areas reduce infiltration capacity, increasing runoff and limiting recharge potential. The impact of this expansion is especially pronounced along the basin's southern regions, where information technology and industrial zones are concentrated. Climate variability also plays a crucial role. Increased frequency of high-intensity rainfall events, as projected under SSP370 and SSP585, leads to higher surface runoff, reducing the amount of water available for recharge. Drought periods further compound water stress, especially in urban areas where groundwater remains a primary water source. Though benefiting from higher infiltration rates, increased irrigation demands, particularly during dry spells, impact rural areas, creating additional extraction pressures. Spatial disparities in groundwater head declines were evident across the basin. Wells in urban areas experienced consistently lower groundwater heads due to constant extraction pressures, while rural wells showed more variability, reflecting the influence of rainfall-driven recharge. However, the growing urban population will continue to increase water demand, potentially lowering the groundwater head further if extraction rates are not managed. The findings of this study highlight the vulnerability of the Chennai basin's groundwater resources to climate change, urbanization, and population growth. Numerical modelling under various climate scenarios demonstrates that urban expansion and increased extraction due to population growth will be critical drivers of groundwater decline in the basin. The most significant predicted declines occur under the SSP585 scenario, emphasizing the need for urgent policy interventions to mitigate potential water shortages. It is recommended that sustainable water management practices be prioritized to preserve groundwater resources. Effective strategies could include promoting rainwater harvesting in urban areas, enhancing irrigation efficiency in rural zones, and imposing restrictions on groundwater extraction. Additionally, irrigation optimization technologies could reduce the agricultural sector's groundwater reliance. Numerical modelling proves invaluable in predicting groundwater trends, enabling regional planners to anticipate resource challenges and adopt appropriate conservation measures. Future studies could enhance this model by integrating more localized socio-economic data. Ultimately, this study outcomes provides a framework for assessing groundwater sustainability in the Chennai basin, helping decision-makers balance development with the need for long-term water security.

Keywords: *Climate change, groundwater modelling, Chennai basin*

ASSESSING THE IMPACT OF THE 2023 FLOODS IN HIMACHAL PRADESH AND PUNJAB IN INDIA ON GROUNDWATER RECHARGE

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The summer monsoon brings South Asia much of its annual rainfall and is vital for the millions of farmers. However, the 2023 monsoon brought exceptional rainfall and multiple incidences of severe flooding. On the 9th of July 2023, the mountainous state of Himachal Pradesh (HP) experienced unprecedented and catastrophic flooding on a scale not seen for half a century. Flooding was triggered by persistent and intense monsoon rain, 400% more rain between 7th and 11th July than normal for that monsoonal period, leading to flash floods and widespread destruction. Rainfall intensity and damage far exceeded predictions, making this event an outlier in the region's hydro-climatic history. This event was followed by persistent heavy rain and subsequent flooding in HP on 12th and Punjab on 17th August. In this study, we have investigated the linked mechanisms and cumulative impact of these events. The flooding in Punjab has implications for regional water and food security. The aquifers of Punjab are heavily exploited for irrigation and as a result Punjab is the regional breadbasket. However, groundwater is overexploited. Furthermore, intensive agriculture severely impacts groundwater quality as fertilisers infiltrate into the groundwater. The scale of the successive floods during the 2023 summer monsoon provides a unique opportunity to investigate the role of flooding in counterbalancing groundwater depletion and in mobilising contaminants. It is critically important to understand the role of floods, like the increasing probable 2023 monsoon floods, play in longer-term regional water and food security.

The aim of this study is to constrain the scale of the extreme flood event that occurred in HP and Punjab in July 2023 and assess the cumulative impact of continued heavy rain and flooding, focusing on groundwater recharge and contamination during the 2023 monsoon. To achieve this, the study has three key objectives: (i) Characterise the hydro-meteorological nature of the floods and the cumulative impacts. (ii) Collect and interpret groundwater level and natural tracer data to quantify the impacts of floods on groundwater levels and recharge in the Punjab plains and relate this to upstream and downstream flood characteristics, and (iii) Quantify flood impacts on water quality by collating baseline data and conducting new groundwater quality sampling and analysis. The study area encompasses the Manali-Kullu-Mandi area in HP and the Bist-Doab and Malwa regions of Punjab, which experienced the most severe flooding. The emerging results are presented here related to groundwater recharge assessment. Drawing on the results of hydro-meteorological and remote sensing analysis, we have identified areas to investigate groundwater recharge. To investigate the floods impact on recharge, we collected groundwater level data, inorganic and organic water chemistry samples, data on stable water isotopes, and natural tracer samples (CFC and SF_6). These data have been used to investigate the source and spatial/temporal extent of flood-related groundwater recharge. We collected groundwater data from the Central Groundwater Board (CGWB) and the Punjab Water Resources Department (WRD). The former consisted of 169 records of groundwater collected twice yearly with records beginning in 2013, the latter consisted of data collected at 15-minute intervals from early 2023 in the Bist-Doab and Malwa regions. We also collected 145 inorganic water chemistry and isotope samples, 36 environmental tracer samples for groundwater residence time assessments, 77 organic matter fluorescence and 77 pesticide samples from across the study area.

Initial results from groundwater level analysis in Punjab indicate that 69% of sites were affected by the floods. 74% of sites with groundwater levels less than 30 m showed an increase in groundwater level after the flood but only 37% of sites with groundwater levels below 30 m showed any response. Fewer (72%) sites in the Bist-Doab were affected by the two flooding events than in Malwa (90%), a higher number of sites in Bist-Doab have groundwater levels > 30 m. Furthermore, we observed distinct response typologies which appear to relate to the separate flood events in July and August. The effect of flooding on groundwater levels depends not only location of the sites, such as distance from surface water and drainage pathways, but also on site-specific characteristics such as depth to groundwater prior to the floods. Many of the samples collected from the Bist-doab and in the shallow to intermediate depth aquifers in the Malwa region (< 20 m depth) have electrical conductivity (EC) values < 1000 µS/cm, which are lower than the EC values observed during pre-flood conditions in 2019-21. Stable isotope values ($\delta^{18}O$) in these aquifers are <-7‰, which is indicative of recharge by surface water sourced from higher altitude regions in the Himalayas, and possibly related to the flooding that occurred in Himachal Pradesh in 2023. Furthermore, several sites in the Malwa region show stable isotope signatures in groundwater at shallow to intermediate depths which are indicative of surface water recharge sources, with slight shifts from -7.92‰ prior to the flooding to -8.67‰ after the floods, further indicating flood derived groundwater recharge. To further fingerprint the source of recharge water, we will use organic matter fluorescence, environmental tracers and pesticides to assess evidence for recent ingress of surface water, i.e., with higher dissolved organic matter (DOM) and more labile DOM, into the shallow groundwater system due to recharge of flood waters. Initial results from isotope, electrical conductivity, and groundwater level data indicate a clear influence of the flooding on groundwater recharge following the 2023 monsoon floods that occurred in Himachal Pradesh and Punjab. Further, work is required to more accurately fingerprint the source of the floodwater, particularly to distinguish between rainfall that occurred over Punjab during the two flood periods and precipitation that occurred in Himachal Pradesh and subsequently caused flooding in Punjab. The next steps will be to more quantitatively link the hydro-meteorological analysis to the hydro-geological and hydro-geochemical data, and to continue interpretation of the groundwater level and hydro-geochemical data.

Keywords: *Groundwater recharge, groundwater contamination, flooding, monsoon*

IDENTIFY THE OPTIMUM RAINFALL PATTERN AND DISTRIBUTION OF GROUND WATER SCENARIO AT DIFFERENT LEVELS AND FLUCTUATIONS OF WATER LEVELS OVER NORTH KARNATAKA, INDIA

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Rainfall is the natural phenomenon, which directly or indirectly affects all life on the Earth in one form or the other. It has large variations in time and space in terms of both amount and intensity. In India, rainfall is received mainly during the monsoon season. The orographic and rain shadow region dominate mainly rainfall distribution patterns over Karnataka during southwest monsoon season. The movement of depressions or cyclone over peninsular India during the northeast monsoon season and pre-monsoon season thunder storm activity is important in the summer season. In the present study, long term rainfall trends over thirteen districts of north Karnataka have been studied from 1901 to 2017 on monthly, seasonal and annual level. Daily rainfall data for 153 rain-gauge stations of North Karnataka have been collected for the period 1951 to 2013 from the database of AICRP on Agro-meteorology, RARS-Vijayapura, and subsequent years till 2017, from Directorate of Economics and Statistics, Bengaluru. Future climatic scenario dataset for 2021-2050 was downloaded from CMIP-5 and processed. Trend analysis has been carried out using Mann-Kendall (MK) test on annual and seasonal rainfall during 1951 to 2017. Results indicated a negative trend in Belgavi, Bidar and Dharwad districts at 1% level of significance and Koppal district showed positive trend at 5% level of significance. In case of south-west monsoon season rainfall, Bidar district showed negative trend with significance at 1% level and Koppal district showed positive trend with significance at 5% level. Study of inter-annual variations of seasonal and annual rainfall studied through moving average method indicated that the cyclic variations of different lengths in various taluks in all districts. In some taluks, the frequency of fluctuation was different from one period to another, for example, high frequency undulations in annual rainfall existed till 1990 but not later. Serial correlation and auto-regression (AR) models which were developed for long range forecast of annual rainfall, indicated high significance at 1% level of significance for Belagavi, Bidar, Dharwad, Raichur and Vijayapura districts. In Dharwad district, AR models for August, September, Kharif season, southwest monsoon and monsoon season showed high significance at 1% level. Comparison of projected rainfall for 2021 with 1988-2017 indicated lower annual rainfall for Ballari, Koppal and Vijayapura districts. Mapping of spatio-temporal variations in rainfall indicated that there was overall decrease over northern Karnataka during 1981-2017. Also, long-term behaviour of groundwater level according to groundwater recharge and draft conditions is presented in this paper based on different agro-climatic zones. The effect of seasonal rainfall on ground water levels was analysed. The highest south west monsoon rainfall of 1083.1 mm was received in the year 2019 in Belgaum and the of minimum 373.7 mm was received in Bijapur. The departure of seasonal rainfall ranged between -16% (Yadgiri district) to 89% (Belgaum district). Similar results have been obtained for individual districts for the projected rainfall patterns. In case of ground water levels, about 67 % and 93.5 % of the wells showed ground water levels within 10 mbgl, during pre- and post-monsoon season of 2019, respectively. It is observed that 78% of the wells in the North Karnataka State are showing fall and 22% of the wells are showing rise in annual water level during pre-monsoon 2019. While, during post-monsoon season of 2019, about 78% and 22 % of the wells are showing rise and fall in ground water levels, respectively. Analysis of the the pre-monsoon and post-monsoon season decadal (2009 to 2018) mean ground water level, indicated that 69% and 38% of wells show fall in ground water level, respectively. Comparison of projected and historical rainfall pattern for selected districts of north Karnataka indicated that in Ballari, Koppal and Vijayapura districts the projected rainfall pattern showed lower rainfall, whereas in Dharwad and Haveri districts it is projected to be higher rainfall. Changes in patterns of cyclicity and trend were also noticed. The spatio-temporal variations of rainfall indicated that there has been overall decrease in rainfall in the Northern Karnataka from Phase I to Phase II in annual, seasonal (*Kharif* and *Rabi*) and monthly rainfall, whereas increase in rainfall during Phase II has been identified in monthly rainfall for June and August. The coefficient of variation of annual rainfall, southwest monsoon season (SWM) rainfall and monthly rainfall of May, June and July increased from Phase I to Phase II, whereas it deceased in northeast monsoon season (NEM) and in August and October months. The study assessed the climatological variations in annual, seasonal and monthly rainfall at the district and taluk level, and also assessed its relation with depth to ground water levels in districts of North Karnataka. This paves way for more intense and focused studies in future.

Keywords: *Rainfall, groundwater, trend analysis, MK test, Karnataka*

ANALYZING THE IMPACTS OF RECENT CLIMATE CHANGES ON THE HYDROLOGY OF SURFACE WATER AND GROUNDWATER USING AN INTEGRATED HYDROLOGICAL MODEL

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Traditionally, assessments of climate change impacts on streamflow have focused primarily on water availability, often overlooking its effects on groundwater (GW) recharge and availability. There is a need for a comprehensive understanding of how changing climate patterns influence GW dynamics because GW plays a critical role in sustaining water resources, especially during dry periods. Therefore, this study aims to evaluate GW availability and its replenishment through recharge at the watershed scale, utilizing an integrated modeling approach. The impact of recent climate changes on streamflow, groundwater recharge (GWR) and groundwater head (GWH) in the Upper Godavari River Basin (UGRB), India, was analysed for the historical period from 1982 to 2020 using the integrated SWAT-MODFLOW hydrological model. The UGRB is a key sub-basin within the larger Godavari River Basin (GRB), located in Maharashtra State. This region spans approximately 21,774 km^2, supporting a population of around 8.6 million people across 1,883 villages and 45 towns. The land is predominantly agricultural, with the remainder classified as barren. Based on LULC data from 1985 and 1995, about 80% of the area is utilized for farming, with surface water from reservoirs serving as the primary irrigation source. The UGRB experiences a tropical climate, receiving nearly 85% of its annual rainfall during the southwest monsoon season, which occurs from July to September. The Bhandardara, Mula, and Jaikwadi reservoirs are the three main reservoirs situated within this basin, beginning operations in 1928, 1972, and 1976, respectively. Together, these reservoirs supply irrigation water to almost 75% of the region's agricultural land.

The integrated SWAT-MODFLOW exchanges data between SWAT and MODFLOW to see the interaction between river and aquifer. The HRUs based recharge output from the SWAT is given to the MODFLOW grid to assess the change in the GWH. The SWAT model inputs included rainfall, maximum and minimum temperature data collected from the Indian Meteorological Department (IMD) at 0.25° × 0.25° resolution. LULC data was collected from the Environmental Systems Research Institute (ESRI) at 10 m resolution. Soil data was collected from Food and Agriculture Organisation (FAO) at 1:5 000 000 scale, which shows four main type of soil class present in UGRB. It consists of clay, clay-loam, sandy-clay-loam and loam. The SWAT model simulated the spatio-temporal distribution of streamflow, GWR rates, evapotranspiration. Then, the HRUs based output is given to MODLOW. Additionally, MODFLOW requires the initial GWH and aquifers properties such as storativity and permeability which are collected from Central Groundwater Board (CGWB).

We have chosen multisite inside the basin to calibrate and validate the model. Multisite calibration is done to see the spatial variation in the calibrated parameters. Calibration and validation of the model was done at two points namely Nagamthan and Jaikwadi gauge

stations, using 19 calibration parameters. The calibration at Nagamthan showed R^2 = 0.69, NSE = 0.69, and PBIAS = -21, while at Jaikwadi, R^2 = 0.69, NSE = 0.69, and PBIAS = 5.1 were observed. For the validation at Nagamthan and Jaikwadi, the statistical parameters the R^2, NSE, PBIAS value were 0.68, 0.69, -2.38 and 0.66, 0.62, -20.2 respectively. Then the setup model was run for time periods of 1982-2000 and 2001 -2020 taking LULC of year 2017 constant for entire simulation. To assess the climate change impact on surface water and GWR, the difference between simulation period 2001-2020 and 1982-2000 was taken. It is observed that in the UGRB, the changes in streamflow, GWR, and GWH resulting from climate change scenarios were significant. Streamflow in most of the sub-basin areas shows a substantial rise, ranging from 1 to 32 mm, in the period from 2001 to 2020 compared to the period from 1982 to 2000. While some sub-basins indicate a decrease in streamflow, the other sub-basins exhibit the greatest increases in streamflow. The GWR has declined in nearly half of the sub-basins, with reductions ranging from -2 to 0 mm. The most notable increase in GWR appears in sub-basin 1, attributed to climate change impacts. The remaining sub-basins display moderate increases in GWR, varying between 0 and 6 mm. It has been observed that among the meteorological factors, rainfall exerts the greatest influence on the streamflow, GWR and GWH. The rise in streamflow coupled with the decrease in groundwater recharge might result in flooding and a decline in the groundwater table within the basin. The findings of this study are expected to provide critical insights to the policymakers in formulating strategic water management plans.

Keywords: *Climate change, SWAT-MODFLOW, streamflow, recharge, groundwater*

NUMERICAL STUDY OF THE HILLSLOPE DRAINAGE PROBLEM FOR A HETEROGENOUS SOIL WITH A CHANGING TOPOGRAPHY

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The study examines the problem of hillslope drainage in heterogeneous soils with varied topographies by developing a robust numerical framework based on the Finite Difference Method. The study focuses on the challenge of accurately predicting the phreatic line, which marks saturated and unsaturated zones, under diverse hydrological and geological conditions. By using Darcy's law and mass conservation principles, the governing equations for groundwater flow in sloping aquifers were derived, which involved spatially varying parameters such as hydraulic conductivity $k(x)$, slope $\alpha(x)$, and recharge rate p. The nonlinear nature of these equations was discretized using the FDM and solved iteratively by the Newton-Raphson method to ensure computational efficiency and precision. The aquifer system considered in the present work involves a sloping soil layer, overlain with an impermeable base under steady recharge conditions from above and appropriate boundary conditions. The study makes three primary cases: uniform slope with constant p/k, a linearly varying slope and hydraulic conductivity, and exponentially varying hydraulic conductivity, as a means to explore their isolated and combined impact on the profile of hydraulic heads. Results show that uniform slopes with constant p/k produce symmetric hydraulic head profiles influenced by boundary conditions, and higher p/k ratios lead to steeper head reductions due to increased recharge rates. When slope and hydraulic conductivity are varied linearly or exponentially, the groundwater flow patterns shift significantly. Linear growth in $k(x)$ enhances subsurface flow with the development of hydraulic head peaks especially at steeper slopes, and exponential growth in $k(x)$ leads to a steep decrease in hydraulic head because of the increase in permeability. Conversely, exponential decreases in $k(x)$ slow down water movement and, consequently, lead to a gradual decline in hydraulic head. These show how heterogeneity in soil and slope dynamics significantly affects groundwater flow. Furthermore, increased slope angles shift the hydraulic head profile due to a lower gravitational head and moving the flow toward downstream boundaries, which points to the importance of including slope variability in models. The study highlights the role of spatially heterogeneous parameters like slope, conductivity, and recharge in defining the groundwater flow in sloping landscapes, and the integration of realistic field observations in the modeling process. Practical implications of these findings extend to sustainable groundwater management and hill drainage planning, offering insights into managing water resources in sloping regions characterized by complex geological and hydrological conditions. The study concludes by demonstrating the significance of integrating heterogeneity and topographical variations into groundwater models and establishes a foundation for future research on transient flow conditions and more intricate terrains. This study provides a holistic numerical approach to address the complexity of groundwater flow in hilly regions, which can improve water resource management and decision-making in regions prone to topographical and hydrological variability. This study has critical implications for advancing the understanding of groundwater dynamics in sloping aquifers and forms the basis for further exploration into the transient behaviour of hillslope drainage systems.

Keywords: *Hillslope drainage, heterogeneous soils, groundwater flow, numerical modeling*

ADDRESSING THE CLIMATE CHANGE IMPACTS IN NAGPUR DISTRICT OF MAHARASHTRA, INDIA: A SUCCESS STORY OF THE GREEN PROJECT

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In India's central region, Nagpur, called the Orange city, is the winter capital of Maharashtra State, characterized by extreme cold and heat waves. Certain sub-districts of Nagpur, despite receiving over 1000 mm of annual rainfall, are struggling with supply and demand management due to recent fluctuations in rainfall patterns and over-exploitation of groundwater. Water scarcity is increasingly affecting in essential government institutions like primary health care centers, schools and remote areas including tribal and non-tribal areas of the district. The challenges of managing supply and demand are further exacerbated by urbanization and intensive agriculture reliant on water, which compete with the needs of the community. Consequently, the unchecked exploitation of water resources and the potential depletion of these resources underscore the urgent necessity for water conservation measures. The region struggles with various challenges in fulfilling water needs for homes, institutions and healthcare due to various factors. These factors include inadequate access to remote areas, financial and management issues, depleting resources, unreliable electricity, high costs, rising electricity demands, inadequate WASH facilities, and uncomfortable conditions in schools due to high room temperature of buildings and availability of water in summer leading to high dropout rates. Therefore, this study presents the success story of 'The Green Project' initiative used to address climate change issues in the Nagpur district (Maharashtra State).

Over a period of time, bore wells can become obstructed by mud, sand and tree roots, rendering them unsuitable for drinking water. To restore these water sources, a cleaning process involving re-drilling or flushing is necessary. As of 2023, the Zilla Parishad in Nagpur has successfully completed the re-drilling or flushing of 2,141 bore wells. However, due to the deep-water levels, the flushed bore wells cannot be utilized for extraction. Instead, 106 of these bore wells have been repurposed as recharge shafts to improve groundwater levels. With a total roof area of 9,858 m^2, this initiative has facilitated the recharge of approximately 7.5 million liters of water annually. The existing bore wells present a cost-effective alternative, eliminating the need for new bore wells and associated expenses. It was found that most government and semi-government buildings especially in remote areas do not have parapet walls on the roof. Due to this, the falling rainwater usually runs off and wasted. The rainwater harvesting system utilizes a catch-and-collection approach by capturing rainwater from public building roofs with a parapet wall and directing it through pipes for storage and groundwater recharge via filters. The buildings' rooftops have been treated to prevent water damage. On the roof, a slight slope of approximately 1° is implemented on both sides. This is complemented by the application of two layers of white heat-resistant paint, which serves to fill in cracks and address minor leakages. Such measures contribute to the reinforcement of the building's structure, facilitate the efficient drainage of water, and enhance the albedo effect, thereby reducing the building's temperature by 3° to 5° C. Consequently, there is a decreased reliance on electrical appliances such as air coolers and air conditioning units during the summer months, leading to a potential conservation of over 30% of natural resources. Every rainwater harvesting system incorporates filtration as a fundamental element. The design of these filters includes a chamber filled with filtration materials, such as coarse sand and gravel layers, which effectively remove debris and contaminants from the water, preventing them from entering the storage tank or recharge structure. These materials require periodic cleaning and replacement, which can increase maintenance costs. To mitigate such maintenance issues, modern systems utilize online self-cleaning filters that operate based on the principles of cohesive and centrifugal forces. The storage tank can be positioned either at ground level or atop the premises to store water for use during dry periods, which is particularly beneficial in health emergencies where water is essential, as well as for fire emergencies, especially in primary health centers. Instead of traditional electric pumps, solar pumps are employed, which operate on sunlight and are more cost-effective. Additionally, solar net metering is a billing system that compensates owners of solar energy systems for the surplus electricity they contribute to the grid. A building equipped with a rooftop solar photovoltaic system can generate more electricity during daylight hours than it consumes, especially when combined with the increased efficiency provided by reflective white paint.

The execution of "The Green Project" presents an environmentally conscious and sustainable strategy for fostering a clean and green environment. According to initial qualitative findings, the initiative is expected to enhance groundwater levels, minimize runoff, and decrease building temperatures, which will lead to reduced energy consumption and improved water conservation and recharge. Additionally, an integrated system of rainwater harvesting and solar energy will contribute to a sustainable future by promoting energy conservation and enhancing energy efficiency. This approach will be cost-effective while also mitigating air pollution through the reduction of greenhouse gas emission. This approach has substantial potential for expansion and duplication to enhance the environmental sustainability of institutional systems, alleviate climate risks, and provide green technologies to underserved populations. The assessment of energy savings, carbon footprints, water availability, and similar factors, both qualitatively and quantitatively, proves valuable. A substantial investment in this strategy would significantly contribute to environmental sustainability and help alleviate the effects of climate change. The initiative referred to as 'The Green Project' has been found very effective to tackle a range of challenges arising from severe climate-related conditions, such as water shortages, rising temperatures, and the effects on service delivery and water accessibility, as well as providing an alternative to artificial energy sources. This project successfully aligns with the mitigation objectives of the Sustainable Development Goals (SDGs) agenda by promoting a resilient community among both service users and providers, while also safeguarding essential rights.

Keywords: *Reuse structure, rainwater harvesting, white paint, solar energy, SDGs*

RAINFALL-DRIVEN GROUNDWATER RESERVES IN THE KOYNA BASIN, INDIA: ASSESSING SEASONAL RECHARGE AND ENVIRONMENTAL INTERACTIONS

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The demand for groundwater resources in India is expected to rise significantly across multiple sectors, placing increasing pressure on water supplies. However, inadequate management has led to challenges such as rising pumping rates, declining well yields, shifting seasonal rainfall patterns, and diminished groundwater reserves, especially in Koyna basin of Maharashtra, Western India where mismanagement can even trigger seismic activity. Fluctuations in groundwater levels, driven by recharge and extraction, can be exacerbated by seismic activity. Numerous studies have demonstrated a link between excessive groundwater extraction and induced seismicity. Despite this, research on the replenishment of natural groundwater reserves by precipitation and its potential impact on seismic activity remains limited. Understanding these reserves is crucial for effective groundwater management and assessing hydrological loads related to seismic events. Remote sensing (RS), GIS techniques, and numerical simulations are increasingly used to assess groundwater reserves and their environmental interactions. Information theory, developed by Shannon, has emerged as a valuable tool in hydrology for estimating hydrogeological parameters, especially in data-scarce regions. This model provides a rapid approach for estimating groundwater reserves. Thus, the objectives of this study are to: (i) estimate rainfall-driven groundwater recharge using an information-based model, and (ii) explore the interplay between groundwater dynamics and environmental factors in the Koyna Basin.

Rainfall is a primary driver of groundwater recharge, influencing fluctuations in groundwater levels. This study calculated marginal entropies for rainfall, H(RF) and groundwater levels, H(GWL), along with their joint entropy, H (RF, GWL), using probability distributions. Trans-information, T (RF, GWL) was then used to assess how rainfall measurements reduce uncertainty in predicting groundwater levels. The natural groundwater reserve (NGR) was estimated based on the ratio of trans-information to the marginal entropy of rainfall, with the percentage of rainfall contributing to groundwater recharge (Re%) calculated accordingly. The NGR was determined using the equation: $NGR=R_e\,(\%)\times rainfall\times A\times 0.00001$. Where A: area influenced by each well, derived using Thiessen polygons. The IMD gridded daily rainfall data of 23 years was used for the Koyna basin analysis. Seasonal groundwater level data from the CGWB wells over the same period were utilized. The Landsat-8 OLI/TIRS images at 30 m resolution were processed in ArcGIS to create a LULC map. Groundwater prospect map was generated using RS and GIS and multi-criteria decision-making (MCDM) based on the Analytical Hierarchical Process (AHP). Finally, monthly total water and groundwater storage data from GLDAS-2.2 have been compared with the estimated natural groundwater reserves.

The gridded rainfall data have been analysed and the highest recorded rainfall occurred in 2005 in the northern part of the basin, an area characterized by dense forest cover. The rainfall data reveal significant spatial variability across the basin. Monthly rainfall patterns

showed that July consistently received the highest rainfall, followed by August and June, reflecting the dominance of the monsoon season. Groundwater levels, monitored by the CGWB, showed seasonal fluctuations. Hydrographs indicated deeper groundwater levels in the south-eastern basin, with shallower levels generally within 16 m, bgl, closely linked to the rainfall patterns. Marginal entropy calculations for RF and GWLs, based on seasonal data, revealed a range of 0.8781 to 1.6889 bits for RF and 0.3902 to 2.5006 bits for GWLs, showing spatial variability in recharge potential. Natural groundwater recharge rates, based on annual rainfall, ranged from 1.4% to 41.0%, with the monsoon months (June to August) being most crucial for recharge. Groundwater reserves from monsoon rainfall was an average of 16.9%, revealing the limited recharge in certain wells, potentially due to human activity and lateral flows. The spatial distribution of recharge showed lower rates in the south-eastern part of the basin having more barren lands. Using the Thiessen polygon method, annual groundwater reserves (AGWR) were estimated for the selective years. As an example, it ranged from 1.50 to 192.95 MCM annually, depending on rainfall. Seasonal groundwater reserve (SGWR) was the maximum at 117.26 MCM, but it was highest in 2005 at one well with a value of 505.19 MCM, while lower reserves were observed at other wells. The LULC map indicated that forests, which dominate the northern and western parts of the basin, significantly contribute to groundwater recharge, with rates of 25.6% during the monsoon, compared to just 5.2% in built-up areas. Satellite and GLDAS-based analyses showed consistent Total Water Storage (TWS) anomalies, with positive anomalies during the monsoon and negative anomalies in the dry season. Seasonal trends in evapotranspiration (ET) and soil moisture (SM) were found to influence groundwater storage, with strong positive correlations between GWS, RF and SM, and negative correlations with ET, found the complex hydrological interactions in the basin.

The study estimates rainfall-driven groundwater reserves in the shallow aquifers of the Koyna Basin, Western India, by integrating groundwater level measurements with rainfall data through information theory. Natural groundwater recharge rates vary between 1.4% and 41.0% of annual rainfall, with an average of 19.3%. Monsoon rainfall, in particular, contributes around 16.9% to groundwater recharge, with forested areas in high groundwater potential zones showing a notable recharge rate of 25.6%. A strong positive correlation (R = 0.88) is observed between forest cover and recharge rates, revealing the role of land use in influencing groundwater dynamics. In contrast, wells downstream of the Koyna Reservoir discovered limited recharge response, likely due to human interventions and lateral groundwater flows. Seasonal groundwater reserves are found with strong correlations to the GLDAS data on the SM and GWS, though an inverse relationship with the ET is observed. These findings emphasize the importance of understanding seasonal recharge patterns and environmental interactions for effective groundwater management in the Koyna basin.

Keywords: *Rainfall, groundwater reserve, trans-information, Satellite and GLDAS data, Koyna basin, Western India*

CLIMATE CHANGE AND GROUNDWATER RESILIENCE IN TAMIL NADU: REGIONAL IMPACTS AND ADAPTIVE STRATEGIES

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Tamil Nadu relies heavily on groundwater for its agricultural, domestic, and industrial water demands. However, climate change is putting immense pressure on this critical resource, with shifts in rainfall patterns, rising temperatures, and increased frequency of droughts leading to notable declines in groundwater levels and quality. These changes have region-specific impacts, particularly affecting semi-arid and coastal areas, where salinization and over-extraction are growing concerns. This study examines the challenges posed by climate-induced pressures on groundwater in Tamil Nadu for two decades (2004-2023), using spatial analysis to map vulnerabilities, their relationship with the climatic factors such as precipitation, temperature etc., and assess adaptive measures. By identifying areas with critical water management needs, this study aims to inform sustainable strategies that enhance groundwater resilience and secure water resources for the future.

The study integrates district-level in situ groundwater data and satellite sourced data for Tamil Nadu to examine the spatial and temporal impacts of climate change on groundwater resources. The methodology encompasses four main stages: spatial and temporal analysis of ground water, computing relation between ground water and other climatic factors, generation of a strategic map for vulnerable regions and suggestion of adaptative strategies. The data collected for the study includes historical groundwater level data obtained from CGWB and Ground Water Storage data from NASA Global Land Data Assimilation System (GLDAS). This study also analyzed both annual and season wise data to provide insights on pre- and post-monsoon recharge rates and declination in ground water levels. Climatic datasets such as temperature, precipitation, extreme weather event frequency, evapotranspiration, storm surface runoff, etc. were sourced from the IMD records and from spatial datasets such as ERA-5 (ECMWF Reanalysis v5) and NASA GLDAS covering a period of 20 years to capture both short-term fluctuations and long-term trends. The Land Use/Land Cover (LULC) maps were sourced from Copernicus mission and significant locations are mapped manually and were sourced from Open Street Maps for the creation of strategy map. The mapping of gradient and district-level Groundwater Storage (GWS) was performed on Google Earth Engine platform. A Composite index of GWS for Tamil Nadu using the slope obtained by linear fitting of decadal, 5- and 3-year dataset was prepared to highlight areas with a significant need for groundwater management. Layers on slope obtained through linear fitting were overlaid by providing weightage to arrive at the index map. The correlation of thus developed GWS index with climatic datasets were also performed to identify the influence of such factors over the depletion or augmentation of groundwater.

From the study, it was identified that coastal districts of Tamil Nadu including metropolitan city of Chennai, Nagapattinam, Kadalur, etc., shows a declining trend in GWS rate. Therefore, a comprehensive note on groundwater management strategies focusing on the coastal regions is provided in the study. This involves Managed Aquifer Recharge (MAR), rainwater harvesting, water quality protection measures and water-efficient agriculture

practices, followed by suggestions on educational awareness and policy interventions under the frame of pre-existing government schemes and programmes. Based on the spatial location of already established freshwater structures such as ‘Aayiram Kanmaais’ (Thousand lake systems), Chain-tank system predominantly found in the coastal regions of Tamil Nadu, and fresh waterbodies, a strategic map with zones with classes of different interventions is proposed. This measure also takes into consideration the existing barren lands in agriculture sector, for suitable recharge zones. In urban regions, rainwater harvesting in residential buildings have proved to be an effective means of intervention. It is also noteworthy to mention that Tamil Nadu is a forerunner in residential rainwater harvesting structures thus allowing the urban regions to be a strategic point of suitable interventions. Altogether a taluk level strategy map with different intervention classes is compiled to facilitate the sensitization of different stakeholders in future. The classes of intervention include: residential rainwater harvesting, GW recharge zones, wetland conservation, identification and rejuvenation of coastal structures, management of water reservoirs, prevention of sea water intrusion, wastewater management, small check-dam constructions, repurposing bore-wells and controlling commercial water consumption. The study also highlights a set of sustainable and just ways for the implementation of the strategies for each of the intervention classes. The future scope of the study lies in initiation of inclusive stakeholder interactions at local level in selected taluks under diverse intervention classes provided in the strategic map. Overall, this study tried to add on to the efforts in bridging the gap between science and policy by embracing the scientific data and just strategic interventions for combating climate change induced ground water crisis.

Keywords: *Groundwater resilience, climate change adaptation, Tamil Nadu, managed aquifer recharge, spatial analysis*

FUTURE-PROOFING GROUNDWATER: MODELLING THE IMPACTS OF CLIMATE, LAND USE AND DROUGHT VULNERABILITY

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Groundwater is a critical resource that supplies fresh water for drinking, agriculture, and industry to large portions of the global population. As surface water sources become increasingly strained by growing demand, pollution, and climate variability, the role of groundwater as a stable water source has become more prominent. However, intensive groundwater extraction, contamination, and climate change impacts have placed severe pressure on groundwater systems, leading to significant depletion and quality degradation in many regions. This study seeks to address these challenges by developing a comprehensive groundwater model for a selected area to support sustainable groundwater management and ensure long-term water security. The groundwater model for this study integrates surface and subsurface water interactions using the SWAT in conjunction with Visual MODFLOW. This combination of tools allows for accurate simulation of the interactions between groundwater and surface water under various climatic and land use conditions. The model will be run for current climate and land use scenarios and then tested under future climate projections to assess potential changes in water demand and groundwater availability. Key parameters such as precipitation, evapotranspiration, soil moisture, and runoff are included to represent surface water components. Groundwater data including water table levels, recharge rates, and aquifer properties, are used to model subsurface conditions. The methodology also includes testing the impacts of current and future land use scenarios. Land use changes influence both groundwater recharge and demand, as urbanization and agricultural expansion alter the natural infiltration processes. Future scenarios considered potential shifts in land use patterns under climate change and population growth projections. A groundwater drought-prone index has been developed based on the model's outputs to identify areas most vulnerable to groundwater scarcity. This index will help prioritize regions requiring immediate attention to prevent long-term resource depletion. Data for this study utilized from various sources to ensure a comprehensive representation of both natural and anthropogenic factors influencing groundwater. Surface water data, including river flow and runoff measurements, have been collected from regional water management agencies and past hydrological studies. Climate data such as precipitation, temperature, and evapotranspiration, are obtained from global climate databases and local meteorological stations. LULC data are sourced from remote sensing imagery and government land-use databases to provide historical and projected land use patterns. Groundwater data include monitoring well records, groundwater extraction rates, aquifer properties, and recharge rates. This data is collected from national groundwater monitoring agencies. Data from the SWAT model outputs are calibrated with observed groundwater levels in Visual MODFLOW to ensure model accuracy. Additionally, high-resolution satellite data such as GRACE (Gravity Recovery and Climate Experiment) is used to incorporate large-scale groundwater storage changes. These datasets are essential for simulating both current conditions and future climate scenarios.

Preliminary results from the groundwater modeling indicates a significant depletion trend in regions with intensive agricultural and industrial activity. Under current climate and land use conditions, certain areas within the region are experiencing groundwater levels that are

unsustainable in the long term. The application of future climate scenarios suggests that groundwater availability may be further impacted by reduced recharge rates, particularly in regions projected to experience decreased rainfall and higher temperatures. Similarly, changes in land use, such as an increase in urbanized areas and agricultural expansion, show an added strain on groundwater systems by reducing infiltration and increasing water demand.

The groundwater drought-prone index has been developed in this study to identify several high-risk zones, primarily in areas with extensive irrigation and lower recharge rates. These zones are found to be most vulnerable to long-term groundwater scarcity and require focused management interventions. The index serves as a valuable tool for prioritizing regions where groundwater conservation and sustainable management practice are most urgently needed. This study presents a comprehensive approach to understanding groundwater dynamics in the face of climate change and land use modifications. By modeling groundwater under both current and future scenarios using SWAT and Visual MODFLOW, this study identified key areas of concern for groundwater sustainability. The results underscore the need for proactive management strategies that incorporate sustainable groundwater extraction rates, balanced with recharge potential under evolving climatic and land use conditions. The study's groundwater drought-prone index offers a targeted approach for prioritizing regions most vulnerable to groundwater scarcity. These findings have significant implications for policymakers, enabling more informed decisions on sustainable groundwater management and planning. The mitigation strategy developed in this study proposes guidelines for a suitable groundwater extraction draft that aligns with recharge potential and resource renewal rates. Recommendations for land use practices are also provided to reduce water demand and enhance natural infiltration. By prioritizing areas identified as high-risk through the drought-prone index, this study contributes to a more resilient and sustainable groundwater management framework that can adapt to future environmental and socioeconomic changes. This comprehensive approach has the potential to support water security in the region, ensuring that groundwater resources remain viable for future generations.

Keywords: *Groundwater modeling, climate change impact, sustainable management, land use scenarios, drought-prone index*

RAINFALL AND ITS VARIATION IN AND ARROUND BHANEGAO AND SINGORI OPEN CAST COAL MINING AREA, DISTRICT NAGPUR, INDIA

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Rainfall plays very vital role in availability of groundwater for various purposes viz. Agriculture, drinking, domestic and Industrial purposes. To understand the seasonal and temporal variation in rainfall large data set is required. The present study is carried out to establish the variation in actual rainfall with respect to normal for understanding its control over occurrence and movement of groundwater with respect to time. The key resource area covered under this study is part of 3 different talukas viz., Kampttee, Parsioni and Saoner from District Nagpur in Maharashtra State. The annual monsoon rainfall data of last 52 years (from year 1971 to 2022) for Parseoni, Saoner and Kamptee taluka is taken from the government web site *services.mahavedh.com* and also from office database of Groundwater Surveys and Development Agency, Nagpur and utilized for understanding the monsoon rainfall behaviour in the study area. The normal rainfall values from India Metrological Department (IMD) were taken and accordingly variation of rainfall was calculated. At the same time percentage variation with respect to normal rainfall is calculated and it is utilized for knowing the cyclicity of rainfall. The findings on the basis of 52 years' rainfall data for Parsioni indicate that there are 26 positive rainfall years and 26 negative rainfall years and same is the case with respect to Saoner where as in Kampttee the positive rainfall years decreased to 19. In the last 52 years, Parseoni received average 941.26 mm rainfall when compared with normal rainfall (919.8 mm) i.e., 21.46 mm or +2.33% more. Saoner has received average 945.12 mm rainfall as compared with normal rainfall 908.40 mm +4.04% more. When rainfall for Kampttee is analyzed, it has been found that it has received 983.97 mm rainfall when compared with the normal rainfall of 1064.80 mm. The rainfall percent deficit is -7.59%. The decadal percent deviation for each decade was analyzed for gaining rainfall behavior pattern on decade level. In Parseoni, the rainfall trend is showing increasing trend when compared with 1971-1980 rainfall decade. The Saoner taluka has received more rainfall during the last 2 decades. From 1981 to 2022, the rainfall shows an increasing trend. No pattern for Kamptee is identified. It can be concluded that the Kamptee has unpredictable behavior with respect to rainfall.

Keywords: *Trend, rainfall, Napur, coal mining*

IMPACT OF URBAN HEAT ISLAND ON GROUNDWATER RECHARGE: A BIBLIOMETRIC ANALYSIS

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Urbanization has grown significantly, with a projected 70% global population living in cities by 2050 compared to only 13% in 1900. This rapid urban growth makes managing urban water systems increasingly critical and complex. Groundwater is a key resource for freshwater. However, urbanization has altered the functioning of natural systems, particularly groundwater recharge processes. The increasing population density in cities, coupled with intensified industrial and economic activities, have exacerbated the strain on urban hydrological systems. The interplay between urban development and natural processes presents challenges that demand interdisciplinary solutions and innovative strategies for sustainable resource management. The present bibliometric review examines existing literature to explore the relationship between urban development, the Urban Heat Island (UHI) effect, and groundwater recharge, while identifying current research trends. The analysis reveals that urbanization typically reduces groundwater recharge due to the increase in impervious surfaces, which inhibits rainwater infiltration and increases the surface runoff. Studies indicate that rising surface and subsurface temperatures can decrease recharge rates by as much as 30% to 50%, particularly in regions experiencing high levels of urbanization. Thermal groundwater systems in cities are influenced by human activities, such as paving surfaces, constructing underground structures, and using groundwater for heating and cooling. The inputs, outputs, and storage of energy, water, materials, and waste in urban areas are key factors leading to adverse urban metabolism, contributing to UHI effects. Cities act as heat sinks due to high resource consumption and altered land surfaces, intensifying UHI. Waste heat from energy systems significantly contributes to UHI. Urban metabolism studies help link energy consumption patterns to UHI effects, enabling targeted reductions in emissions and waste heat outputs. Social, political, and economic factors also influence urban development and groundwater management. The methodology involves an extensive literature review of more than 200 articles from Scopus, Web of Science, and Google Scholar, covering the period from 2010 to 2024. Keywords such as "Urban Heat Island," "groundwater recharge," "urban hydrology," "urban metabolism," "water-energy nexus," "sustainable urban design," "green infrastructure," and "climate-resilient cities" were used for searches. Data cleaning and preparation processes ensured consistency in author names, institution names, and keywords. The R Bibliometrix tool was used for advanced statistical and graphical bibliometric analysis. Metadata (title, authors, keywords, abstract, citation counts) was formatted for compatibility with bibliometric tools (e.g., CSV, RIS). Duplicates were removed, author names were standardized, keywords were harmonized, and irrelevant studies were filtered out. The bibliometric analysis focused on emerging themes through keyword clustering and co-citation analysis. Co-authorship and citation patterns indicated strong collaboration among developed countries, while contributions from developing countries were limited. The thematic analysis identified gaps in understanding the long-term impacts of UHI on groundwater quality and recharge sustainability. Limited studies integrated field data, remote sensing, and hydrological modelling. The results highlight a steady increase in publications on this topic, with a marked rise after 2015, coinciding with a global emphasis on sustainable urban development. Leading contributions came from regions experiencing rapid urbanization, such as China, the United States, and India. Top journals in this field included *Hydrological Processes, Urban Climate*, and the *Journal of Hydrology*. Keyword clustering revealed three dominant themes: the influence of impervious surfaces on urban hydrology, UHI effects on evapotranspiration and recharge variability, and green infrastructure and artificial recharge as mitigation strategies. The review also revealed significant regional variations in the impacts of UHI and urbanization on groundwater recharge, driven by climatic, geological, and socioeconomic factors. For instance, arid and semi-arid regions experienced more pronounced reductions in recharge rates due to higher temperatures and limited precipitation. The findings further highlight the increasing use of advanced technologies such as GIS, remote sensing, and machine learning models in urban hydrology research. These tools are crucial for mapping impervious surfaces, identifying recharge zones, and predicting future scenarios under varying urbanization and climate conditions. Policymakers and urban planners must prioritize UHI mitigation strategies as part of sustainable urban water management to ensure resilience against climate change and urbanization pressures. The present review provides a comprehensive overview of the research landscape, presenting valuable insights for researchers and policymakers to analyze the complex interactions between urbanization, UHI, climate change, and groundwater systems. Sustainable urban designs, such as green infrastructure and water management practices like permeable pavements and rainwater harvesting systems, can mitigate adverse effects. Some studies suggest that urban environments can increase recharge under specific conditions, such as through managed storm water systems. Balancing urban growth with groundwater conservation efforts is essential. Comprehensive models that incorporate both hydrological and anthropogenic factors are urgently needed to analyze and mitigate the impacts of urbanization on groundwater resources effectively.

Keywords: *Urbanization, urban heat island, groundwater recharge, sustainability*

VARIABILITY OF THE SPRING ARCTIC SEA ICE AND ITS IMPACT ON INDIAN SUMMER MONSOON: A HYDROLOGICAL PERSPECTIVE

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Recent studies have identified the Arctic summer sea ice and Indian summer monsoon (ISM) as pivotal tipping elements within the climate system. Tipping elements are critical components of the Earth's climate system that can undergo abrupt and irreversible changes once they cross a critical threshold. Such elements of the climate system significantly influence the biosphere and population. The decline of Arctic Sea ice since the beginning of satellite monitoring underlines the reality that the Arctic is highly vulnerable to global warming. The seasonal dynamics of Arctic Sea ice play a crucial role in regulating the global climate, and it substantially affects the local and regional climate. The sea level changes and increase in extreme weather events in the form of heat waves and floods over Europe are a few examples of the impact of Arctic Sea ice reduction. On the other hand, the ISM, which occurs annually from June to September, is characterized by variability in rainfall, often leading to floods and droughts that impact groundwater storage. These hydrological extremes including floods and droughts, referred as an events having a relatively lower probability of occurrence, significantly impact socioeconomic activities and ecosystems across the World. Any changes in the ISM characteristic features would significantly affect the freshwater availability and the livelihoods of the population. Various ocean-atmospheric processes, including the El Niño-Southern Oscillation, Indian Ocean Dipole, and Eurasian snow cover, are considered to contribute to the ISM rainfall variability through the process known as teleconnections. In the past years, only a few studies acknowledged the existence of teleconnections between the ISM and Arctic Sea ice. Climate model studies predicted that the frequency of extreme weather events associated with the Indian monsoon may increase due to global warming, which would affect the Arctic Sea ice. Therefore, the current study seeks to investigate the existence of a teleconnection between the Spring Arctic Sea ice variability and the subsequent ISM during June-September.

Past studies have indicated that the decline of Arctic Sea ice began during the late 1970s, with a marked reduction occurring after 2000. Similarly, the time series of interannual variability of the ISM illustrates an increase in drought years after mid-1990s. This study is designed into parts focusing on the periods before and after 2000. The first part of the study examines fifty years of data from 1951-2000, where study investigates the period during which there was no sudden decrease in Arctic Sea ice or monsoon. The variability of sea ice concentration and atmospheric circulation changes over the Arctic region during spring (March-May) and the interannual variability of the ISM rainfall during (June-September) over the Indian monsoon region is analyzed. To establish a clear understanding of the teleconnection between Arctic Sea ice and the ISM, various methodologies including anomaly computations, the student-t test, standardization, and time series analysis, are carried out in this study. Observational, satellite and reanalysis datasets from multiple sources are analyzed. The atmospheric parameters are from the monthly National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis dataset, sea ice and sea

surface temperature data from the Hadley Centre Sea Ice and Sea Surface Temperature data set, and the daily gridded precipitation dataset (0.25 x 0.25°) from the India Meteorological Department over the period of 1901-2023.

A close examination of the interannual variability of the ISM rainfall during 1951-2000 shows seven strong monsoon years and eight weak monsoon years. Composite analysis of flood and drought years, together with the analysis of various datasets during 1951-2000 illustrates that in addition to the North Atlantic Sea surface temperature and circulation changes, the Eastern Arctic Sea ice variability during spring significantly influences the onset and progress of the ISM. A comprehensive analysis of datasets spanning fifty years from 1951-2000, focusing on the Spring (March-May) Arctic Sea ice, Atlantic atmospheric circulation changes, and the interannual variability of the ISM rainfall (June-September) were carried out. The findings indicate that, together with the North Atlantic Sea surface temperature and atmospheric circulation, Eastern Arctic Sea ice variability during spring plays a crucial role in influencing the onset, progress, and hydrological cycle of the ISM. This evidence highlights a significant teleconnection between the Spring Arctic Sea-Ice and the ISM. Incorporation of climate model simulations and further analysis with satellite, reanalysis, observational datasets, are expected to enhance the understanding of the physical processes involved in this relationship.

Keywords: *Arctic sea ice, Indian summer monsoon, groundwater, sea surface temperature, teleconnection*

LAND USE CHANGES AND THEIR IMPACT ON GROUNDWATER SUSTAINABILITY IN NARKHED-PANDHURNA, CRITICAL ZONE OBSERVATORY, CENTRAL INDIA

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Groundwater is a vital resource for agriculture, horticulture and domestic use in arid and semi-arid regions, where there is limited surface water availability. The Narkhed-Pandhurna Critical zone observatory of CSIR-NEERI is located in agriculture intensive watershed of Central India. The region is heavily dependent on groundwater for agro-horticulture practices, predominantly orange orchards and other crops. However, over extraction of groundwater has resulted groundwater stage development of 100.16%. The changes in land use pattern, increasing population, and shift in agricultural practices significantly influences the hydrologic cycle, as these factors impact groundwater recharge as well as groundwater extraction. Substantial decline in groundwater has been observed in the watershed due to expansion of agriculture, especially the change of horticulture areas to agriculture land, forest degradation and minimal changes in built-up areas. The present study attempts to investigate the impact of change in land use patten on groundwater availability. The groundwater monitoring data and satellite imagery were analysed to understand both spatial as well as temporal variations in land use change and groundwater levels. The supervised classification using Landsat-8 data were used to analyse the changes in land use/cover (LULC) for the years 2005, 2010, 2015, 2020 and 2024. The land-use have been classified into five distinct class agriculture, horticulture (orange orchids), forest, barren land and built-up areas. The groundwater level data were collected from monitoring wells and hand pumps throughout the study area during the pre- and post-monsoon seasons. Groundwater data were correlated with land use patterns to understand the how shifts in land use especially changes horticulture, agriculture, forest and barren land, influenced groundwater levels. The investigation develops a hydrological framework to further comprehend groundwater replenishment trends, particularly in relation to agriculture practices and land cover. The analysis of land use data indicates significant changes including a shift from horticulture (orange orchids) to agriculture land. Loss of forest cover has also been observed while the built-up areas remained largely unchanged. This alteration from orange orchards, that require less water, to agricultural crops that require frequent irrigation, particularly during the dry season, is leading to increased groundwater extraction. Forest degradation has contributed to issue of decline in groundwater levels, as forests and vegetation play crucial role in groundwater recharge via natural infiltration. The coupled effect of loss of vegetation and forests leads to reduction in groundwater recharge during the monsoon periods.

The analysis reveals that the during pre-monsoon season, the area experiences significant decline in groundwater levels, while groundwater levels during the post monsoon season are observed to improve due to precipitation. However, the area has not exhibited recovery rates comparable to the pre monsoon depletion rates. This indicates that monsoon recharge is insufficient to compensate the high groundwater consumption driven by agriculture demands. Both horticulture and agriculture seem to be the primary contributors to this depletion. as

irrigation requirements exceed the natural recharge ability. The study highlights the impact of land use changes on groundwater in the Narkhed-Pandhurna critical zone observatory region particularly the conversion of horticulture land to agriculture land, degradation of forests and elevated groundwater demand due to irrigation. A substantial reduction in the Groundwater levels have been observed during the pre-monsoon season, which is vital for irrigation. The forest degradation has further contributed to reduction in groundwater by impacting the natural processes for groundwater recharge. The declining groundwater levels indicate an imminent threat to the region's agro-horticultural productivity and water security. In order to restore the balance between the groundwater resources and land use, it is critical to implement effective irrigation systems, adopt rainwater harvesting methods, rejuvenate degraded lands, and, restore and conserve forests. These steps would contribute to restore the natural processes that support groundwater recharge and sustainability. Policymakers ought to prioritize combining land use management and water conservation techniques to make certain that future land use changes do not worsen the existing water crisis. This study provides insight into the air-plant-soil and water continuum in the context of land use changes, groundwater dynamics and ecosystem health. The findings highlight the urgent need for sustainable water management and conservation strategies to mitigate land degradation, protect ecosystems and ensure long term resilience of agricultural productivity, ecological systems and the water resource security in the region.

Keywords: *LULC, groundwater recharge, orange orchards, water conservation, central India*

HIGH-RESOLUTION CLIMATE PROJECTIONS FOR GROUNDWATER SUSTAINABILITY IN THE HIMALAYAS USING WRF-BASED DYNAMICAL DOWNSCALING

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The Himalayas and their surrounding regions are ecologically sensitive and climatically significant areas, often referred to as the "Third Pole" due to their crucial role in sustaining the global hydrological cycle. They serve as a vital water source for billions of people, supporting agriculture, drinking water supplies, and energy production across Asia. However, these regions are highly vulnerable to the impacts of climate change, evident in the increasing frequency and intensity of extreme weather events such as heavy precipitation, flash floods, and glacial retreat. These climatic changes directly affect the groundwater systems, which are intricately linked to precipitation and surface hydrology, posing challenges to water resource management and security. Accurately assessing the impacts of future climate change on groundwater recharge and availability in the Himalayas is critical for developing sustainable management strategies. Yet, the complexity of the region's topography and climatic variability presents significant challenges. Global Climate Models (GCMs), including those used in the Coupled Model Inter-comparison Project Phase 6 (CMIP6), are valuable for studying large-scale climate processes. However, their coarse spatial resolution on the order of hundreds of kilometers limits their capacity to capture localized climatic phenomena such as orographic precipitation, glacial melt, and localized storm systems, which are pivotal to groundwater dynamics in mountainous regions. This limitation introduces uncertainties in regional and local climate projections, rendering them less effective for guiding groundwater management strategies.

Dynamical downscaling, a technique that enhances the spatial resolution of climate projections, provides a robust solution to address these challenges. By employing high-resolution regional climate models (RCMs) such as the Weather Research and Forecasting (WRF) model, it becomes possible to bridge the gap between global climate outputs and the need for detailed regional insights. The WRF model is particularly well-suited for this purpose due to its flexibility, detailed physical parameterizations, and proven ability to simulate complex climatic processes over mountainous terrain. Numerous studies have demonstrated its effectiveness in improving the representation of regional climate variability and extremes, especially in regions like the Himalayas, where topography plays a dominant role. In this study, the WRF model is used to dynamically downscale CMIP6 climate projections over the Himalayas and surrounding regions. The focus is to produce high-resolution climate datasets capable of informing groundwater studies. By resolving topographically driven processes and localized climatic phenomena, this approach offers a more accurate representation of factors affecting groundwater recharge, such as seasonal precipitation patterns, temperature extremes, and glacial melt contributions. Historical climate data, including observations and reanalysis datasets, are used to validate the WRF model’s performance, ensuring reliability in its projections.

The results demonstrate the significant advantages of high-resolution downscaling in capturing localized precipitation and temperature patterns. For instance, the WRF model effectively resolves orographic precipitation processes, showing improvements over raw CMIP6 outputs in simulating monsoonal variability and extreme weather events. These improvements are critical for understanding changes in precipitation intensity, duration, and distribution, which directly influence groundwater recharge rates. The model also enhances the representation of temperature extremes, which are pivotal for understanding the dynamics of snowmelt and glacial retreat, key contributors to downstream aquifer recharge. The downscaled climate projections reveal significant shifts in precipitation seasonality and intensity under future scenarios. These changes have profound implications for groundwater systems. An increase in heavy precipitation events may lead to enhanced surface runoff, reducing infiltration and recharge potential in some areas. Conversely, warming-induced glacial melt may temporarily boost groundwater recharge in downstream regions, though this benefit is likely to diminish as glaciers retreat further. Such findings underscore the need for adaptive strategies that account for spatial and temporal variability in recharge processes, particularly in areas reliant on seasonal snowmelt and glacial contributions. Integrating these high-resolution climate projections with groundwater models provides valuable insights into the potential impacts of climate change on aquifer dynamics. Initial analyses suggest a decline in recharge rates in the western Himalayas, driven by reduced winter precipitation and increased evaporation due to rising temperatures. Meanwhile, the eastern Himalayas exhibit more complex patterns, influenced by intensified monsoonal activity and changes in land use. These spatial variations highlight the importance of localized studies to inform region-specific groundwater management strategies.

The importance of high-resolution climate projections for groundwater studies cannot be overstated. They provide critical insights into recharge dynamics by resolving fine-scale climatic processes that are essential for accurate hydrological modeling. This is particularly relevant in the Himalayas, where groundwater resources are vital for sustaining agricultural productivity and meeting the water demands of rapidly growing populations. Moreover, such projections enable more precise risk assessments for groundwater security, helping to identify areas vulnerable to depletion or contamination due to climate extremes. By informing the design of adaptive management strategies, including managed aquifer recharge and drought mitigation plans, high-resolution projections contribute significantly to regional water security. This study highlights the transformative potential of WRF-based dynamical downscaling in addressing the limitations of coarse resolution GCM outputs for groundwater applications. By capturing the intricate interplay of topography, precipitation, and temperature in the Himalayas, the approach provides a robust foundation for understanding the impacts of climate change on groundwater systems. Future efforts will aim to incorporate socio-economic factors, land-use changes, and policy scenarios into the modeling framework to develop a comprehensive understanding of groundwater sustainability in the context of coupled human-natural systems. Additionally, extending this methodology to other mountainous regions worldwide could significantly enhance global efforts to address water resource challenges under a changing climate.

Keywords: *WRF model, dynamical downscaling, CMIP6, groundwater recharge, climate change, high resolution projections*

CLIMATE CHANGE IMPACT ASSESSMENT ON GROUNDWATER RECHARGE IN NARSINGHPUR DISTRICT OF MADHYA PRADESH, INDIA

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Climate change, which has now become a reality, is one of the biggest challenges facing the world today and almost all sectors are ought to be impacted. Water is one of the key sectors that is likely to be impacted through which other water dependent sectors like forest, health, urban, and agriculture sectors may also be impacted. Groundwater is one of the major sources of freshwater particularly in major parts of India and largely caters to both domestic and irrigation demands in a big way. Climate change impacts on the groundwater system could affect the freshwater supplies leading to sustainability issues. Climate change can affect the groundwater recharge and storage due to changes in soil infiltration, deep percolation and higher evaporative demand owing to rising temperatures. The future changes in the groundwater storage could affect the base-flow contribution to streamflow and may also alter the groundwater availability for irrigation and domestic use. The impacts of the climate change on the groundwater recharge are generally based on hydrologic modelling studies. The groundwater models are calibrated and validated using the observed climate and groundwater datasets and thereafter driven using the General Circulation Models (GCMs) based climate data for multiple future climate scenarios. GIS-based Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (WetSpass) model has been used with ArcGIS to estimate the groundwater recharge using future climate datasets at 0.25°x0.25° resolution from 13 GCMs under two future climate scenarios viz., SSP245 and SSP585. The model uses both physical and hydro-meteorological inputs including soil texture, digital elevation model (DEM), land use/cover, temperature, precipitation, potential evapotranspiration, and groundwater depth. WetSpass was initially setup, calibrated and validated using IMD gridded precipitation at 0.25°x0.25° resolution and IMD gridded temperature at 1.0°x1.0° resolution. The frequency of very hot days (MaxT > 40°C), hot days (MaxT > 35°C), very hot nights (MinT > 25°C) and tropical nights (MinT > 20°C) are all projected to increase substantially in future whereas the number of cold nights (MinT < 10°C) is projected to decrease significantly. This clearly indicates a warming in the study area in future as a direct consequence of climate change. The average annual rainfall is projected to increase considerably during all future time periods under SSP245 and SSP585 future climate scenarios. Higher groundwater recharge is projected in future in the Narsinghpur district as evaluated using WetSpass model mainly due to the increase in rainfall. The higher groundwater recharge may result in higher groundwater levels in future assuming that there may not be significant increase in the groundwater draft in future. Also, the groundwater recharge is projected to be marginally higher under SSP245 scenario as compared to SSP585 scenario.

Keywords: *Climate change, groundwater, groundwater recharge, modelling*

HYDROLOGICAL ANALYSIS OF SURFACE RUNOFF ESTIMATION IN BALLIA DISTRICT FOR SUSTAINABLE WATER RESOURCE MANAGEMENT

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Accurate estimation of surface runoff is a crucial component of hydrological studies and is essential for the sustainable management of water resources, flood mitigation, and groundwater recharge. Surface runoff is a key process that directly influences various hydrological events, including flood risks, water availability, and the overall water cycle. Among the numerous methods available for estimating surface runoff, the Soil Conservation Service Curve Number (SCS-CN) method, developed by the United States Department of Agriculture (USDA), has gained significant prominence due to its simplicity, adaptability, and reliability. This method is highly valued for its ability to integrate key factors such as land use, soil type, and antecedent moisture conditions (AMC) in estimating runoff, making it suitable for a wide range of environmental conditions and land-use scenarios.

This study applies the SCS-CN method to estimate surface runoff in Ballia District, located in the northeastern region of Uttar Pradesh, India. The district is characterized by diverse land-use patterns and heterogeneous soil types, offering an ideal setting for testing the applicability of the SCS-CN method in a complex environment. A detailed land-use and land-cover (LULC) analysis of the district was performed using high-resolution Landsat-8 satellite imagery from the year 2020. The LULC classification revealed that agricultural land is the dominant land-use type, occupying approximately 71% of the total area of the district. Built-up areas, including urbanized regions and infrastructure, account for around 16% of the total area. Other land-cover types, such as water bodies, barren land, scrublands, and vegetated areas, were also identified and played an important role in runoff estimation.

To estimate surface runoff, the study incorporated a five-day antecedent rainfall dataset to determine the antecedent moisture condition (AMC) for each land-use category. AMC is a critical factor in adjusting the curve numbers (CNs) assigned to different land-use types. Higher soil moisture conditions generally increase runoff potential, and this dynamic relationship was considered while assigning CN values to various land-use classes based on their respective Hydrologic Soil Group (HSG) classifications and AMC levels. The integration of these factors allowed for a comprehensive runoff estimation for Ballia District using daily rainfall data collected over a ten-year period (2001–2010). The analysis of rainfall patterns demonstrated significant temporal variability in runoff volumes, with the highest runoff occurring during the monsoon months, particularly from June to September.

The results of the runoff analysis revealed clear seasonal fluctuations, with the highest runoff occurring in July, when a total runoff volume of 358 million cubic meters (MCM) was recorded. This was followed by a decrease in runoff volume in August (233 MCM) and September (66 MCM), with seasonal variation aligning with the region’s monsoon rainfall patterns. The total annual average rainfall in Ballia District was approximately 1207 millimeters, of which around 20% (approximately 238 mm) contributed to surface runoff.

The remaining rainfall either infiltrated the soil or was lost through evapotranspiration, underscoring the critical role of vegetation and soil properties in regulating runoff and maintaining water retention within the landscape.

The study highlighted that agricultural land, predominantly composed of soils classified in Hydrologic Soil Groups C and D, contributed significantly to surface runoff due to its relatively low infiltration capacity. This effect was particularly pronounced during the monsoon season when intense rainfall events lead to substantial runoff. In contrast, built-up areas, characterized by impervious surfaces such as roads and buildings, contributed even more to surface runoff as these surfaces completely eliminate infiltration and increase the volume of surface flow. On the other hand, vegetated areas and water bodies were identified as natural buffers that promote infiltration and reduce runoff, demonstrating the positive impact of these land covers on groundwater recharge and water retention.

The findings of this study underscore the importance of managing land use and land-cover types to mitigate runoff and improve water retention. Sustainable land-use practices, such as implementing soil conservation measures, increasing vegetative cover, and incorporating rainwater harvesting systems, can significantly reduce surface runoff and enhance groundwater recharge. By managing the spatial distribution of land-use categories, it is possible to balance runoff generation and water retention, promoting both agricultural productivity and water resource sustainability. These findings also highlight the necessity of integrated water management strategies that consider both surface and subsurface water resources to ensure long-term water security.

This research demonstrates the applicability and effectiveness of the SCS-CN method in estimating surface runoff in Ballia District and provides valuable insights into the interplay between land use, soil characteristics, and hydrological processes. The study emphasizes the need for sustainable land-use planning, hydrological management, and water conservation strategies to mitigate runoff, reduce flood risks, and enhance groundwater recharge. The findings further suggest that integrating scientific analysis with practical interventions can lead to more effective solutions for addressing the challenges posed by water management, particularly in regions facing challenges related to water availability, climate variability, and changing land-use patterns. By incorporating both scientific methodologies and actionable water management strategies, the study proposes an integrated approach to address the ongoing challenges of water resource management, agricultural planning, and groundwater sustainability, especially in the context of rapidly changing climatic and land-use conditions.

This study not only demonstrates the robustness and adaptability of the SCS-CN method for surface runoff estimation in a complex region like Ballia District but also provides actionable insights for the sustainable management of water resources. The integration of remote sensing data, GIS-based land-use analysis, and the SCS-CN method offers a powerful framework for understanding runoff dynamics and informs the development of long-term strategies for sustainable land and water management in regions facing similar challenges.

Keywords: *Surface Runoff, SCS-CN, LULC, hydrologic soil groups, remote sensing*

CLIMATIC IMPACTS ON GROUNDWATER RECHARGE ESTIMATES FOR INDIAN GANGA BASIN (IGB)

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Groundwater (GW) recharge is the main forcing for aquifer-scale groundwater flows. It is a challenging task to quantify the spatial and temporal variability of GW recharge. It is an important component of aquifer water balance and extremely sensitive to climatic and anthropogenic stressors like groundwater extractions. Sustainable take of groundwater depends largely on the amount of water annually replenished through recharge. As the world's largest consumer of groundwater for irrigation, India is highly vulnerable to climate change impacts, making it crucial for water managers to understand groundwater recharge patterns. Despite the groundwater contributing to India's GDP, the estimations of recharge rates remain constrained, owing to the intricate nature of recharge mechanisms and the feasibility of practical measurement techniques. Traditional means of estimating groundwater recharge rely on the use of chemical tracers, isotropic analysis, and lysimeters all of which are limited by spatial and temporal resolutions. Several studies have also examined groundwater recharge variability by using a combination of GW level fluctuations, satellite-derived data, data-driven and physics-based numerical models.

Realistic representation of groundwater dynamics in Land Surface Models (LSMs) have received significant attention by the research community. LSMs are known to enhance our understanding of how climate impacts surface variables, by integrating sophisticated model physics of water, carbon and energy cycles. Many studies conducted over the Indian Ganga Basin (IGB) region, showed a consistent decrease in groundwater storage, driven largely by anthropogenic influences such as intensified agricultural activity. Existing studies over IGB have quantified GW recharge using empirical water balance, isotope analysis, in-situ water level, satellite data and hydrological models. However, there is a dearth of studies using LSMs that considered land-atmospheric interactions for the recharge estimation.

Every LSM differ in the representation of mass (water), energy, momentum and CO^2 exchange. The present study presents preliminary results of GW recharge estimates using the Noah-MP (Multi Parameterization) LSM that was developed based on the Noah land surface model. The latest Noah-MP model has options to choose the desired physical process (parameterization) for 10 modules (runoff, leaf dynamics, stomatal resistance, radiation transfer, etc.,), making possible for 4608 different simulations using a single Noah-MP model. This study focuses on understanding how differences in Noah-MP model structure and parameterization affect the GW recharge simulation. The main research problems addressed are: 1). Does Noah-MP provide reasonable estimates of GW recharge over IGB? 2. What are the fundamental reasons for GW recharge estimates to differ when using various runoff schemes? 3. Do the amount, seasonality, trend and spatial pattern of recharge vary based on the choice of runoff scheme? In Noah-MP, spin-up was executed using the ERA-5

Land data to bring the system to dynamic equilibrium or a stable state before starting the actual simulations. After initialization, the Noah-MP LSM was run at a 30-minute time step, thereby updating all the surface variables every half hour and the outputs were saved only every 12 hours. The model generating two outputs a day of all the surface variable have been run for a period of 15 years from 2009 to 2023, to capture long-term variations in recharge.

The LSM-derived recharge estimates were validated by comparing them with the recharge estimated using in-situ GW-level data from CGWB. The CGWB in-situ groundwater level data for the IGB has been filtered to retain only those wells with at least four consecutive observations, for validation purposes. The point GW recharge has been calculated by the difference in water level fluctuations assuming constant specific yield. The resulting in-situ GW recharge data were fitted to different variogram models, with the spherical variogram model providing the best fit (highest R-squared value). Consequently, kriging with a spherical variogram model was used as the interpolation technique, creating spatially varying annual and seasonal recharge datasets for the IGB.

Preliminary results shall be presented for the simulated GW recharges obtained from the multi-model Noah-MP towards selecting the best parameterization schemes for the IGB region. Results reveal a good correlation of LSM-derived recharge during monsoons. As the LSM models do not have provisions to include anthropogenic activities, the non-monsoonal abstractions were not reflected in the modelled recharge. The Noah-MP recharge estimates were found to effectively capture the spatial patterns observed in in-situ recharge and precipitation datasets, thereby supporting their reliability. These spatio-temporally continuous recharge estimates can serve as valuable inputs for high-resolution groundwater models, facilitating the simulation of surface and groundwater interactions. These model estimates could help communities better understand and adapt to climate-induced shifts in groundwater availability, offering a proactive approach to water scarcity. Even though the sub-surface physics of the LSM is optimized for IGB, its future scope can be further improved by governing limitations like irrigation modules and static land cover data. The recharge due to the flooded irrigation in non-monsoon seasons cannot be modelled, due to the lack of an established crop map for the study region. And also, the extant LSMs does not precisely depict surface roughness, surface albedo and leaf area index as the change in land cover is not considered.

Keywords: *Land Surface Model (LSM), groundwater recharge, Indian Ganga basin (IGB), climatic variations, sustainable water management, groundwater depletion*

INFLUENCE OF CLIMATE CHANGE ON MILAM GLACIER DYNAMICS (GORI GANGA RIVER BASIN, CENTRAL HIMALAYA, INDIA)

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The Himalayas are among the most ecologically sensitive and fragile regions on Earth. This region is warming at a rate exceeding the global average, making climate change a significant threat to both the local environment and interconnected ecosystems. Growing concerns about global warming have sparked widespread scientific interest in the behaviour of glaciers. Numerous studies have confirmed that glacier melting has accelerated over the past three decades across many mountain ranges worldwide, including the Arctic and Antarctica, and is now occurring at an unprecedented rate. The rising global temperature is having devastating effects, including accelerated glacier retreat, glacial lake outburst floods (GLOFs), global mean sea-level rise, altered precipitation patterns, an increase in extreme disaster events, and shifts in biodiversity. Despite these alarming trends, a critical knowledge gap remains regarding how the Himalayan cryosphere system will respond to these environmental changes. Therefore, understanding the mechanisms and behaviour of the Himalayan cryosphere is essential for quantifying the influence of climate change and assessing future water availability.

The present study focuses on assessing the evident effects of climate change on the Milam Glacier, which originates from Trishul Peak (7,001 m a.s.l.) in the Gori Ganga River Basin, Uttarakhand (Pithoragarh district). The Milam Glacier catchment spans an area of 235.28 km², with a total glacierized area of 66.45 km². As the second-largest glacier in the Kumaon division of Uttarakhand, Milam Glacier is the principal glacier of the river basin, extending 16.55 km in length with an approximate area of 52.7 km², and ranging in elevation from 6,656 m to 3,603 m a.s.l. It is located between latitudes 30°36' to 30°28'N and longitudes 80°00' to 80°07'30"E. The glacier is oriented northwest to southeast and is fed by five major tributary glaciers: Surajkund Glacier (~5.4 km), Mangron Glacier (~6 km), Pachhmi Bamchhu Glacier (~7.7 km), Syakaram Glacier (~6.2 km), Billanlari Glacier (~5.3 km), and an unnamed glacier. The accumulation zone of Milam Glacier is well-developed with steep slopes, and numerous transverse and longitudinal crevasses are observed near the lower accumulation zone, equilibrium-line altitude (ELA), and the upper ablation zone. However, the ablation zone is relatively narrow compared to the accumulation region and is characterized by gentler slopes. The ablation zone is covered by near-continuous rock debris and contains numerous supraglacial lakes, most of which are temporary. The Gori Ganga River catchment falls within the temperate-humid zone of India and is primarily influenced by western disturbances during winter (November to April) and the Indian Summer Monsoon during summer (June to September).

To analyse the impact of climate change on Milam Glacier dynamics and understand glacier-climate interactions, this study adopts a coupled approach that integrates in-situ/ground-based observations with space-based monitoring. The study estimated the retreat rate of Milam Glacier from 1968 to 2024 and examines the effects of climate change, particularly the formation of supraglacial lakes. Snout recession patterns were mapped using Landsat and Sentinel series satellite images supplemented by ground control points (GCPs) established during the ablation seasons of 2022–23 and 2023–24 hydrological years. The analysis revealed that between 1968 and 2024, the snout area decreased by 0.0194 km², with an average recession rate of 28.30 m per year. Additionally, the total glacier area declined by approximately 1.0 km² during this period. Furthermore, this study explores the dynamics of supraglacial lakes on the glacier surface. These lakes were mapped using the Normalized Difference Water Index (NDWI) applied to Landsat imagery for 2001 and LISS-4 imagery for 2017, 2023, and 2024. The lakes mapped in 2024 were further validated through a ground survey. The study identified a significant increase in the number of supraglacial lakes, rising from 28 in 2001 to 52 in 2017, 58 in 2023, and 72 in 2024. However, the total lake area varied over these years. In 2001, the total lake area was 0.79 km², which decreased to 0.028 km² in 2017, then increased to 0.034 km² in 2023, before slightly declining to 0.029 km² in 2024. The relatively larger lake area observed in 2001 may be attributed to the 30 m spatial resolution of Landsat imagery. The increase in the number and area of supraglacial lakes from 2017 to 2023 suggests intensified glacier melting in the ablation zone, while the slight decrease in total lake area in 2024 may be due to the fragmentation of larger lakes. Field investigations confirmed that many large lakes had disappeared and drained out by the end of the ablation season of 2023-24 hydrological year. These findings indicate a trend toward the formation of larger supraglacial lakes, which, in turn, accelerate glacier melting in the ablation zone.

The observed snout recession and supraglacial lake formation correlate with historic temperature and precipitation trends, derived from CORDEX and GLDAS datasets, respectively. Statistical analysis reveals that between 1968 and 2024, the average valley temperature increased from 5.69 °C to 7.63 °C, while annual precipitation rose by approximately 302 mm. Furthermore, an analysis of historical records suggests that between 1849 and 2017, the snout of Milam Glacier retreated by 2.90 km, with an average recession rate of 17.24 m per year. A comparison of these historical observations with present data indicates an accelerated glacier mass loss due to warmer climatic conditions, leading to an increase in supraglacial lake formation.

The findings of this study suggest that these contrasting meteorological changes have collectively influenced the dynamics of Milam Glacier and the formation of supraglacial lakes, highlighting the significant impact of climate change. This study is crucial for forecasting changes in the Himalayan ecosystem and assessing the cascading effects of cryosphere mass retreat on mountain ecosystem services and future water availability. Additionally, it helps bridge the knowledge gap in understanding contrasting climate forcings and their impact on high-altitude Himalayan watersheds. The study also provides insights into monsoonal and non-monsoonal climatic influences at a regional scale under changing climate conditions.

Keywords: *Himalayan glaciers, climate change, snout recession, supraglacial lakes, mountain meteorology*

INSIGHTS INTO THE AUGUST 2023 PUNJAB FLOODS: HYDROLOGICAL AND OPERATIONAL PERSPECTIVES

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Extreme precipitation events are intensifying globally due to climate change, often leading to unprecedented flood risks and challenges in water resource management. In August 2023, Punjab, India, experienced catastrophic flooding, impacting 11,927 villages and resulting in 65 reported fatalities. It highlighted the need to better understand the multifaceted drivers of such extreme events, especially in regions dependent on major dams. Public concerns emerged over the potential role of the Pong Dam, managed by the Bhakra Beas Management Board (BBMB), in exacerbating flood conditions downstream in Punjab. This study investigates the hydrological and operational factors contributing to the August 2023 flood events, with a focus on both meteorological conditions and operational dynamics of Pong Dam. The study area encompasses the Beas River basin and the state of Punjab, which was segmented into three zones for analysis: Beas River basin within Himachal Pradesh, Beas River basin within Punjab, and the remaining areas of Punjab. This segmentation enabled a focused analysis of rainfall patterns, soil moisture conditions, and their variations across different geographic contexts. In this study, precipitation and soil moisture data were analysed for each region to understand the hydrological setting leading up to the flood events. Additionally, hydrological simulations were conducted using the HEC-RAS model to assess flood scenarios under hypothetical "no-dam" conditions, providing insights into potential impacts without regulated outflows from Pong Dam. A detailed analysis of inflow and outflow dynamics at Pong Dam was carried out to assess how authorities managed the intense inflows during the peak periods of July and August 2023, as well as to evaluate the potential impact of these releases on downstream flooding.

Our analysis revealed that the baseline for the August floods was set by the intense rainfall experienced upstream of Pong Dam in July 2023. Specifically, the state of Himachal Pradesh experienced an intense period of precipitation between July 8th and July 12th. During these five days, the region recorded an extraordinary 224.1 mm of rainfall, a volume substantially surpassing the typical 42.2 mm expected for this period. This represents an anomaly of 431% above the average rainfall. The excessive precipitation during this time notably elevated soil moisture levels and contributed to increased inflows into Pong Dam, thereby creating critical preconditions that amplified flood risks. The SMAP soil moisture analysis indicated elevated moisture levels both at the surface (0-5 cm) and in the root zone (0-100 cm) across the study area. In August, the pattern of intense rainfall events continued, resulting in substantial and sustained inflows into Pong Dam over consecutive days. On August 13th and 14th, strong negative vertical wind velocities were recorded in upper Beas River Basin, with values of -1.6 Pa/sec and -1.92 Pa/sec, respectively. These negative velocities indicate significant upward wind movement, signaling the formation of strong upwelling zones. This atmospheric condition likely contributed to intense convective activity, further enhancing the heavy rainfall events over the region. Soil moisture values in the root zone over the Beas

Basin in Himachal Pradesh peaked on August 14th and 23rd, reaching 0.39 and 0.40 m^3/m^3, respectively, which aligned closely with the heavy rainfall recorded on those dates. Similar trends were observed in surface soil moisture levels. These conditions led to substantial inflows into Pong Dam, with the inflow reaching 4,058 m^3/s on August 13th, escalating to 5,907 m^3/s on August 14th, and peaking at an exceptional 12,469 m^3/s on August 15th. This surge in inflow raised the reservoir's water level to 426.54 m, approaching the maximum permissible level of 433.12 m. In response to these critical hydrological conditions, BBMB authorities maintained a controlled and phased water release strategy while balancing the dam's capacity and minimizing the downstream flood risks. The HEC-RAS analysis was conducted on the downstream sections of Pong Dam, which were divided into four key areas to capture a detailed picture of potential flood impacts. Flood conditions were specifically simulated starting from August 15, a peak period for inflows, and the observed scenarios were compared with a hypothetical "no-dam" condition. Results demonstrated that, without Pong Dam's regulation of the heavy inflows, the downstream regions would have faced a major disaster, with significantly increased flood extent, depth, and velocity. The controlled release strategy implemented by dam authorities effectively mitigated these risks, reducing the potential severity of flooding and underscoring the critical role of dam management in safeguarding downstream areas. The analysis revealed that the controlled release strategy not only mitigated the intensity of the flooding but also delayed the onset of flooding conditions, providing critical time for downstream communities and authorities to respond. This comparative approach highlights the importance of controlled inflow management in protecting vulnerable regions from extreme flood impacts.

Sentinel satellite imagery provided additional insights, illustrating extensive inundation following the August flood events. The imagery captured the expanded floodplain along the Beas River, demonstrating the widespread reach of floodwaters into previously unaffected areas. The combination of soil saturation from July rains, intense rainfall in August, and strategic dam management highlights the interplay between natural and operational factors that shaped the flood outcomes. This study emphasizes the critical role of Pong Dam operations in managing flood risks, particularly in the context of extreme precipitation events. By analysing both the hydrological setting and operational responses, this research offers a detailed understanding of how pre-existing conditions, such as elevated soil moisture, and active dam management contribute to flood severity. The insights gained from this analysis are essential for refining flood management strategies in Punjab and similar regions facing the dual challenges of intense rainfall and reliance on dam infrastructure.

***Keywords**: Punjab floods, flood modelling, dam operation, hydrological modelling, Beas basin*

Theme 2
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ENVIRONMENTAL FLOW AND REJUVENATION OF RIVER GANGA

REJUVENATING KALI RIVER IN UTTAR PRADESH – A CASE STUDY OF RIVER FLOWS ENHANCEMENT THROUGH AGRICULTURE WATER MANAGEMENT

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The known large river systems gain might and prominence through the contributions of numerous smaller tributaries, streams, rivulets, and healthy aquifer systems. These freshwater systems, not only support the flows in the large rivers but also build and strengthen the very character of such large rivers. They support them in extending various services to nature and the people. Various biotic and abiotic components are dependent upon the healthy state of these freshwater systems. Kali River, one such tributary of the mighty River Ganga originates in Muzaffarnagar (Uttar Pradesh) and joins the Ganga River in Kannauj district of Uttar Pradesh. During 420 plus km of the river course, the Kali faces several issues like – pollution from urban and industrial hubs, catchment fragmentation, over-abstraction of both surface and groundwater coupled with low water use efficiencies in agriculture, which uses almost 80% of freshwater, making the flows leaner with degraded water quality. Despite this, the Kali River with a catchment area of 9400 km^2, is one of the critical tributaries of the Ganga River. The restoration of freshwater flows in a river can be achieved through diverse strategies. Whilst, one of the most talked about approaches is releases from dams and barrages; however, other crucial approaches, such as optimized agricultural water management, can significantly reduce water usage (canal and groundwater withdrawals). In irrigation canal systems, the available and saved water through demand and supply side management in canal command areas can be routed through the passage from the tail-ends of the canals to the nearby rivulets and drains or ponds, thereby enhancing flows. This approach offers dual benefits: rejuvenated ponds enhance year-round water security for riparian community and flows released into river systems improves hydrological health of rivers.

A 3-year journey of Kali River flows enhancement which commenced in 2020, was implemented through multi-stakeholder-led collective actions by 40,000 farmers of command area farmers through their respective Water Users Associations (WUA), Uttar Pradesh Irrigation & Water Resources Department, the Kasganj District Administration and World-Wide Fund for Nature India. A three-pronged approach was adopted to demonstrate the hydrological gains in Kali River: (a) Demand-side interventions – reducing irrigation water application thereby improving the water use efficiencies. In this regard, various package of practices pertaining to agriculture water management was promoted, demonstrated and implemented across the crops of wheat and maize in the command area. This included line sowing, application of bio-fertilizers, bio-pesticides and micronutrients; (b) Supply Side Interventions – rehabilitating the irrigation canal infrastructure and rejuvenating/creating the passage from the tail-end of the canals with the nearby drains/rivulets/ponds. This work included the rehabilitation of the entire canal system comprising of the installation of metal

gates at the heads of all 10 canals to ensure better water regulation across canals, installation/rehabilitation of outlet heads, rehabilitation/construction of gauges (pansaal) near head and tail of the canal, construction/rehabilitation of tail-fall and passage to connect the canal tail end to nearby river/rivulet bank; (c) Institutional strengthening – awareness, mobilization, and capacity strengthening of existing WUAs in the command area. This work included in-room training on guidelines and provisions of prevailing legislations on Participatory Irrigation Management, exposure and knowledge-exchange activities across the areas of active WUAs in the state and the country.

As part of this initiative (till June 2024), with the support of command area farmers, over 2 billion liters of saved and available water from the command areas of 10 irrigation canals (08 Minors and 02 Distributaries) of the Bachhmai Distributary Canal System (part of Farrukhabad Branch Canal of Lower Ganga Canal system) is released into Kali River. This not only led to enhancing Kali River flows but also improved its assimilative capacity. Besides the enhancement of flows in the Kali River, on the agriculture front, the reduction in the input cost has been observed. Now the farmer's reliance on chemical inputs in reducing, as there is gradual reduction in chemical inputs application as bio-fertilizers and bio-pesticides are being promoted and demonstrated, as part of Demand-Side Management activities. The farmers are also trained on the preparation of these bio-products. This aspect complements Government of India's initiative on National Mission on Natural Farming (2023-26), *Paramparagat Krishi Vikas Yojana* and other such programmes. The farmers have also observed agricultural productivity gains while implementing various measures under the Demand Side Management. Another dimension of this initiative is engagement with the District Ganga Committee (DGC) Kasganj, wherein the Kali River initiative is presented, discussed, deliberated, and guided by various members of the DGC. A joint team led by DGC members having representation from district authorities, Uttar Pradesh Pollution Control Board, Uttar Pradesh Irrigation & Water Resources Department, concerned Water Users Associations, and WWF India, conducted a field survey to verify the on-ground status. This joint team concluded the same, i.e. the health of Kali River from the perspective of assimilative capacity is improving.

The Kali River initiative, documented in this paper, has the potential to act as a roadmap for flows enhancement in those rivers, which traverse through agrarian landscapes characterized by irrigation canal systems and low water use efficiencies in agriculture. On these lines, through similar multi-stakeholder-led approaches, the work is underway with over 200,000 farmers spread across 800 villages in 7 districts of Uttar Pradesh and Madhya Pradesh. The objective herein is to benefit the health of 7 small or large rivers (Kali, Karula, Gaagan, Ramganga, Parbati, Noon, Sindh). Whilst, the farmer, is always referred as the biggest user of freshwater; however, the Kali case study exemplifies and demonstrates how the very same farmer can support river rejuvenation programmes and projects. The approach discussed in this paper has the potential of upscaling and mainstreaming across canal water management, leading to revival of local freshwater resources.

Keywords: *Flows enhancement, irrigation, canal system, agriculture, Environmental Flows, Ganga River, Kali River*

ASSESSMENT OF THE ECOSYSTEM SERVICES OF A SEMI-ARID REGION OF INDIA

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Ecosystems worldwide are facing increasing pressures from human-induced activities, including climate change, habitat fragmentation, and nutrient pollution. These challenges significantly impact ecosystem functions and the services they provide, such as water quality, climate regulation, and agricultural productivity. Ecosystem services are vital for human well-being and sustainable resource management, underscoring the need for comprehensive assessment tools to understand their dynamics and inform effective management strategies. Water-related services, including water yield, purification, flow regulation and climate control, are particularly crucial for understanding basin-level ecological health. This study examines the spatiotemporal variations of ecosystem services within the Ken Basin, a key tributary of the Yamuna River in India, over the period 1985–2009.

The study used various data sets to run the Soil and Water Assessment Tool (SWAT) model, which simulates hydrological and ecological processes in the Ken Basin. Climatic data, such as daily precipitation and temperature, were used. Observed discharge data from the Banda gauging station (1985–2009) were used for model calibration and validation. Geospatial data, including Digital Elevation Models (DEMs), soil data, and land-use data were also incorporated to simulate the hydrological processes within the basin. The basin was divided into four subbasins, which were further subdivided into 698 Hydrological Response Units (HRUs). The model was calibrated for the period 1985-1995, resulting in a coefficient of determination (R^2) of 0.91 and a Nash-Sutcliffe Efficiency (NSE) of 0.88. Validation for the period 1996–2009 resulted in R^2 and NSE values of 0.84 and 0.83, respectively, indicating the model's dependability. After the SWAT model simulations were completed, the data were utilized to assess four key ecosystem services: water yield, purification, flow management, and climate control. These results were subsequently included into the Total Ecosystem Services (TES) index, which combines the performance of all four ecosystem services into a single statistic. The entropy weight method was used to determine the relative value of each service, with weights assigned based on its variability and significance. The entropy weights assigned to each ecosystem services were 0.19 for water yield, 0.236 for total nitrogen, 0.173 for total phosphorus, 0.249 for flow management, and 0.149 for climate control.

The results of the analysis showed that the Total Ecosystem Services (TES) index remained relatively stable, ranging from 0.8 to 0.9 over the 24-year study period. Water yield and climate control services showed decreasing trends, indicating the difficulties in preserving water supply and mitigating climatic variations. These changes are related to variations in precipitation patterns, evapotranspiration rates, and soil water dynamics, all of which influence streamflow and water supply. In contrast, ecosystem services related to purification (total nitrogen and total phosphorus) and flow management showed increasing trends. The increase in purification services indicates rising nutrient loading in the basin's water systems, owing mostly to agricultural operations. The widespread use of nitrogen- and phosphorus-based fertilizers for agriculture has resulted in significant nutrient runoff into the river, especially during the monsoon season. Flow management services also increased, demonstrating the basin's ability to control water availability in response to changing climatic and anthropogenic stresses. However, increased nutrient loads caused by agricultural runoff put the basin's ability to sustain water quality at risk, emphasizing the significance of integrated water resource management measures. The study's findings emphasize the complex interaction of natural processes and human activities that affect ecosystem services. While water yield and climate control services are under significant pressure due to changing precipitation patterns and human activities, the increased nutrient and flow regulation services highlight the dynamic nature of ecosystem functions. These trends underscore the important need for sustainable land and water management strategies that prioritize the balance of ecosystem services, especially in the context of rising agricultural demands and climate variability. This study contributes to the broader understanding of ecosystem service dynamics in river basins and provides valuable insights for policymakers and resource managers. By integrating the SWAT model with entropy weight calculations, the study offers a robust framework for evaluating ecosystem services at the basin scale. The findings highlight the necessity of continuous monitoring and adaptive management in preserving ecosystem services and promoting sustainable development in the face of rising environmental and anthropogenic challenges.

The Ken Basin ecosystem services are changing significantly, with implications for water availability, quality, and management. The trends observed in this study highlight the importance of proactive strategies for addressing growing difficulties and ensuring the long-term viability of ecosystem services. Integrated approaches that integrate sustainable farming practices, efficient water resource management, and climate adaption strategies will be vital to the basin's ecological health and functionality. This study emphasizes the importance of ecosystem service assessments in guiding evidence-based decision-making and advancing the goals of sustainable development.

Keywords: *SWAT model, Total ecosystem services, Ken basin, entropy weight method, water yield, purification, flow management, climate control*

STREAM DYNAMICS ANALYSIS OF STRETCH OF GANGA RIVER USING GEO-SPATIAL TECHNIQUES

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The behavior of river systems is essential for comprehending the environmental processes that influence landscapes, eco-systems, and human communities. Rivers, such as the Ganga, are integral to the socio economic and cultural identity of the regions they flow through, particularly in India. This research aims at examining the stream dynamics of the Ganga River at Kanpur by utilizing Remote Sensing (RS) and Geographic Information System (GIS) methodologies. The main goal of this study is to evaluate changes in flow dynamics, meandering patterns, and the Entrenchment Ratio (ER) along the portion of the Ganga River that runs through Kanpur, covering the period from 1985 to 2021. The investigation uses satellite imagery and geo-spatial data to monitor the spatial and temporal changes in the morphology of the river and its ecological effects on the surrounding landscapes.

The area being studied encompasses a 39 km segment of the Ganga River, stretching from the Brahmavart Ghat (Latitude 26°36'49.62"N, and Longitude 80°16'28.83"E) to the Hanuman Temple at Dhori Ghat (Latitude 26°22'40.79"N, and Longitude 80°29'24.94"E), and is noted for its active river morphology and regional significance. The river flows in a north-to-south trajectory through varied landscapes that feature open fields, farmland and regions on the periphery of Kanpur city, Uttar Pradesh (India). The analysis period, which ranges from 1985 to 2021, reveals considerable changes in the path, width, and overall behavior of the river. Satellite data from 1985 to 2021 have been employed to digitize the full width of the bank, central flow lines, and Bankline of the Ganga River. These digitized features have then been compared across the years to identify changes in the flow dynamics of the river, meandering tendencies, and consequent changes in the ER. The analysis has been conducted at the interval of 3 km along the study stretch, providing a detailed view of how the course of the river has shifted over time.

The findings of the study indicate a marked shift in the flow of the river over the 36-year period. One of the most significant observations has been the continuous lateral movement of the river towards the left-hand side, particularly observed at a location approximately 13 km from the Brahmavart Ghat. At this location, the river has shifted by approximately 1.8 km from its original position in 1985. This movement has been especially prominent in open fields and agricultural land where the river has altered its course, potentially affecting both the local eco-system and human infrastructure. The research has observed also the widest point of the river as 4150 meters and the narrowest point as 190 meters. These differences in width reflect the ever-changing nature of the river, and point to the locations where bank erosion or sediment build-up could have influenced the path. The ER has reached a maximum of 98.31, indicating the river system that is highly entrenched. The Sinuosity Index, has peaked at 1.098, suggesting that the river displays a relatively low level of curvature despite showing notable meandering patterns.

The results of this study are a testament to the utility of Remote Sensing and GIS technologies in understanding the river dynamics. By using satellite imagery, the study was able to capture large-scale changes in the river’s morphology and track subtle variations that might otherwise go unnoticed. These findings are important for the management of the Ganga River, especially considering the increasing human settlement and agricultural activities along its banks. As the river continues to shift, the need for effective river management strategies becomes even more critical. The study emphasizes the importance of continuous monitoring and the integration of advanced RS and GIS technologies to track changes in river systems, predict future trends, and develop strategies for sustainable management.

The study also brings attention to the broader environmental and social implications of the river dynamics. The shifting course of the river can have significant consequences for local agriculture, water availability, and infrastructure. In particular, the areas of significant erosion or sediment deposition could face challenges related to flooding, loss of agricultural land, and displacement of communities. Furthermore, changes in the river's flow patterns could have ecological impacts, potentially altering habitats for aquatic species and affecting the overall health of the river eco-system. The study also points to the importance of taking proactive steps to mitigate the adverse effects of the river dynamics. As the Ganga River plays a vital role in the livelihood of millions of people, particularly in Uttar Pradesh, it is essential to implement measures that safeguard the river's integrity while minimizing human-induced impacts. These measures could include the construction of river training structures such as embankments and check dams as well as the implementation of policies that regulate land use along the riverbanks to reduce the risk of further erosion and encroachment.

In conclusion, this study demonstrates the effectiveness of using Remote Sensing and GIS technologies to assess the stream dynamics of the Ganga River at Kanpur. The analysis of flow dynamics, meandering and Entrenchment Ratio has provided valuable insights into the changing morphology of the river and the potential implications for local eco-systems and human activities. The findings underscore the importance of continuous monitoring and adaptive management strategies to ensure the long-term sustainability of this vital waterway. As such, the study calls for a concerted effort to mitigate the adverse impacts of the river dynamics and ascertain the sustainable use of the river resources for future generations. Given the rapid pace of environmental changes, this research also serves as a reminder of the necessity for interdisciplinary approaches that combine advanced technology with policy interventions to manage the river system effectively. The Ganga River with its immense cultural, ecological and economic significance requires careful and informed management to preserve its integrity for future generations.

Keywords: *Ganga, environment, entrenchment ratio, Brahmavart Ghat, remote sensing, morphology*

INTEGRATED ENVIRONMENTAL FLOW ASSESSMENT FOR THE SUBARNAREKHA RIVER: A HOLISTIC APPROACH TO SUSTAINABLE ECOSYSTEM MANAGEMENT

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The assessment of environmental flows (E-Flows) is crucial for the sustainable management of river ecosystems. Various methods have been developed to determine the E-Flows, ranging from hydrological records to sophisticated frameworks that incorporate ecological, hydraulic, and socio-economic considerations. This study focuses on the Subarnarekha River, an interstate river flowing through Jharkhand, Odisha, and West Bengal, with a particular emphasis on a holistic approach to E-Flow assessment that integrates hydrological, hydraulic, and habitat simulation methodologies.

The evolution of E-Flow assessment methodologies dates back to the 1940s, with initial efforts in the United States emphasizing minimum flow requirements. Over the time, methodologies have expanded, categorized into hydrological, hydraulic rating, habitat simulation, and holistic approaches. Hydrological methods rely on long-term streamflow data to estimate flow statistics, while hydraulic rating methods focus on the relationship between discharge and hydraulic parameters such as depth and velocity. Habitat simulation methods extend hydraulic approaches by linking physical conditions to habitat suitability for specific aquatic species. Holistic methods, developed in the 1990s, consider the entire aquatic ecosystem, incorporating diverse factors like hydrology, ecology, and socio-economic needs. Globally, over 240 methodologies have been identified for E-Flow assessment, demonstrating the complexity and adaptability of approaches to address site-specific challenges. Notably, the classifications by Tharme (2003) and others provide a structured framework for understanding these methodologies, emphasizing their applicability in different ecological and hydrological contexts. The present study employs a combination of hydrological, hydraulic, and habitat simulation methods for the Subarnarekha River. Long-term discharge data were analyzed using flow duration curves (FDC) and Indicators of Hydrologic Alteration (IHA). Hydraulic and habitat simulations were conducted using the HEC-RAS 1D model to establish depth-discharge relationships and evaluate flow requirements for maintaining suitable habitats for indicator fish species.

FDC analysis was used to assess hydrologic scenarios across different dependability years. For a 34-year period (1986–2019), the study identified critical flow thresholds such as Q90 and Q95, representing 90% and 95% probability of flow availability, respectively. These thresholds inform the baseline for maintaining ecological health. Additionally, the FDC provides insights into seasonal variations, particularly during lean months, highlighting intervals that influence riverine conditions and aquatic life. IHA analysis categorized flow conditions into five environmental flow components (EFCs): low flows, extreme low flows, high-flow pulses, small floods, and large floods. These EFCs highlight the ecological functions of various flow conditions, such as sustaining aquatic habitats, supporting biodiversity, and facilitating nutrient transport. By maintaining these flow components, the

study ensures the ecological integrity of the river system, emphasizing the interconnectedness of hydrological patterns and ecological processes. Hydrodynamic modeling using HEC-RAS provided insights into the flow-depth-velocity relationships at different river sections. Depth-discharge curves were developed to determine the flow requirements for maintaining specific water depths essential for the survival of the indicator species, *Bagarius bagarius* (Hamilton-Buchanan). This endangered fish species, known for inhabiting rocky pools and rapids, requires water depths of 0.25 to 1.5 meters and velocities ranging from 0.1 to 1.5 m/s. The study used HEC-RAS simulations to generate depth-discharge relationships for various locations along the river. Scenarios were modeled to maintain depths of 0.3m, 0.4m, and 0.5m during lean and monsoon seasons, ensuring ecological connectivity and suitable habitats for aquatic species. This approach highlights the critical role of hydrodynamic modeling in bridging data-driven assessments with ecological needs.

The results highlight the critical discharge values required to sustain ecosystem health at different river locations. For location 1 (13.66 km downstream), 2.15 cumec discharge is required for maintaining a depth of 0.4 m. Similarly, 0.77 cumec discharge is necessary for maintaining same depth at location 2 (16.30 km downstream). The recommended E-Flow regimes for the Subarnarekha River account for seasonal variations and habitat requirements, balancing ecological sustainability with water resource management. The analysis underscores the importance of adaptive flow regimes that cater to varying ecological and hydrological demands across different locations. This integrated approach to E-Flow assessment has significant implications for the sustainable management of the Subarnarekha River. By aligning hydrological, hydraulic, and ecological considerations, the study offers a comprehensive framework for decision-making. The inclusion of habitat suitability for indicator species ensures that the recommendations are grounded in ecological reality, addressing both biodiversity conservation and ecosystem functionality.

The E-Flow assessment in the Subarnarekha River underscores the significance of integrative methodologies combining hydrological, hydraulic, and ecological approaches. Employing hydrodynamic modelling tools like HEC-RAS and prioritizing indicator species ensures the development of scientifically robust flow recommendations. These findings support sustainable water resource management, aligning ecological conservation with socio-economic demands. Future research should integrate broader biodiversity assessments and stakeholder engagements to enhance the applicability of E-Flow frameworks. For holistic understanding of riverine ecosystems, the present methodology for E-Flow assessments in other river basins may be employed.

Keywords: *Environmental flow, indicators of hydrologic alteration, flow duration curves, HEC-RAS model, Subarnarekha River*

FOSTERING SOLUBILIZATION AND BIODEGRADATION OF OMPS USING THERMAL HYDROLYSIS PRETREATMENT

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Recently, sewage sludge (SS) has gained much attention as meritorious source rich in nutrients and trace elements, that can prove beneficial for soil repairment. Recovery, reuse and recycling of nutrients from SS along with synthesis of renewable energy source (biogas), at acceptable capital and operational costs has proved beneficial for ecosystem sustainability. Sewage sludge produced from wastewater treatment plants (WWTPs) is obligated to be disposed after proper treatment. However, its disposal has become as one of the critical issues associated with wastewater treatment plants. Our study emphasizes the effectiveness of thermal hydrolysis for sludge obtained from a sequencing batch reactor (SBR) system operating at a high solids retention time (SRT) of 40 days. Given the limited research on thermal hydrolysis of sludge regarding the fate of micropollutants and microbial diversity in digesters, this study aimed to evaluate the impact of thermal hydrolysis on: 1) sludge solubilization and methane production, 2) the removal of organic micropollutants, and 3) the microbial community structure within the digester. The thermal hydrolysis process (THP), an advanced steam explosion pretreatment, is primarily used to enhance sludge solubilization and boost methane production during downstream anaerobic digestion (AD). However, its effectiveness in treating high solids retention time (SRT) sludge, reducing emerging organic micropollutants, and its impact on the anaerobic microbial community remain uncertain. In this study, sludge from a sequencing batch reactor (SBR) operating at a 40-day SRT was subjected to THP at temperatures ranging from 120 to 180°C for 30 to 120 minutes. The effects of THP on organic solubilization, methane yield, organic micropollutant removal, and microbial community dynamics were investigated.

Dewatered sludge (20% TS) was collected from SBR-based STP at IIT Roorkee and was pretreated using CAMBI thermal hydrolysis at 6 bar pressure and at different temperatures and treatment time ranging from 120-180°C and 30-120 minutes. Both raw and thermally pretreated sludge samples were characterized for total solids (TS), volatile solids (VS), carbon to nitrogen ration (C/N), total phosphate (TP), total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), NH4-N, total alkalinity, total and soluble carbohydrates, total and soluble proteins, and, total and fecal coliforms. Tests for pH, total solids (TS), volatile solids (VS), total organic carbon (TOC) determination were conducted according to Standard Methods (APHA, 2017). HACH Nessler method (8075) was used to measure the ammonia. Proteins and carbohydrates were analysed by the conventional Lowry and anthrone reagent methods, respectively. For the isolation of OMPs, the solid-phase extraction method was employed using 200 mg OASIS HLB cartridges. The raw sludge and Cambi pretreated sludge (after AD) samples from each temperature with highest biogas yield were used for metagenomic and organic micropollutants characterization. For metagenomic analysis, 16s RNA sequencing was done using V3-V4 region primers.

Out of the THP tested conditions- 120-180℃ for 30-120min, the best COD and Protein solubilisation of 40% and 37%, respectively, was achieved at 160℃/30minutes. The cumulative methane yield was 4 times higher in thermally pretreated sludge (507mL/gVS) in comparison to control (123 mL/gVS). VS reduction in CAMBI was 54% as compared to Control (21%). Cambi followed by AD also enhanced biodegradability of few organc micropollutants (OMPs) like Enrofloxacin, Ciprofloxacin, and Bezafibrate (>80% removal) and estrone, 17β-estradiol and diclofenac (50-70% removal). Within the bacterial domain, the most abundant phyla were Proteobacteria, Firmicutes, Chloroflexi, and Bacteroidetes, collectively accounting for >70–80% of bacterial reads. These phyla have been reported to dominate in anaerobic digesters treating sludge. Overall, THP enhanced anaerobic digestion, demonstrated superior performance compared to control digestion, with improved methane yields, higher volatile solids and micropollutant removal, and a more diverse microbial community in the digester. It improved biodegradability, biogas yield, pathogen annihilation, sludge solubilisation, high organic loading rate (OLR), dewaterability and energy recovery. Microbial community structure is a vital parameter for better performance of AD process. Thermal hydrolysis and typical anaerobic microbial consortium effectively mitigate organic micropollutants after AD.

Keywords: *CAMBI, solubilization, sewage sludge, thermal hydrolysis process, OMPs*

SYSTEM CHARACTERISTICS OF HIMALAYAN TRIBUTARIES OF UPPER GANGA BASIN, INDIA

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Climate change is altering the temporal and spatial distribution of different components of hydrologic cycle. Any change in the quality and quantity of the Himalayan tributaries of River Ganga under the climate change regime will impact the quality parameters of River Ganga. Some studies on the chemical characteristics of melt water discharged from glaciers indicate that chemical activity is more intense in these regions than in tropics. Altered flows in the rivers may change the habitat (depth, velocity, temperature, pH, DO, BOD, COD, sediment concentration) required for survival of various aquatic species. As these species are very important considering the fact that they are responsible for the self-purification capacity of the rivers. Hence, it becomes imperative to study the impact of climate change on the river ecology. River systems, generally regarded as 'pipes' play a crucial role in the global carbon cycle exporting carbon dioxide (CO_2) via the water-air interface to the atmosphere. Inland waters discharge about 0.9 Gt of carbon each year into the oceans. While only a small proportion of carbon entering a river network ultimately makes it to the ocean, increasing evidence suggests that a significant portion would be buried within the river network or released back into the atmosphere while en route. Rivers are hence considered sources of atmospheric carbon dioxide. The partial pressure or effective internal pressure of riverine CO_2, or pCO_2, is recognised as a significant factor in estimating CO_2 outgassing because it shows the gradient in river CO_2 concentration in relation to atmospheric equilibrium (i.e., 410 atm) and further reflects both biogeochemical processes and in situ carbon dynamics and in the watershed. Moreover, the complex pCO_2 dynamics in river waters are often driven by both internal and external environments involving physical, chemical, and biological factors. The $p(CO_2)$ signature of meltwater can be used to characterize different glacial hydrological weathering environments. When proton supply equals the consumption, the $p(CO_2)$ of the solution remains in the equilibrium with the atmosphere, the system is said to be open. If pCO_2 of solutions are not equal to atmospheric pCO_2 ($10^{-3.5}$atm), it can be said to be in disequilibrium with respect to the atmosphere. When the supply of protons is more than their consumption, then high $p(CO_2)$ conditions arise. Low $p(CO_2)$ conditions arise when the demand of protons for chemical weathering is more than the rate of CO_2 diffusion into the solution indicating closed system weathering.

In the present paper, the system characteristics of Gangotri glacier, the source of River Bhagirathi and River Alknanda were discussed. For Gangotri glacier, hydrochemical data of meltwater evolved during ablation period of the year 2014-2016 was used for the study and hydrochemical data of River Alaknanda evolved during the year 2016-2018 was used and hydrochemical analysis for different water quality parameters was performed as per standard methods prescribed in APHA. Gangotri glacier system is dominated by high $p(CO_2)$ closed system associated due to higher proton release from oxidation of sulphides and low $p(CO_2)$ closed system during the times of prolonged snow cover and under developed subglacial drainage system. The river chemistry is predominately controlled by chemical weathering with carbonation being the major proton-producing reaction. The pCO_2 values were

consistently higher than atmospheric levels, indicating a closed system with a substantial carbon dioxide contribution. Further, the Alaknanda River was identified as high-pCO$_2$ closed system. The observed trends in pCO$_2$ highlighted complex interactions between various factors, including flow dynamics, biological processes, and the influx of tributaries. The elevated pCO$_2$ levels further emphasize the river's role as a significant carbon dioxide source. The study showed the persistence of high pCO$_2$ closed system characteristics associated with increased suspended sediment concentration resulting from carbonate weathering, dominance of HCO_3^- over SO_4^{2-} and thereby results in high values of C ratio in River Alaknanda. The open and closed system characteristics based on pCO$_2$ levels reveals the influence of geochemical mechanisms and environmental factors on the river's carbon dioxide saturation. Understanding the open and closed system behaviour has important implications for aquatic ecosystems and water quality management. The persistence of high pCO$_2$ closed system conditions downstream can significantly impact aquatic ecosystems, potentially causing stress to aquatic organisms.

Keywords: *Hydrochemistry, pCO$_2$, open system, closed system, suspended sediment, C ratio*

ENVIRONMENTAL FLOW ASSESSMENT FOR YAMUNA RIVER, INDIA FROM HATHNIKUND BARRAGE TO OKHLA BARRAGE

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River Yamuna during non-monsoon season carries very less flow in its stretch from Hathnikund to Okhla barrage, which adversely affects the quantity and quality of water in the river. The assessment of e-flows for the study reach is based on integrated hydrodynamic and hydrological modelling using SWAT and HEC-RAS 1D models. A variety of datasets are required as model inputs as well as to validate the model outputs. Besides the river water quality, the study also investigates the variation in groundwater levels over a period of more than four decades. All such necessary data were collected from concerned agencies. In addition, exhaustive field surveys were carried out for the following: (1) identification of the indicator fish species and assessment of their habitat requirement-based investigations in the river, and (2) river cross-section surveys for a total of 306 lines at closely spaced intervals.

The analysis of depth to groundwater levels for pre-monsoon and post-monsoon over a period of four decades from 1975 to 2018 has revealed maximum depletion in water levels ranging from 10 to 20 m in the Mawi-Baghpat reach during the months of April and May. Receding groundwater levels have in turn affected the baseflow contribution to the flows in Yamuna. For the study reach, the ratio of baseflow to total river flow is found to be higher in the non-monsoon season than in the monsoon season. This pattern is representative of other gauges in the study reach and shows the importance of baseflows in sustaining river flows during non-monsoon period. Water quality analysis have shown that between the Wazirabad and Okhla barrage, the river receives approx. 6140 kg/hr BOD load out of which around 70% load is contributed through Nazafgarh drain. The average non-monsoonal DO value in this river stretch is 0.4±0.12 mg/l as O2. During the field surveys, the DO value in this stretch was non-detectable indicating the BOD load to the river higher than the assimilative capacity of the river. The water quality up to Wazirabad barrage is good for fish proliferation, however, the reduction in DO values downstream of Mawi is a cause for concern. Field surveys have revealed three major fish habitats types such as pools, riffles and runs at the sampling sites in Yamuna River. The identified indicator species, *Bangana dero* and *Raiamas bola* are thriving well in run habitat of channel with depth ranging from 60 to 90 cm and velocity in the range of 0.1 m/s. Hence, ensuring minimum water depth of 60 cm and velocity of 0.1 m/s at riffle/run habitat in the river will safeguard the fish diversity in Yamuna River.

The integrated hydrologic and hydrodynamic modeling approach has been adopted to assess the e-flows between Hathnikund barrage and Okhla barrage and to compute the releases required from Hathnikund barrage for maintaining these e-flows. For converting the habitat suitability depth values into the flow values, depth versus discharge curves have been developed at selected 13 locations covering the whole hydrologic regime using HEC-RAS simulations. Using the developed depth vs discharge curves for different sites, the minimum desirable flow values required for maintaining suitable physical habitat in terms of desirable flow have been estimated. The flows required to be released from Hathnikund barrage for maintaining the minimum desirable amount of flow at different sites during different seasons have been estimated using the flow series simulated by the calibrated hydrologic model SWAT. The releases required from Hathnikund barrage during a specific month is computed by taking the maximum of the releases estimated from Hathnikund barrage for meeting the minimum depth requirement of 0.60 m at 13 identified locations corresponding to the specific month.

For carrying out various functions, the aquatic ecosystem needs natural flow variability within the year, for its sustenance. Incorporation of natural variability of flows has been carried out by taking the minimum depth of 60 cm for the month of May (being the driest month at all the G&D sites downstream of Hathnikund barrage) and modifying the releases as per the existing natural variability as observed in long-term historical data. Final recommended releases from Hathnikund barrage for maintaining required habitat conditions between Hathnikund and Okhla barrage during different months of a year ranged from 23 to 220 cumec ranging from Jan to Aug have been estimated.

Keywords: *E-Flows, River ecosystem, keystone species, hydrodynamic modelling, hydrological modelling*

RESTORING OF POLLUTED RIVER STRETCHES IN TAMIL NADU: A STATUS AND STRATEGIC FRAMEWORK

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The water quality management in India is performed under the provision of the Water Act, 1974 and basic objective is to maintain and restore the wholesomeness of national aquatic resources by prevention and control of pollution. Increasing demand of water for human consumption, irrigation and growing industrial activities have the impact on the water quality of rivers due to declining flows in rivers and depleting water levels of subsurface resources. The discharge of untreated domestic sewage, unscientific disposal of municipal solid waste, and untreated or partially treated industrial effluents cause pollution in rivers. Under National Water Quality Monitoring Programme (NWMP), the Central Pollution Control Board (CPCB) in association with State Pollution Control Boards (SPCBs) is monitoring the water quality of rivers in India. The water quality data is analysed and the monitoring locations exceeding the water quality criteria parameter of BOD 3 mg/L are identified as polluted locations and the polluted locations in a continuous sequence are defined as polluted river stretches. In 2015 based on 2009 to 2012 data, the CPCB has identified 302 stretches across 275 rivers in India as polluted river stretches (PRS). This status report is being updated periodically. As per 2022 report, there are 311 PRS identified in 279 rivers in India, out of which 10 river stretches are located in Tamil Nadu State. In order to restore these rivers, the CPCB has prioritized the PRS based on the concentration of BOD from priority I to V. Accordingly, Priority-I refers to highly polluted river stretch which need immediate action and Priority-V refers to relatively less polluted stretch which need secondary attention. Priority-I: BOD exceeding 30 mg/L [standard for discharge of treated sewage and effluent into rivers for dilution] and all locations exceeding 6 mg/L on all occasions, Priority-II: BOD having 20-30 mg/L and all locations exceeding 6 mg/L on all occasions, Priority-III: BOD having 10-20 mg/L and all locations exceeding 6 mg/L on all occasions, Priority-IV: BOD in the range of 6-10 mg/L and Priority-V: BOD in the range of 3-6mg/L.

Thus the 10 PRS in Tamilnadu are classified as follows: Priority-I six stretches (i) Cauvery [Mettur to Mayiladuthurai, 200 km], (ii) Vasista [Manivilundhan to Thiyaganur, 10 km], (iii) Sarabanga [Thathayampatti to T. Konagapadi, 15 km], (iv) Thirumanimutharu [Salem to Papparapatti, 15 km], (v) Adyar [Tambaram to Nandanam, 30.1 km], (vi) Cooum [Avadi to Sathyanagar, 31.7 km], Priority-IV one stretch (i.e) Bhavani [Sirumugai to Kalingarayan 60 km], Prioirty-V three stretches (i) Amaravathi [Madathukulam to Karur 108 km], (ii) Palar [Kodaiyanchi to Marapattu, 16.3 km], (iii) Tamirabarani [Pappankulam to Arumuganeri 80 km]. These river stretches need to be restored to the primary water quality criteria for bathing wasters as prescribed in the Environment (Protection) Rules, 1986. As per the CPCB guidelines, Tamil Nadu Pollution Control Board (TNPCB) in association with line departments have prepared action plan for each PRS. The action plan covered identification of polluting sources including functioning status of sewage treatment plants (STPs), effluent treatment plants (ETPs), common effluent treatment plants (CETPs), solid waste management and processing facilities, quantification and characterization of solid waste, trade effluent from industries and sewage from local bodies generated in the catchment area of polluted river stretch. The gaps identified is addressed with proposal for establishment of new STPs, solid waste processing facilities, and CETPs for industrial effluent. The action plan also addressed the issues relating to groundwater extraction, adopting good irrigation practices, protection and management of flood plain zones, rain water harvesting, groundwater charging, maintaining minimum environmental flow of river and plantation on both sides of the river. The plan also covered setting up of biodiversity parks on flood plains by removing encroachment as an important component for river rejuvenation. The plan also focused on proper interception and diversion of sewage carrying drains to the STP and emphasis on utilization of treated sewage so as to minimize extraction of ground or surface water. The action plan also has defined specific timelines for execution. The action plans are being implemented by the respective line departments and it is being monitored by the high-level committees from state and central governments. The TNPCB monitors the water quality of these river stretches at selected locations under NWMP on monthly basis and upload the data in their website. Parameters being monitored include fecal coliform, fecal streptococci, pH, DO, and BOD which are prescribed as primary water quality criteria for bathing waters.

As per the CPCB draft criteria for deletion of river stretches from the list of identified PRS, water quality data of the river stretch for all the locations should comply with primary water quality criteria for bathing waters at least consecutively for a period of two years. Accordingly, the level of fecal coliform should be <500MPN/100 mL, fecal streptococci <100 MPN/100mL, pH 6-5 to 8.5, DO >5mg/L and BOD <3 mg/L. The monitoring data of these 10 PRS for last two years (i.e. 2022 to 2023) are plotted in graph. From the plotted graphs, it is noted that in river Cauvery, 10 of the 19 monitored locations met bathing water standards in 2022, increasing to 17 locations in 2023. In river Bhavani, all seven monitored locations met the standards consistently in 2022 and 2023. Similarly, in river Tamirabarani, all 12 monitored locations met the standards in 2022, with slight deterioration in one location in 2023 when 11 locations complied with. The Palar River, monitored at a single location, met the standards for both years. However, Adyar and Cooum rivers failed to meet the standards across all the monitoring locations. The Vasista, Thirumanimutharu, and Sarabanga rivers, monitored at single location each, failed to meet the standards in both years. In Amaravathi River, out of three monitored locations, two locations achieved compliance in 2023. Based on these results, it is inferred that Bhavani, Tamirabarani, and Palar River stretches are in compliance with standards for bathing waters and hence eligible for removal from the PRS list. However, it is essential to ensure consistent compliance with the standards.

The data demonstrate that there is a significant improvement in water quality in river stretches of Bhavani, Tamirabarani, and Palar, which highlights efficacy of targeted restoration measures. However, Adyar, Cooum, and other Priority-I rivers calls for enhanced efforts. The successful restoration of PRS hinges on completion of proposed action plans, strict enforcement of pollution control regulations, and sustained monitoring. Intensified efforts are required to address the gap for management of sewage and solid waste by the local bodies. Public participation in river conservation and the adoption of community-driven initiatives are critical for long-term success. Advanced technologies for real-time water quality monitoring can help to identify challenges promptly and adopt management strategies as needed. The restoration of polluted river stretches is essential for ensuring sustainable development and fulfilling the SDG related to water.

Keywords: *Pollution, water quality, restoration strategies, sustainable development*

ASSESSING RIVER DISCHARGE PATTERNS FOR ECOSYSTEM SUSTAINABILITY: A CASE STUDY OF THE WAINGANGA RIVER

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Water is essential for sustaining life on earth and protecting environmental balance. Availability of water is prerequisite for various biological and ecological processes crucial for and ecosystems. Anthropogenic activities triggered significant harm to aquatic environments. To preserve and restore healthy river ecosystems, there is an urgent need for well-planned, seasonal, and year-round management strategies. Historical 30 years discharge data of the Wainganga River at the Satrapur gauging station were analyzed using Weibull's method to perform a probability analysis. The study identified three types of years: wet (Q10), normal (Q50), and dry (Q90). These three year types provided insights into the seasonal flow patterns and water availability of the river. To better understand seasonal variations, each year was divided into monsoon, winter, and summer seasons. Dry, normal, and wet years, the corresponding discharge rates were 625, 1763, and 4993 cubic meters per second (m^3/s). In a dry year, seasonal flows were recorded as 51.37 m^3/s during the monsoon, 7.10 m^3/s during the winter, and 0.76 m^3/s during the summer. In a typical (normal) year, flows were 144.47 m^3/s in the monsoon, 17.65 m^3/s in winter, and 5.01 m^3/s in summer. Higher fluctuations were observed in the wet years with monsoon flows of 342.79 m^3/s, winter flows of 120.64 m^3/s, and summer flows of 9.35 m^3/s. These seasonal and annual variations highlight the dynamic nature of the river and the challenges of managing water resources sustainably. They underscore the need for improved planning and water management strategies to maintain river ecosystems effectively.

Keywords: *Aquatic ecosystems, Wainganga River, Weibull's probability analysis, seasonal variations, sustainable water management*

Theme 3
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MOUNTAIN HYDROLOGY AND SPRINGSHED MANAGEMENT

SPRING OUTFLOWS IN DIVERSE LITHOLOGICAL AND GEOMORPHOLOGICAL SETTINGS OF MID-HILL REGION OF WESTERN NEPAL

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The most springs are drying up and declined their water outflow in the non-snow fed watersheds of mid-hill region in Nepal, which is leading to water scarcity. The water related issues are directly affecting the community's livelihood and overall ecosystem. This study aims to understand the springs characteristics and analyze the spring discharge variations between the two high flow seasons based on parameters such as lithology, occurrence, elevation, landform, and land cover. This study highlights the importance of understanding landform-specific spring water flow dynamics for water resource management and planning, especially in regions with high seasonal variability.

The study area Seti Khola watershed is located in the mid-hill of western Nepal within Parbat and Syangja districts, which is about 115 km^2. During fieldwork, spring locations were explored and assessed through transect walks conducted with the assistance of community resource persons. Altogether, 168 perennial springs were identified over seasonal springs after the compilation of databases of high and low flow season. Among spring inventories, high flow periods of two consecutive years 2022 (Y1) and 2023 (Y2) were conducted, respectively. Several methods were used depending on the spring type and available kits such as bucket and stopwatch method for minimal discharge (MND), weir and float method for intermediate discharge (ID) and maximal discharge (MXD). The percentile-based discharge classification established for lower 25% of the values as MND, middle 50% of data as ID and upper 25% of the values as MXD.

Springs were inventoried gathering spatial distribution and societal information. The households and socio-economic information about the springs were obtained from the permanent residents of the local community. The spatial distribution of springs was analyzed using lithological and geomorphological data. The lithological data was extracted from the latest published literature published in the Bulletin of Central Department of Geology and added from the field observations, which is then simplified as carbonate and non-carbonate lithology. The geomorphological parameters such as elevation classes derived from a 5-m DEM were categorized into three groups: Class I (below 1000 m), Class II (1000–1500 m), and Class III (above 1500 m above mean sea level (amsl)). Soil data from SOTER were classified into Eutric Cambisols (CMe), Chromic Cambisols (CMx), and Gleyic Cambisols (CMg). Similarly, land cover from FRTC data included forest, grassland, and cropland. The site-specific occurrence of springs was categorized by depression spring, fracture spring, karst spring, and rock-sediment spring.

Local communities indicated complete reliance on spring water for their livelihoods and daily needs, emphasizing the vital role these sources play in maintaining the flow of their rivers. Seti Khola originates from springs during dry period and surplus contribution of rainfall during wet season in the region that flows across the varieties of rock types and landforms

from northeast to southwest. Geologically, the area lies within the Tansen Group, Sirkot Group, Upper Nawakot Group and Lower Nawakot Group. About 44% of the area consists of Carbonate rocks while the remaining 56% are non-carbonate rocks regardless of thin carbonate bands of thickness in few mm to cm. The major rock types in the study area are Dolomite, Limestone, Quartzite, Slate and Phyllite. The carbonate springs consistently have higher discharge compared to non-carbonate springs across seasons. The carbonate terrain had an accumulated discharge of 3549.03 lpm, exceeding the non-carbonate discharge of 2682.29 lpm by 866.74 lpm in Y1 whereas in Y2, both decreased, with carbonate at 3033.79 lpm and non-carbonate at 2428.18 lpm, a difference of 605.61 lpm.

The occurrence of springs is high in 15-30° slope and 1000-1500 m amsl. The analysis shows that ID is the most frequent across both seasons, especially in elevation Class II. The MXD is uncommon, particularly absent in Class I, with a slight decrease from Y1 to Y2. The MND increases in Y2, in Class II and Class III, suggesting seasonal flow reduction. The elevation Class II consistently experiences the highest water flow across discharge categories, while Class I shows the lowest, particularly for MXD. The forest areas dominate in all discharge classes, with ID being the most frequent in both Y1 (55 springs) and Y2 (52 springs). The MND increases from Y1 (61 springs) to Y2 (67 springs), particularly in Forest and Cropland. The springs with MXD is rare, with less counts across land types and a slight decrease from Y1 (25 springs) to Y2 (22 springs). Grassland consistently shows the lowest counts across all discharge categories.

Fracture springs and rock-sediment interface springs are key to maintaining ID and MXD, due to their geological characteristics allowing water movement. Depression springs, on the other hand, show vulnerability to MND, indicating poor outflows or slower recharge rates. Seasonal shifts, particularly reductions in MXD from Y1 to Y2, reflect environmental factors. The Eutric Cambisols dominate both ID and MXD, with 53 springs in Y1 and 50 springs in Y2 for ID, and 19 springs and 18 springs for MD, reflecting their high fertility and good outflows. Chromic Cambisols contribute consistently to ID (25 springs in both seasons) and MND (increasing from 14 to 16 springs), indicating stable but less frequent water flow. Gleyic Cambisols, due to their poor outflows, have minimal contributions across all categories, particularly MXD, with no spring counts. CMe keeps the widest range of water outflows, while CMg reduces discharge.

The study reveals that the ID is the most frequent in both Y1 and Y2 (~ 48%). MXD has the least number of springs (~ 14%), decreasing across seasons, indicating its rarity and potential seasonal influence. MND has about 38% springs increases in Y2, especially in non-carbonate areas, reflecting seasonal water flow shifts where the non-carbonate regions consistently show higher ID. Spring usage in the region shows MND supports soil moisture retention, ID aids local water supply, and MXD is essential for large-scale supply and ecosystem health, emphasizing their hydrological importance. Forest areas experience the most significant water flow variations, followed by cropland, while grassland shows minimal variation. Overall, water flow tends to diminish from Y1 to Y2, due to seasonal factors such as reduced rainfall and increased evaporation.

Keywords*: Springs, spring discharge, carbonate rocks, elevation, soil and landcover*

DISTRIBUTION OF SPRINGS ALONG THE PHALEBAS THRUST IN MIDDLE HILL REGION OF WESTERN NEPAL

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Springs play a crucial role as to fulfil fresh water demand of local communities situated in dispersed settlements situated in the middle hill region of the Nepal Himalaya. The study investigates the significant influence of the Phalebas Thrust on the distribution and discharge variabilities of springs in the study area. The study area is located in the Syangja District of Western Nepal with area coverage of 28.53 km^2. The study area includes varied topography with elevations ranging from 780 to 2008 m above mean sea level (amsl) in the sub-tropical climate with average annual precipitation 2426.1 mm and dominated with dendritic drainage pattern. The study area includes various metasedimentary formations of the Lesser Himalayan Sequence, which significantly influence groundwater dynamics. The major geological structure of the region is the Phalebas Thrust, which runs southwest-northeast across the study area. The thrust plays a crucial role in controlling the spatial distribution of springs, as the fracture networks associated with the thrust provide pathways for groundwater movement. The study also examines the role of thrust-induced fractures and joint networks in facilitating groundwater flow, thus impacting the frequency and discharge of springs.

A systematic spring inventorization was conducted as part of this research, utilizing both primary and secondary data. The spring inventory, which involved direct field observations with the assistance of local resource person. Geological data, including bed orientations and lithology, were collected from field survey. In addition, spring discharge was measured using the volumetric method, which involves calculating the time taken to fill a calibrated container. The geological formations of the area were classified based on lithology, whereas the proximity of springs to the Phalebas Thrust was analysed in intervals of 100 meters as of Euclidean distance. The geological formations of the study area are part of the Upper and Lower Nawakot Groups, consisting of the Benighat Slates, Dhading Dolomite, Nourpul Formation, Nayagaun Formation, Naudanda Quartzite and Kuncha Formation. The study area is highly deformed, with numerous thrusts and folds contributing to the geological complexity. From this study, it revealed that there is a total of 92 perennial springs within the study area. These springs were classified into different types based on their origin, including depression, fracture, fault, karst and contact springs. The highest spring density was observed within 0 to 100 m of the Phalebas Thrust, highlighting the significant influence of the thrust on groundwater flow. Springs in the area were predominantly found in carbonate terrains, where dolomitic formations contribute to higher discharge rates. Notably, the Dhading Dolomite exhibited the highest spring discharge, with one of the largest springs having discharge rate of 39.79 lpm.

The findings of this study have important implications for groundwater management in the middle hill region where there is a significant role of not only lithology but also of geological structure. The high concentration of springs near the Phalebas Thrust indicates that geological structures, particularly thrust zones, play a critical role in determining groundwater availability. The data also suggest that the interaction between geological contacts and thrust-related fractures significantly influences spring discharge. Approximately 62% of the total

spring discharge in the study area is contributed by springs located within 400 meters of the Phalebas Thrust. The study also highlights the influence of topography on spring distribution. Springs were found to occur at various slope angles, with the majority located on moderate slope range between 15° to 25°. The springs were also distributed according to aspect, with a significant concentration on south-east facing slopes. These findings suggest that topographic factors, in combination with geological structures, play an important role in determining the location and behaviour of springs in the region. The geomorphology of the area further impacts groundwater flow, particularly in the southern part of the study area, where karst features are prominent. The karst geomorphology, characterized by soluble rock dolomite, creates conditions that enhance secondary porosity and permeability, allowing for increased groundwater flow. This is reflected in the higher discharge rates observed in springs located in dolomitic terrains. The study found that the majority of the springs with high discharge rates were located in these karstic areas, further emphasizing the importance of geological formations in controlling groundwater behaviour.

The study underscores the critical role of geological structures, especially thrust zones, in shaping the distribution and behaviour of springs. The Phalebas Thrust, in particular, plays a significant role in controlling the occurrence and discharge of springs, with higher spring density and discharge rates observed in the periphery of the thrust alignment. Approximately, 23% of the springs are located within 100 meters of the thrust alignment, with a gradual decrease in spring frequency observed as the distance from the thrust alignment increases. The lithology proximity to the thrust, Benighat Slates has highest number of springs and higher amount of discharge with respect to the area of the geological formation. These findings have important implications for the sustainable management of groundwater resources, especially management of springs and their springsheds in the Himalaya. This study clearly emphasizes that a proper understanding of geology and hydrogeological settings of any study area is a key to address spring hydrogeological issues, which can also provide fundamental knowledge about drying springs in the middle hill region of the Nepal Himalaya.

Keywords**:** *Phalebas Thrust, lithology, springs, discharge, middle-hill*

STAGE-DISCHARGE RATING CURVE AND PARTICLE-SIZE DISTRIBUTION OF SEDIMENT OF RANIKHOLA RIVER, SIKKIM, INDIA

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During the rainy season, river streams in Sikkim have high runoff volumes and flow velocities, requiring periodic measurement of river stage and discharge. The Teesta River, the most important in Sikkim, covers the entire state and tributaries include the Ranikhola River. River discharge measurement is crucial for hydrologic and hydraulic design, as it aids in planning and managing water resources. It is estimated through cross-sectional area and velocity measurements, and is linked to water surface elevation, known as stage, using the rating curve. The rating curve is a crucial tool in surface hydrology, as its reliability relies on a satisfactory stage-discharge relationship at the gauging station. It is also very important in the validation and calibration of rainfall-runoff and flood routing models. Therefore, it was felt necessary to develop a rating curve for the *Ranikhola* River, one of the major tributaries of Teesta River in Sikkim.

River-suspended sediment concentrations are crucial for pollution, channel navigation, reservoir filling, and fish habitat. Sedimentation, a weathered material, is used in erosion hazards evaluation, water resource management, and dam design. Reservoirs created by dams receive silt, reducing water storage space and reducing benefits. Siltation can also cause increased evaporation losses, backwater flooding, and damage to powerhouse turbines. Sedimentation transport occurs in two forms: bed load and suspended load. Bed load is the coarser fraction of sediment, while suspended load is the fine-grained sediment that remains in water during transportation. The amount of load carried depends on the stream's volume, velocity, disintegrated materials, vegetative cover, and stream bed. The study aims to estimate the rate of sedimentation in the Ranikhola River, a mountainous stream, by collecting weekly water samples, estimating suspended load, and estimating bed load. The study also considers human activities along stream banks, such as sand quarrying operations, land clearing, and landslides, which affect sedimentation rates.

Particle-size analysis is a crucial tool in soil science to assess soil texture, which is determined by the distribution of sand, silt, and clay particles in a soil sample. Mechanical analysis, which involves the separation of soil into different size fractions, is performed in two stages: sieve analysis for coarse-grained soil and sedimentation analysis for fine-grained soils. In this study, various methods for calculating different parameters in the field as well as in the laboratory have been discussed. The various parameters are stage flow, velocity and discharge of the *Ranikhola* river at cross-sections, sediment rate at the same cross-sections, and channel scouring and braiding of the mountain streams. To derive the stage-discharge rating curve, the flow velocity and cross section of the river at the various sections were estimated. The section chosen was such that it is easily accessible in the time of flood. One site was selected on the *Ranikhola* river and other one at Hanging bridge to establish stage-discharge rating curve and sediment analysis. The Hanging bridge was selected to study the

scouring and braiding in the *Ranikhola* river. For establishing stage-discharge rating curve, the selection of the site was such that the cross-section does not change with time. Stage-discharge rating curve was created by plotting the stage and accompanying discharge values on arithmetic and logarithmic scales.

In this study, river water samples were collected on the regular basis from the Hanging bridge section on the *Ranikhola* by using plastic sampling bottles. The particle size distribution analysis of the sediment samples in the *Ranikhola* river can be established by sieve analysis. The braiding analysis was performed to check the change in the river bed. The river stage and corresponding discharge was taken on the *Ranikhola* river in Sikkim for 1-month duration. The measured stage was plotted against the observed discharge on the arithmetic and logarithmic plots with stage as ordinate and discharge. The coefficient of determination (R^2) was observed to be 0.94. The corresponding logarithmic equation for the *Ranikhola* river equation can be used to compute the flow discharge in the *Ranikhola* river for the measured stage near hanging bridge cross-section. The total sediment load in the *Ranikhola* river ranged between about 1.1 to 7995 tonnes/day at the hanging bridge section. The highest sediment rates were found to be on April 07, 2022.

The particle size distribution curve for the sediment sample collected at the upstream side of the hanging bridge cross-section on the *Ranikhola* river. The percentage of gravel is 46% sand is 54 %, Coefficient of Uniformity Cu = 18.88, Coefficient of curvature Cc = 0.56. The sediment is classified as well graded sand. As per USDA textural soil classification system, it is observed that the sediment comprises of 69.2%, 27.2% and 3.6% of clay, sand and silt, respectively and as per USDA, it can be classified as clay soil. As per ISSS classification system, it is observed that the sediment comprises of 69.2%, 30.6% and 0.2% of clay, sand and silt, respectively and it can be classified as clay. The hydrometer analysis showed that the river sediment mostly contains clay as per both soil classification systems. The braiding analysis was done for the same section of the *Ranikhola* river for different dates at 1 m, 2 m and 3 m distance from the left water edge. It can be observed that the river bed depth in the stream apart from the section below the bridge changes significantly. For e.g., the channel bed gets deposited during the high flows on 07/04/2022 by about 17 cm at 1 m distance and 5 cm at 2 m distance, whereas at 3 m distance, the scouring of 8 cm has been observed. As compared to the channel banks, more scouring has been observed near the centre of the flow. It can be reveals from 3 bars of the diminishing sizes on 12/04/2022 with braiding depths of 23 cm, 3 cm and 1 cm at the distance of 1 m, 2 m and 3 m, respectively. The developed stage-discharge rating curve equation ($h = 0.2953 \ln(Q) + 821.87$) can be used to estimate discharge in the *Ranikhola* river from measured stages. The range of sediment discharge in the *Ranikhola* river is observed to be 1.1 to 7995 tonnes/day. It can be concluded that as the flow discharge reduces, the braiding of the channel bed increases near the stream banks as conferred to that near the flow centre. This may be attributed to the human activities like sand quarrying, land clearing for buildings, landslide, etc. Thus, channel braiding analysis leads to the conclusion that the river bed varies considerably, sighting that a considerable scouring and deposition. The large sediment inflow in the *Ranikhola* River necessitates large scale catchment area treatment programmes including structural and non-structural control measures in the watershed area of the river.

Keywords: *Stage-discharge, sedimentation, particle size distribution, channel braiding*

SPATIO-TEMPORAL DISTRIBUTION OF NATURAL WATER RESOURCE IN KANGRA BLOCK, HIMACHAL HIMALAYA: A HYDROCHEMICAL AND HYDROLOGICAL ANALYSIS

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Groundwater is a valuable resource for various domestic uses, including irrigation, drinking, and manufacturing deeds. The main components of groundwater research emphases on its quality and quantity. The hydrochemical study determines whether the water is safe to drink, while assessing water amount ensures its availability for future necessities. Changes in quality or quantity are primarily impacted by rock-water interactions, climate inputs, and human activities. The sustainable growth requires an effective management of natural water resources. Springs, a major source of freshwater, serve an important role in supporting several people throughout the Indian Himalayan region. However, rising freshwater demand, along with rapid population increase, shifting weather patterns, and different development activities such as contemporary agricultural methods, industrialization, and urbanization has resulted in major changes in land use and cover. These changes have degraded spring ecosystems, impacting both water quality and availability. These changes have adversely affected spring habitats, reducing both water quality and availability. Addressing the numerous issues of drying springs or declining volume in hills requires a thorough investigation of both socioeconomic and biophysical factors, as well as their relationships. This can be accomplished through cohesive study that actively engages local communities or end users. Spring discharge is directly related to the recharge area characteristics, such as shifts in rainfall patterns, changes in land use or cover, and the aquifer ability to store and transmit groundwater. Each spring is unique in terms of its type, catchment area, form of discharge, terrain, and geological structure under the surface. The change in rainfall patterns in the Himalayas not only influences the water supply and livelihoods, but it also causes challenges for downstream communities. To assess the utility of these fresh water sources for domestic purposes, a total of 21 spring water samples were collected during pre- and post-monsoon seasons (2021-2022) in the Kangra block of Himachal Pradesh. Different geochemical modeling tools, multivariate statistical analysis, and graphical plots were employed to comprehend the major geochemical processes and the impact of anthropogenic forcing on spring water chemistry. The collected samples were analyzed for various water quality characteristics along with their discharge pattern and further compared with Bureau of Indian Standards (BIS). Spring discharge was measured periodically (once in a month) where measuring locations referred to as spring sites, which are natural outlet channels or man-made outflows such as plastic or metal pipes. The discharge was further calculated by using Time Volume Method, where flow (Q) can be captured into a container of known volume (V), one of the most straight forward methodologies for determining discharge is to time (t) the filling of the container and calculate the water flow from springs i.e. Q=V/t. The most abundant cations were found to be Ca^{2+}, Mg^{2+}, Na^{+}, & K^{+} followed by Cl^{-}, SO_4^{3-}, NO_3^{-}, & F^{-} as predominant anions. The analyzed chemical composition of springs met the standard criteria for drinking water quality by BIS. Nevertheless, the physicochemical characteristics of the spring water were found to be varied both spatially and seasonally. The chemical analysis obtained for most of the samples reveals CBE levels of about ±10%. The results from bivariate plots and PCA indicate that the lithological characteristics with some extent to anthropogenic inputs are the dominant processes controlling the chemical evolution of spring water in the region. The selected parameters were all under the permissible limits therefore the collected samples were of good quality and suitable for human consumption, however prior treatment of water is advised before consumption. The mean spring discharge peaked at 25 Lt/m during post monsoon and further diminishes to 1.5 Lt/m during pre-monsoon. The spring discharge exhibits an annual, periodic rhythm which is significantly impacted by rainfall patterns with discernible time lags. Even though the variations in ionic concentration of springs are observed, which might be season-specific. However, it is equally important to have further studies regarding total coliform, heavy metal, and pesticide pollution to reach at better and holistic understanding of the water quality of these springs. The study reveals that the hydrochemical composition of spring water is influenced not only by geogenic processes, such as rock-water interactions, but also by anthropogenic activities in the region. Findings indicate that springs located near settlements are more susceptible to contamination from human activities, while those in sparsely populated areas face the risk of depletion due to inadequate catchment management and sanitation practices. Additionally, a noticeable decline in water discharge during the summer season is linked likely to ongoing development activities in the area. However, rising temperatures and precipitation variability caused by climate change have aggravated the spring water catchment areas. A comprehensive hydrogeological mapping of the spring shed endeavor is designed to identify unique recharging zones and aquifer interferences. It also contributes to a better understanding of aquifer hydrodynamics and water storage-discharge interactions. This study provides valuable baseline data on spring water availability and accessibility, facilitating better management of these critical groundwater sources during essential periods. Moreover, it contributes to a deeper understanding of the region's microclimatic conditions.

Keywords: *Natural resources, springs, water quality, water discharge, sustainability, longevity*

TRACING SOLUTE SOURCES AND DERIVATION PATHWAYS IN TRANS – HIMALAYAN GROUNDWATERS OF THE INDUS RIVER BASIN IN LADAKH, INDIA

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Observed groundwater chemistry of a region is the result of several inter-related factors: precipitation chemistry, water – aquifer matrix (rock) reactions, mixing with other sources of water, and anthropogenic disturbance. Of these, the type and intensity of water, rock interactions are perhaps the most important, given the differential solubilities and dissolution rates of minerals, especially in a multi-lithology terrain. Although solute sources and release mechanisms to groundwater are well established in the middle and lower transboundary Indus River basin aquifers, such delineations are relatively scarce in its mountainous stretches. The present study aims to delineate these processes and the sources of solutes in the upper Indus River basin in Ladakh, India, through geochemical mass balancing, thermodynamic (saturation indices calculation, stability diagram, phase diagrams), statistical approaches and $^{87}Sr/^{86}Sr$ isotopic systematics.

The study has been conducted for the Union Territory of Ladakh, India, between north latitudes 33° 40’ N and 35° 0’ N and east longitudes 75° 29’ and 78° 10’ E, covering an area of 36,000 km^2 of the Leh and Kargil districts. The region experiences a cold-arid climate. Geologically, the area can be divided into four tectono - stratigraphic zones. From SW to NE these are: Zanskar Zone, Indus-Tsangpo Suture Zone (ITSZ), Shyok Suture Zone (SSZ) and the Karakoram Zone. Groundwater samples were collected from bedrock and over-burden aquifers across four tectono–stratigraphic units of the ITSZ namely: Dras volcanics (DV), Indus Formation (IF), ophiolitic mélange (OM), Ladakh Plutonic Complex (LPC), and the SSZ. Samples were collected from hand-pumps and tube wells after sufficient flushing and field readings were noted. Collected samples were preserved and analyzed for major, minor, and trace solutes and $^{87}Sr/^{86}Sr$ ratios. Cations were analysed in the ICP-OES and anions in an ion chromatograph. For $^{87}Sr/^{86}Sr$ analysis, approximately 2000 ng of Sr was extracted using the BioRad AG 50W 8X resin. Isotopic composition was measured in a MC – ICP - MS in static, multi - collector mode.

Groundwater aquifers are composed of fluvial, fluvio-glacial, aeolian, lacustrine sediments in river valleys and adjoining bedrocks, ranging in composition from ultrabasic to acidic and from carbonate to siliciclastic. Basic hydrogeochemical assessment reveals water temperature varies between 8 - 18°C. Waters are circum – neutral, mildly reducing to oxidizing, and are of Ca-HCO_3 and Ca-Mg-HCO_3 type. Waters plot in the rock weathering domain of the Gibbs Plot and seem to be affected by a combination of carbonate and silicate weathering. Cation exchange occurs minorly. Mass balancing predicts simultaneous dissolution of calcite and dolomite, incongruent dissolution of pyroxenes, feldspars, serpentine, olivine, biotite and chlorite to kaolinite, smectite, vermiculite, and illite. Thermodynamic calculations suggest that waters are sub to super saturated in calcite and quartz, undersaturated in amorphous silica, supersaturated in Fe oxy (hydr) oxides, in equilibrium with kaolinite, and in disequilibrium with feldspars and muscovite.

Groundwater Sr varies from 57 to 3416 µg/L and $^{87}Sr/^{86}Sr$ from 0.7075 to 0.7275. Strontium exhibits moderate positive correlations (with albeit scattering) with other solute parameters while, $^{87}Sr/^{86}Sr$ shows none. $^{87}Sr/^{86}Sr$ also doesn't correlate with 1/Sr and indicators of silicate weathering (SiO_2/TDS, Na* + K/ total cationic charge). Median groundwater Sr/Ca (6800 µg Sr/g Ca) and $^{87}Sr/^{86}Sr$ (0.711) ratios are significantly higher than those of typical carbonates (Sr/Ca: 1000 - 2000 µg/g; $^{87}Sr/^{86}Sr$: 0.707–0.709) suggesting a major input from silicate sources. Groundwater $^{87}Sr/^{86}Sr$ ratios in the IF, LPC, and OM aquifers matches well with the whole-rock $^{87}Sr/^{86}Sr$ ratios of these units, suggesting derivation of solutes from them. However, $^{87}Sr/^{86}Sr$ of DV and SSZ waters are significantly higher than their bed rock values, suggesting prolonged interaction of recharge water with the more radiogenic over burden. $^{87}Sr/^{86}Sr$ signature suggests DV waters are deriving (at least a part) of their cationic budget from the Higher Himalayan Crystalline and Tethyan Sedimentary Sequences derived detritus brought in by the Dras and Suru rivers, while solutes sources to SSZ waters is the LPC.

The work suggests that the groundwater composition in the upper Indus River basin of Ladakh, India, is dominantly controlled by water-rock (aquifer matrix) interaction processes taking place within the subsurface. Although preliminary hydrogeochemical investigations suggest that the waters are affected by a dual carbonate-silicate weathering pathway, significantly higher groundwater Sr/Ca and $^{87}Sr/^{86}Sr$ ratios than those of typical carbonates, suggest a dominance of silicate weathering. Scattering in Sr–solute relationships, lack of a linear trend between 1/Sr and $^{87}Sr/^{86}Sr$ and correlations of $^{87}Sr/^{86}Sr$ with other solutes and indicators of silicate weathering indicate the existence of multiple silicate sources. A variety of silicate minerals, are predicted to weather to kaolinite, vermiculite and illite. Among mafic phases serpentine, olivine, chlorite, pyroxene, and biotite are deduced to be the main solute sources while both plagioclase and alkali feldspars constitute the felsic contributor pool. Groundwater $^{87}Sr/^{86}Sr$ ratios in LPC, IF and OM aquifers matches well with their aquifer matrix values establishing them as their solute sources. Strong mismatch between aqueous and solid phase $^{87}Sr/^{86}Sr$ signatures in DV and SSZ aquifers suggests that the solutes in them are derived from more radiogenic Himalayan sources. The work signifies, the role of weathered residuum and infiltration zone processes in controlling water chemistry of bedrock aquifer systems.

Keywords: *Ladakh, Indus River basin, groundwater, aquifers, Himalayan geology*

GRAVITY-BASED PRESSURIZED PIPE IRRIGATION NETWORKS (GPPINS) USING SPRINGS IN HILLY AREAS: OPPORTUNITIES AND CHALLENGES

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Most of the agriculture lands in hilly areas do not have any irrigation facility. Gravity piped irrigation networks (GPPINs) are generally feasible in hilly areas having perennial springs and surface streams. The GPPINs tap the water in a flowing stream at a certain height on the hill-tops and carry the water through a network of pipes until the delivery points, i.e., the individual lands of farmers. Unlike open channel flow, the water is mostly carried through underground pipelines. A low-head barrier across the stream at the source point is commonly used to rise the water level and divert the water into the pipeline. The water flows under pressure through the pipe network using the static energy of water at the source point. A typical GPPIN consists of five components, viz., water source, main pipeline, branch or sublines, individual delivery pipes and outlets, and minor components for regulation of water flow. The GPPINs typically follow a tree-and-branch type configuration. Based on the physical configuration and flow of water in the network, the GPPINs may be classified into two types, viz., open network and closed network. Open networks will be having main pipeline and all the branch pipelines plugged at their end points. The water will be either delivered through the outlets or remain in pipelines. On the other hand, the closed networks will have closing loops between selected ends of main or branch lines. In the case of open channel and open pipe networks, in the absence of extensive drainage channels, the excess water has to flow from the plot of land to the plot downstream. In contrast, GPPINs permit application of the required quantity of water for the selected crops, effectively preventing excess flow of water to downstream plots. Furthermore, GPPINs permit farmers to rotate crops seasonally as per the soil conditions, local climate and market demand. While farmers prefer to cultivate paddy during the monsoon season, they shift to short-duration less-water-intensive crops like vegetables, flowers, and tubers during winter and summer months. GPPINs deliver water across the command area, by laying of pipelines across undulating slopes as well as against falling slopes. There is no loss of land as most of the piping is done underground. The piping done using UPVC or HDPE (High-Density Polyethylene) lasts for 15–20 years.

Though, there are several advantages of GPPINS, they are not devoid of limitations and disadvantages. The GPPINS require skilled engineers and experienced workers to plan, design and construct them. Skillful pipeline alignment reduces capital costs on pipeline and improves the system performance in terms of lesser head-loss in pipes. The capital costs of GPPINS are relatively higher, though they come with durability and longer functional life. Often, transporting construction materials and machines to remote hill-tops become difficult due to the lack of motorable roads. Though the HDPE pipes cost 20-30% more than the UPVC pipes of the same diameter, HDPE pipes have several advantages. They may be bent easily to follow the curvature in pipeline alignment. HDPE pipes are available as rolls, for diameters up to 110 mm. Though the use of rolls has the definite advantage of reducing the number of joints and lesser time in pipe laying, transporting and handling of rolls of HDPE

pipe is more cumbersome. Pipe joints and valve connects are prone to leakages and breakages, if the GPPIN is designed for pressures more than 10 m at the outlets. Typically, joints between UPVC pipes and between HDPE and UPVC pipes may weaken over time and result in leaks. Such leaks lead to pressure-loss in the system and reduced discharge at some outlets. Therefore, it is important to attend to such minor repair and maintenance works as soon as they are noticed. There are no specific guidelines available for the planning and design of GPPINs in India. Based on the field experiences in India and Bhutan, the practical insights in designing gravity irrigation systems have been narrated here. Gradually falling land slope with an elevation difference of 30-40 m over a ground distance of 1.0-1.5 km between the stream source and the last point is ideal for building GPPINs. Maintaining a pressure of 7-10 m at each outlet point is desirable for optimum cost and performance. Closed-loop design always helps in equalizing the pressure from different outlets. The HDPE pipes emerge as the best choice for these networks owing to their flexibility, durability and ease in assembling of joints. Environmental Protection Agency Network Evaluation Tool (EPANET) software is very useful not only in the design of new GPPINs, but also in simulating the function of existing networks under different water demand scenarios. Overall, GPPINs have a high potential to meet the irrigation water needs of farm lands in many hilly areas, to boost the agricultural production and substantially increase the farm incomes of small farmers.

Keywords: *EPANET, gravity irrigation, irrigation network, pipe flow, hill springs*

INTEGRATING SCIENCE AND COMMUNITY ACTION FOR SUSTAINABLE SPRINGSHED MANAGEMENT IN THE INDIAN HIMALAYAS

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The Hindu Kush Himalayan (HKH) region, often referred to as the "water tower of the Asia," plays a crucial role in providing freshwater to millions of people. However, this region is facing a growing challenge of water scarcity, exacerbated by a decline in spring discharge. This decline can be attributed to a combination of factors including climate change, unsustainable human activities, and increasing water demand. These changes have significant impacts, particularly on rural agriculture, urban migration, and socio-economic stability. A case study conducted in the Kulgad sub-watershed of the Upper Kosi River watershed in Almora, Uttarakhand, sought to address this pressing issue by identifying the importance of stakeholder engagement in springshed management. The study reveals that the decline in spring discharge can be mitigated through a collaborative approach that integrates scientific knowledge with community-driven interventions. The research emphasizes that water management is not solely a technical challenge, but also a matter of human values, behaviors, and political dynamics. Discharge of major streams were measured by using V-notch and current flow meters, while the volumetric method was adopted for the discharge calculation of springs. The river's stage was continuously monitored using an Automatic Water Level Sensor (AWLS), which was installed in a stilling well-constructed from perforated pipes. The AWLS utilized a capacitance-based water level recording system, integrated with a data logger to ensure accurate and real-time monitoring of water levels. One of the key findings of the study is the critical role of public-private partnerships (PPP) and participatory approaches in large-scale spring rejuvenation efforts. By involving various stakeholders, including local communities, government bodies, and private organizations, these approaches create a more sustainable and effective management model. Additionally, the study highlights the importance of capacity development and knowledge transfer as science of springshed management is not so simple like watershed management. This includes training local hydrogeologists, mapping recharge areas, and implementing sustainable land-use practices, which are essential for ensuring the long-term sustainability of water resources. The research underscores the need for a transdisciplinary approach to addressing the challenges of declining these community resources. By incorporating the perspectives of various stakeholders, such as policymakers, researchers, and practitioners; this approach aims to promote sustainable water management. It also aligns with the broader goals of the United Nations Sustainable Development Goals (SDGs), particularly those focused on clean water and sanitation, sustainable cities, and climate action.

The study engages the village community in water conservation, focusing on training locals in smart cash crop-based agribusiness, spring discharge calculation and rejuvenation techniques. By involving women in sustainable agriculture-based startups, the study strives to

achieve gender equity (SDG 5), empowering women to become key players in water and resource management. The study seeks to increase water availability, directly contributing to SDG 6 (Clean Water and Sanitation), and improve the community's economic, physical, and mental well-being, addressing SDG 10 (Reduced Inequalities). By involving the community in water management and sustainable practices, the study promotes responsible consumption (SDG 12). It is also supporting climate-resilient agriculture, like mulberry cultivation, contributing to carbon sequestration (carbon credit) and reducing soil loss, addressing SDG 13. The new line of action in terms of the young generation will be trained to develop young entrepreneurs in the region by linking springshed management to the local livelihood. Ultimately, this will ensure the long-term sustainability of the springs, fostering economic prosperity and community well-being. Our ultimate objective is to restore the region's diminishing water resources, a task that cannot succeed without the active involvement of local villagers. Due to limited empowerment opportunities, villagers have shown little interest in rejuvenation efforts. The region's economic development is hindered by the decreasing availability of water resources. As climate change affects rainfall patterns, rainfed agriculture is in decline, making the need for climate-resilient crops essential for agri-based socio-economic development. Therefore, the empowerment of local villagers and low-income families depends on the rejuvenation of water sources. A key crop for this project will be Mulberry, which has not been widely prioritized in the region. Mulberry leaves are rich in antioxidants, and products derived from both the fruit and leaves such as tea, extract, juice, and jam offer viable solutions for sustainable springshed management and improved livelihoods in the HKH region. In conclusion, the Kulgad case study offers a valuable framework for addressing the issue of declining spring discharge in the HKH region. By fostering a community-centric, collaborative approach and prioritizing knowledge-sharing and capacity-building, it provides a roadmap for managing the region's vital water resources in a sustainable manner.

Keywords: *Hindu Kush Himalaya, sustainable spring water management, transdisciplinary approach, hydrological investigation, social hydrology*

APPRISAL OF HYDRO-CHEMICAL REGIME FOR WATER RESOURCE CHARACTERIZATION IN SOUTHERN PART OF GAULA MICRO-WATERSHED, UTTARAKHAND, INDIA

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The scarcity of freshwater resources has become a harsh reality for many regions, with factors like excessive groundwater abstraction and water pollution exacerbating the issue. This has even been noticed in the upper reaches of the Himalayan region that had remained untouched by human interventions up until recently. The need for management water resources in this region is extremely critical as some of the most prominent freshwater sources originate here and therefore their deterioration would not only affect the freshwater resources in their vicinity, but also create pressure on area in downstream regions. In this view, the study tries to highlight the hydro-chemistry in the southern parts of Gaula micro-watershed, Uttarakhand. This area located at the foothills of the Kumaon Himalayas, has witnessed a drastic rise in human encroachment in recent years. The study focuses on a stretch of about 48.8 km^2 that lies between the upstream parts of Baliya River and Gaula River up until the parts of Haldwani city, located in the alluvial fan of the river system. While the river system is most primary water body in the area, it also has a variety of water sources, ranging from streams and springs that moves along hill slopes in the upstream parts to groundwater occurring in the lower reaches. This transition in natural water sources led to an appraisal of water chemistry included collection and analysis of 13 water samples from different sources (including river, streams, canal, and groundwater from both deep and shallow aquifers) at regular intervals to evaluate their spatial and seasonal variability and vulnerability to contamination using water quality indices. It also included remote sensing-based assessment of the area to review land use changes as well as morphometric characterization of the watershed. Some of the primary observations from the pre monsoon phase of this work revealed some significant inferences to delineate water sources based on their source as well as chemical features.

The pH value of all the water samples range between 7.39 to 8.6 averaging 8.04 indicating slightly alkaline conditions, while EC values range from 28.13 to 1203.13 µS/cm, averaging 453.33 µS/cm. Notably, the Nitrate concentrations, which is common indicator of anthropogenic influences, was confined to water samples from shallow aquifers and ranges from 19.41 to 175.48 mg/L, averaging 38.978 mg/L, among which 2 water samples showed values which was beyond the WHO standards. In addition, the water samples were also viewed for hydrochemical facies variation which highlighted the prominence of Ca-HCO_3 type in all samples. However, when viewed as per the different sources, there was a clear distinction between facies for groundwater and surface water sources. The Ca-HCO_3 type water in the stream and Gaula River system could be distinguished from Na-HCO_3 types facies in shallow aquifer samples in transition area. Similarly, inferences from the Durov Plot showed the when facies were further delineated with respect to EC, majority of the water samples, including from river and springs, remained below 300 µS/cm, with only exception being the handpumps (shallow aquifer) samples. Further, evaluation of hydrochemical character of was conducted using other tools such as the Richard's plot for irrigational suitability and weighted arithmetic water quality index (WAWQI) for vulnerability to contamination. According to Richard's Plot, 25% of the surface water belongs to C2-S2 category, 25% of the surface water belong to C1-S1 category and 50% of the surface water belongs to C2-S1 category. The 50% spring water belongs to C2-S1 category and remaining 50% belongs to C1-S1 category. The 33% of groundwater belong to C2-S1 category, 33% of the groundwater belong to C2-S2 category, 16% groundwater to C3-S1 category and remaining 16% belong to C3-S4 category. The result revealed that surface and springs water are ideal for irrigation purpose while groundwater needs to be treated properly before using for irrigation purpose. Similarly, the WAWQI used in the study showed highly variable values for all water samples ranging from 34.55 to 341.19. However, when observed for separate sources, the average WAWQI values of groundwater was much higher than that of surface water and springs.

The extensive hydrochemical characterization of this area was further explored for both spatial and seasonal variation. While the post monsoon phase of the water quality assessment added a few more insights into the characterization, it was the spatial aspect of the study that gave some critical inferences. The morphometric analysis highlighted the high stream order and distribution of streams and springs, while the land use pattern supported the notion of anthropogenic influence limiting to the lower reaches of the area. It could be proposed that the although the area has been isolated from human activity, the growing development in lower reaches and the disruption of surface water sources have strong effect on water quality. Furthermore, the different sources of water in the area have strong geomorphic control, which seems to be weaning for more urbanized lower reaches of the study area.

Keywords: *Hydro-geochemistry, Gaula micro-watershed, water quality indices, land use pattern, morphometric analysis*

HYDROLOGICAL VULNERABILITY AND DISTRIBUTION OF SPRINGS IN THE LIDDER WATERSHED, KASHMIR HIMALAYA, INDIA

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The Lidder Watershed located in the Kashmir Himalaya, is a vital region for both the local ecosystem and human populations, primarily due to the essential role that springs play in providing water resources. This study examines the spatial distribution and hydrological status of springs within the watershed. Its primary focus is to explore the causes behind spring desiccation and the factors contributing to the growing vulnerability of these water sources. In the Lidder Watershed, springs are crucial to the local hydrological cycle, supporting water supplies, agriculture, and biodiversity. However, recent observations have shown a troubling decline in the discharge of these springs, indicating a potential hydrological crisis. Through field surveys and the analysis of geospatial data, this research maps 82 springs across varying altitudes, geological conditions, and land-use types. Springs are primarily located between 1500 and 1800 m above mean sea level, with a higher concentration near urban areas. Geologically, these springs are situated in areas conducive to groundwater storage and discharge, such as regions with alluvial deposits and Triassic limestone, which exhibit high porosity and permeability. These geological conditions facilitate groundwater flow and storage, supporting the sustained discharge of springs. In contrast, areas with less permeable formations show a lower density or absence of springs, highlighting the critical role of geology in the availability and sustainability of spring water. Despite the relatively high density of springs in certain areas, the study reveals an alarming trend: seven springs have completely dried up, signalling a concerning decline in the watershed's hydrological stability. The drying of these springs indicates an increasing hydrological vulnerability, influenced by both natural and anthropogenic factors.

This study identifies land-use changes, rapid urbanization, and ongoing climate change as the primary drivers of spring desiccation in the catchment. The analysis of the spatial distribution of drying springs reveals a strong correlation with areas undergoing land use changes and rapid urbanization. Urban sprawl significantly reduces the recharge capacity of local aquifers. The conversion of natural landscapes into urban environments, characterized by impervious surfaces like concrete and asphalt, disrupts the natural water infiltration processes. As a result, groundwater recharge is severely limited in urbanized areas, preventing the replenishment of aquifers that supply spring water. Consequently, the groundwater table does not recover quickly enough to sustain spring flow, leading to the drying of previously reliable water sources. Alongside urbanization, climate change is increasingly influencing the region's hydrological patterns. Shifts in temperature, precipitation, and snowmelt dynamics are having a profound impact on local water resources. Altered precipitation patterns, such as reduced snowfall and irregular rainfall events, coupled with changes in snowmelt timing, disrupt the region's natural water balance. Warmer temperatures lead to earlier snowmelt, reducing the water available for groundwater recharge during crucial months. Moreover, erratic rainfall patterns and increased evaporation due to higher temperatures exacerbate challenges in maintaining sufficient groundwater levels. These disruptions are likely to

increase the vulnerability of springs, as the natural recharge processes essential for sustaining these water sources are increasingly interrupted.

The consequences of spring desiccation in the Lidder Watershed are far-reaching, impacting both local communities and surrounding ecosystems. Springs are a critical water source for many rural areas where piped water access is limited. The loss of spring water would significantly affect agriculture, drinking water supplies, and daily life. Additionally, springs are vital for maintaining riparian ecosystems, wetlands, and local biodiversity. The depletion of spring water could lead to the collapse of these sensitive ecosystems, further intensifying the environmental impacts of spring drying. This study provides essential baseline data for managing and conserving water resources in the Lidder Watershed. The findings highlight the need for a comprehensive understanding of the factors influencing spring sustainability, including geological conditions, land-use practices, and climate change. Effective management strategies must account for the complex interplay between these factors. Urban development should be carefully managed to minimize disruption to natural recharge areas, and land-use policies should prioritize the preservation of groundwater recharge zones. Furthermore, water resource management must incorporate climate change projections to address future shifts in precipitation patterns, temperature, and snowmelt timing. To mitigate spring drying in the watershed, adaptive strategies should focus on restoring aquifers, constructing recharge structures, and promoting water conservation. Sustainable urban planning, such as reducing impervious surfaces and utilizing green infrastructure like permeable pavements and rainwater harvesting, can help support groundwater replenishment. Regular monitoring of climate and hydrological variables is essential to adapting to future changes in water availability. This study underscores the region's growing hydrological vulnerability and the need for integrated water resource management that considers geological, anthropogenic, and climatic factors, ensuring the long-term sustainability of spring water for local communities and ecosystems.

Keywords: *Springs, vulnerability, climate change, Lidder watershed, Kashmir Kimalaya*

INVESTIGATION OF GROUNDWATER RECHARGE ZONES IN THE UPPER GANGA BASIN, INDIA

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The groundwater has immense importance in sustaining high-altitude streams during the dry season. Previous studies on groundwater age tracers inferred that shorter groundwater flows having low residence times supply streams and springs at higher elevations, while longer, geochemically mature groundwater flows are sources for streams at lower elevations. Though flatter alluvial terrains are appropriate for groundwater storage but crystalline fracture networks in the mountainous regions can also serve as good aquifers. In shorter groundwater flows, recharge is directly correlated with discharge, whereas longer flows retain recharge for extended periods and are more sensitive to recharge rates. Also, snow-melt pulses contribute more to runoff, inter-flow and soil water whereas, groundwater fraction increases as the pulse is reduced. This creates an importance of researching on the groundwater potential of the Himalayan rivers, particularly how it is vulnerable to recharge rates. In the Himalayan watersheds, streamflow is sustained by snow/glacier melt during the ablation season (May-June), rainfall during the Indian Summer Monsoon (ISM) (July - September), and groundwater during the dry months (December-March). The Main Central Thrust (MCT) zone in the Higher Himalaya is known to be the source of numerous springs, but how it functions as a recharge-discharge zone in the Upper Ganga Basin (UGB) on an annual basis remains unclear.

This study aims to investigate the recharge-discharge zones in the two Himalayan watersheds in the UGB in India using satellite reanalysis data. Our study encompasses the Bhagirathi and Alakananda Basins which are two pristine watersheds in Uttarakhand, India. Originating from glaciers in the Higher Himalaya, these two rivers form sources of the extensive River Ganga, which sustains the livelihoods of nearly half of India's population. In their upper courses, the rivers drain over the Higher Himalayan Crystalline rocks, comprising high-grade meta-sedimentary schists and gneisses. These rivers then cross the MCT zone at elevations of 1000 to 1500 m above mean sea level (amsl) before flowing over the low-grade Lesser Himalayan sandstones, quartzites, and carbonates. The two basins receive an annual average rainfall of 1000 to 2000 mm, with precipitation occurring primarily as ISM rainfall from July to September and as snowfall spells from October to March. For this study, we used hourly data on surface runoff, subsurface runoff, and volumetric soil water layer (VSWL) from 2019 to 2023, across 14 locations in the Bhagirathi Basin and 12 locations in the Alaknanda Basin, covering elevations from 500 to 3000 m amsl. This data was sourced from the ERA5 reanalysis data provided by the Copernicus Climate Change Services at the European Centre for Medium-Range Weather Forecasts (ECMWF). We aggregated the hourly data to a daily scale and calculated an average value for each month, which we refer to as the monthly average data.

The monthly average surface runoff increases by 8-9 times in the peak ablation month (June) and by 5-6 times during the ISM period compared to other months in the Bhagirathi Basin. In the Alaknanda Basin, ISM surface runoff increases by almost 12 times in August, however, no peak is observed in June. Further, June runoff peaks occur between 1500 and 3000 m amsl, while ISM runoff peak is observed between 1000 and 1500 m amsl. The monthly average sub-surface runoff also shows 5-7 times increase during the late ISM (August and September) between 1000 and 1500 m amsl elevation, but no significant increase is seen during the ablation period. The region between 1000 and 1500 m amsl altitude is the MCT zone which is a broad zone of brecciated metasedimentary rocks characterized by faults and fracture networks. The soil-water content also increases with depth in this zone as observed from the VSWL data. The monthly variations of surface, sub-surface, and VSWL are persistent across the years 2019-2023. The annual runoff and VSWL variations in the basins suggest that the MCT zone between 1000 and 1500 m amsl altitude acts as an active recharge–discharge zone in the Bhagirathi and Alaknanda Basins. The snow/glacier melt during the peak melting season (May-June) from higher altitudes percolates within the fractures of the MCT and recharges the carbonate aquifer system of the Lesser Himalaya below 1000 m amsl. Similarly, recharge occurs again during the late ISM (August - September) as indicated by the sub-surface runoff trends. In the early ISM season (July), the stored ablation water along with the rainfall drains over the terrain, and only after sufficient rainfall, the fracture-aquifers of the MCT get recharged. This late ISM recharge emerges as springs and seeps in the valley during the post-monsoon month of October. Our study highlights the importance of the Himalayan thrust zones as potential groundwater recharge zones. The fracture networks of the MCT zone between 1000 and 1500 m amsl in the Bhagirathi and Alaknanda Basins store glacial meltwater and late monsoon rainwater, which sustain the rivers during the dry months at lower altitudes. Further studies could focus specifically on the sensitivity of Himalayan groundwater to climate change.

Keywords: *Upper Ganga Basin, Himalayan aquifer, groundwater recharge, main central thrust, fracture networks*

SPRINGSHED MANAGEMENT IN THE LESSER HIMALAYAS USING A GEOHYDROLOGICAL, GEOSPATIAL AND GEOPHYSICAL TECHNIQUE

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Springs are vital sources of drinking water for mountain communities worldwide. These communities rely heavily on accessible springs for agricultural, household, and economic needs. Beyond domestic and commercial uses, springs also provide the essential base flow for rivers during dry periods. Despite their critical importance, Himalayan springs have been under increasing natural and human pressures, leading to a decline in their discharge over recent decades. Natural factors, such as fewer rainy days and shifts in rainfall patterns, along with human activities like vegetation loss, urban expansion, and the construction of roads and tunnels, are significant contributors to spring depletion. This research aims to conduct a comprehensive analysis of the hydrological factors influencing spring emergence and distribution by developing an integrated approach for effective springshed management in the Kalsi region of Uttarakhand, located in the Lesser Himalayas. Studying the hydrological control factors and recharge structures in accordance with the geological characteristics of the Himalayan region could help rejuvenate these diminishing springs. Springs play an indispensable role in supporting the livelihoods and ecosystems of mountain communities worldwide, providing a primary source of drinking water and serving essential agricultural, household, and economic functions. This study emphasizes the critical assessment of spring occurrence (GWSPZ) and its hydrological drivers as an important concern for institutions responsible for water resource management, regional land use planning, and environmental conservation. This research seeks to improve the understanding of spring hydrology in the Himalayan region.

The study delineates groundwater potential mapping and spring sustainability evaluations by utilizing a combination of GIS-based multi-criteria decision analysis (MCDA) through the Analytic Hierarchy Process (AHP) and geophysical Electrical Resistivity Tomography (ERT) surveys. Numerous factors, directly and indirectly, affect the behavior of springs. So, the methodology involves the selection and analysis of thematic layers controlling the spring emergence based on the literature survey and advice of hydrological experts such as lineament density, slope, lithology, geomorphology, drainage density, rainfall, soil, Aspect, LULC and Normalised Difference Vegetation Index (NDVI). The geology and geomorphological layers were downloaded from the Bhukosh portal. The Digital Elevation Model (DEM) was downloaded from ALOS PALSAR data with a resolution of 12.5 m. The LULC map was created by training the Landsat 8 satellite image samples in a GIS environment using the Support Vector Machine algorithm in ArcGIS software. The vegetation index NDVI was calculated for the Landsat 8 image using the raster calculator in ArcGIS. All the thematic layers were analyzed in a GIS environment with the same resolution. A pairwise comparison matrix was created by allocating weights to various parameters using the AHP methodology. Following the allocation of weights to each parameter and its sub-parameters based on their significance in Spring hydrology, a spring potential map is generated by superimposing and integrating all layers on a pixel basis using a weighted overlay approach inside the ArcGIS environment. This methodology is validated with field-based data, including spring locations and ERT pseudo-sections, ensuring

robustness and reliability. The study used location data of 180 springs collected from the field to validate groundwater potential maps. The relationship between the different thematic layers and the groundwater potential values presents the relative importance of different hydrologic layers in controlling the emergence of springs. A hydrogeological field survey was also conducted to assess the geological conditions that lead to the formation of groundwater pathways channeling toward the spring flow.

The study region is categorized into five distinct groundwater spring potential zones: very low (0.1%), low (5.4%), moderate (39.01%), high (50.7%), and very high (4.75%). Approximately 93% of the research region is classified within the "moderate" to "very good" potential zones. The Receiver Operating Characteristic (ROC) curve indicates that the area under the curve (AUC) was 85%. The 2-D electrical resistivity tomography (ERT) measurements conducted at five sites underscore the significance of shallow preferential and saturated zones in channelizing springs. The findings also highlight the strong correlation between geological structures like fractures, faults, etc., identified by geospatial, hydrogeological survey, geophysical resistivity method, and spring emergence. This study seeks to address this pressing issue by analyzing the hydrological factors that influence spring emergence and distribution. The results demonstrate the efficacy of integrating GIS with geophysical methods to create more precise and comprehensive groundwater potential maps. Through an integrated approach to springshed management in the Kalsi region of Uttarakhand in the Lesser Himalayas, study identified strategies that align recharge structures with the region's unique geological characteristics, ultimately contributing to the rejuvenation of the region's declining springs. This study provides valuable insights for planners and policymakers to develop targeted, region-specific recharge structures and management strategies. The proposed framework contributes to the sustainable management of springsheds, improving water security and resilience for local communities facing climate and human-induced water stress. Future study should focus on more geophysical surveys to understand different types of geological conditions which are governing the springs.

Keywords: *Spring, Himalaya, GIS, AHP, ERT, rejuvenation*

EVALUATING MULTIPLE DATASETS FOR MODELLING SNOW-GLACIER MELT RUNOFF DYNAMICS IN BHILANGANA BASIN, INDIA

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The Himalayas are home to an extensive network of glaciers, which act as significant freshwater reservoirs feeding major river systems. These play a crucial role in shaping the hydrology and climate of any region. These glaciers are essential for sustaining hydrological processes, agricultural productivity, and ecological balance. However, in recent decades, accelerated glacier melting due to climate change has raised serious concerns about long-term water availability and the stability of hydrological systems. This study evaluates the impacts of climate-induced snow and glacier melt runoff on the total discharge of the Bhilangana River Basin, a significant tributary of the Bhagirathi River in Uttarakhand, India. The study area is located in the Garhwal Himalayas of the state and the total area of basin is around 1500 km^2. One of the major Glacier presents in the basin is Khatling glacier, whose terminus is the source of origin of the Bhilangana River. Being dependent for its discharge, primarily on glaciers, future climate change projections and impacts make this river more vulnerable. The Spatial Processes in Hydrology (SPHY) model was employed to simulate the hydrological processes governing snow and glacier melt runoff in the basin. SPHY model is well known for its capabilities to simulate the snow-glacier induced melt runoff dynamics particularly for Himalayan areas. To set up the model, sensitivity analysis was carried out to identify critical model parameters and their influence on discharge simulation, enhancing the model's calibration and validation accuracy. Parameterization is one of the pre-requisite steps to allow the model to simulate the various scenarios based on the data and other climatic conditions. Available precipitation and temperature global gridded satellite products such as ERA5 (0.25 x 0.25^o resolution), IMDAA (0.125 x 0.125^o resolution), IMD (0.25 x 0.25^o resolution for precipitation and 1 x 1^o resolution), and APHRODITE (0.25 x 0.25^o resolution), were downloaded for the study area and used comprehensively to analyze snow glacier melt dynamics for the period 2020-2023. Data for the model setup period (i.e. precipitation, average temperature, minimum temperature and maximum temperature) were extracted from the downloaded nc files into csv files using the python script. Widely used RGI 7.0 inventory was used to delineate the glaciers present in the basin. Statistical evaluation of the model results was done using the Nash–Sutcliffe efficiency (NSE), Coefficient of determination (R^2), and mean bias between the observed and simulated dataset.

The model results showed that the utilized satellite products, known for their high temporal and spatial resolution, effectively captured variations on total discharge generation which is the sum of snow q, base q, glacier q and rain q. The performance matrix revealed that the ERA5 dataset performed better than other datasets with an R^2 of approximately 0.74, NSE of 0.72, and a bias of -4m^3/s on a daily time scale. These values suggest that the ERA5 dataset reliably captures the hydrological dynamics of the basin, with minimal deviation from observed data. The relatively high R^2 and NSE values highlight the model's accuracy in simulating snow and glacier melt processes, while the bias of -4 indicates a slight underestimation of runoff in the model. Subsequently, scatter plots showed a strong agreement between the observed and modeled runoff values. The average variation during

2000-2023 in snow q was found in the range of 12 to 25%, rain q from 10 to 60%, glacier q from 60 to 20% and base q from 10 to 20 %, respectively while moving from selected high elevation points to low elevation points inside the basin. The analysis further revealed that 11 parameters were found to be critical in influencing the model's output e.g. Degree Day factor for snow (DDFS), Glacier debris degree day factor (DDFG), Tcritical, Glacier melt frac runoff. Degree day factor for snow and glaciers are crucial parameters which should be finalized combing the literature values with the hit and trail approach. Also, critical temperature needs to be adjusted based on the local conditions, and practically can vary from zero degrees in most of the cases. The study also suggest that the debris cover should be properly delineated to account for change in glacier melt fraction runoff.

The study finding reinforces the suitability of satellite gridded datasets in absence of station rainfall data of the area. The applicability of ERA5 dataset is well reinforced for hydrological modeling in glaciated basins like Bhilangana, for providing a reliable basis for future predictions. However, continuous monitoring and refinement may be necessary to further reduce model biases and improve the accuracy of runoff projections under changing climatic conditions. By focusing on the critical parameters, analysis can better provide a deeper understanding of the system's sensitivity, facilitating better decision-making in glaciated basins. Furthermore, this research underscores the suitability of the SPHY model for analyzing snow-glacier melt runoff dynamics and the importance of integrating multiple climate datasets to accurately predict the water resource scenarios in glaciated basins.

Keywords: *Bhilangana, glaciers, SPHY, degree day factor, ERA5*

MAPPING AND MANAGING OF SPRINGSHED FOR WATER CONSERVATION USING GEOSPATIAL TECHNOLOGY IN KALIMPONG DISTRICT OF DARJEELING HIMALAYA, INDIA

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Spring is a natural discharge point of groundwater system. Many of India's rivers, both large and small are formed from springs. More than 15% of the populations of India rely on natural springs for all or part of their water needs. In the mountainous districts of the Indian Himalaya Region (IHR), millions of people and their livestock depend on springs as their main source of water. Spring water is an essential life sustaining resource to the people living both in rural and urban areas of IHR for their agricultural, domestic and drinking purposes. The groundwater movement, which is usually discharged as spring water, is influenced by the underlying geology, lineament and the characteristics and slope of the rock’s beds located below the surface. Springshed of a particular spring is an area of recharge to discharge point of spring including aquifer and its movement. The complex geology of the Himalayan region, characterized by folds and fault structures, often reshapes springsheds. The conservation of springsheds involves protecting the IHR ecosystem that feeds the spring water supply from the land surface to the groundwater. Effective springshed conservation techniques often include the factor of land use practices in the IHR agriculture production Roots from trees, grasses, and shrubs improve soil structure and allow for better infiltration of water into the ground. Long-term spring flow in the springshed depends on sustainable water use. Regular monitoring of the spring's water quality and quantity, together with changes in the surrounding land use, can help identify possible issues early. Integrating geospatial technology and hydrological modeling techniques, this study attempts to delineate the springshed and spring water conservation.

The study area covers entire Kalimpong district situated at an average altitude of 1250 m above mean sea level (amsl) on the eastern part of Darjeeling Himalayas of West Bengal splitting from the Darjeeling district. The district of Kalimpong is one of the northern districts under the jurisdiction of West Bengal lying on the lesser Shivalik Himalayas. The drying of springs during the lean season has led to acute water shortages and great distress to the people of Kalimpong District along with their livestock. A conceptual hydro-geological layout is developed which serves as the basis for identifying the springshed (recharge zone, aquifer, flow direction and discharge point). Springshed mapping are done using Remote Sensing (RS), GIS and Global Nevigation Satelite System (GNSS) with a field survey identifing the rock type and structures around the springs and other factors. The main factors considered in the present study, which are influential to the occurrence of a Spring Recharge Zone (SRZ), are Rainfall, Slope, Geology, Lineament, LULC, NDVI, Soil (Hydrological Group), and Land Gravity. The spring discharge points are then identified using field survey by handheld GPS and secondary data. A vector-type spatial database has been obtained by transforming raster to vector format using the digital elevation model (DEM) for deliniationg spring recharge zone by overlay analysis, which represents the quantitative relationship between spring occurrence and different causative parameters as there is a perfect linear relationship exists among them. The Landsat and SRTM DEM (30 m) data have been

collected from USGS earth explorer whereas Soil HSG map from NASA EATHDATA, rainfall data from IMD, Geomorphology, Geology and Land Gravity data from Geological Survey of India, Spring location and typology data have been collected from CGWB. The rock's strength is determined by its geological structure. There are two geological layers in the Kalimpong district: undivided Paleozoic rock and undivided Precambrian rock. The maximum elevation of the Kalimpong area ranges from 660 m to 3124 m amsl. Very high maximum relief is found in a small portion of northern Kalimpong, high maximum relief is found in the northeastern part of Kalimpong and very low maximum relief is found in a small southern area of Kalimpong. These geological beds make up 40.70% and 59.30% of the study area, respectively. The northern middle section of Kalimpong contains undivided Paleozoic rock, whereas the remaining portion is covered with undivided Precambrian rock. Finally, the springsheds are created using the various thematic maps and field-based expertise and knowledge.

The investigation has revealed that the type of spring sources are Fault springs, Fracture springs, Perennial springs, and Seasonal springs which are collectively contributing to the needs water of the local population and feed the river. The results indicate that the predominant land-use type in the Kalimpong-I and Gorubathan blocks are settement and agricultural, whereas in the Kalimpong-II block is the main land cover type consist of forest and farmlands. Conceptual framework of the springshed has been developed and the different types of springs were categorized indentifying the boundary of springshed. The outcome of this research work is expected to make a strong foundation for springshed delineation and used for water conservation in future. Proper spring water management is necessary for the development of rejuvenating springs in order to sustain soil fertility by preventing soil and water erosion and promoting horticulture. The conservation technique and management strategies of springsheds help with ensuring the sustainability of natural water resources for agriculture, ecosystems, and people. This makes it possible to employ timely interventions and flexible management techniques, such as changing land use type or replanting plants. For springshed conservation initiatives to be successful in the future, local residents must be involved. Better practices at the individual, community, and governmental levels may result from this study on the value of springs and strategies for their protection.

Keywords: *Spring water, springshed, spring recharge zone, hydro-geology and geospatial techniques, Indian Himalayan region*

INVESTIGATING THE GEOCHEMICAL CHARACTERISTICS OF SPRINGS AND GROUNDWATER POTENTIAL IN ASSAM HILLS FOR SUSTAINABLE SPRINGSHED MANAGEMENT

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Springs are vital water sources for millions residing in hilly and mountainous regions. Factors influencing spring discharge include underground rock cavities, aquifer pressure, basin area, rainfall, and human activities like groundwater extraction. It has been reported by previous researches that India's springs are facing water scarcity due to groundwater overuse with increasing population growth and climate change. Recommended strategies for effective springshed management include hydrogeological mapping, discharge monitoring, water quality assessment, and recharge modeling, etc. Studies show that springs can be contaminated by waste disposal, agricultural runoff, and other human activities. Thus, monitoring physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), major anions (HCO_3^-, Cl^-, NO_3^-, PO_4^{3-}, SO_4^{2-}), and microbial contaminants is essential for evaluating spring water quality. Certain regions like Assam, where spring water is presumed pure, have seen less focus on water quality. This study explores both the hydrogeological settings and water quality of springs in the hills of Assam's Dima Hasao district, where these parameters are not well documented. During the dry season of January 2024, 46 spring locations were examined. GPS coordinates, slope, rock types, and land use data were collected, along with discharge rates measured by recording the time taken to fill a container. The springs, found in fracture zones joint planes, and contact zones between residual soil and bedrock with varying elevations. Discharge rates ranged between 0 to 12 liter/minute (lpm) with a mean discharge of 2.38 lpm. All are non-thermal springs, with temperatures less than 37°C. They can also be categorized as fracture/joint springs and depression springs based on geology. As per Meinzer's classification, springs are ranked as sixth, seventh and eighth magnitude. Field water quality testing kit was used to measure pH, TDS, EC, and temperature. Major cations and anions, Fe were analyzed following the standard procedures of APHA using flame photometer, spectrophotometer, volumetric titration methods as required. All the parameters were within acceptable values of WHO and BIS Standards. Water types identified included Ca-Mg-Cl-SO_4, mixed Ca-Mg-Cl, and Ca-Mg-HCO_3, indicating mixed temporary and permanent hardness. Precipitation is found as the primary factor controlling the water chemistry. The off-axis integrated cavity output spectroscopy method was used to determine the $\delta^{18}O$ and $\delta^{2}H$ concentrations in the Liquid-Triple Isotopic Water Analyzer (L-TIWA). The analysis of stable hydrogen and oxygen isotope indicated the contribution of recycled moisture to local precipitation with a few secondary evaporative effects. The Water Quality Index was calculated for drinking water suitability based on basic chemical parameters. For irrigation, indices like Sodium Adsorption Ratio, Sodium Percentage, Residual Sodium Carbonate, and Permeability Index were used.

Water Quality Indices from chemical parameters showed that most springs had excellent to good water quality for drinking. All springs are suitable for irrigation as per irrigation indices. Most Probable Number (MPN) determination by following APHA. Findings from bacterial analysis showed significant faecal contamination in all springs. Thematic layers including slope, drainage density, lineament density, land use land cover, geomorphology, and lithology were generated using remote sensing and GIS techniques to delineate Groundwater Potential Zones (GPZs). Analytical Hierarchy Process was used for factor weighting, the consistency Index and consistency Ratio verified the accuracy of these weights for GPZ mapping. Weighted overlay analysis was conducted in ArcGIS 10.8.2 software. GPZ mapping revealed that 58.20% of the total area had moderate groundwater potential, while 26.65%, 13.04%, 2.09%, and 0.03% had high potential, poor potential, very high potential, and very poor potential respectively. The occurrence of springs in the area is compared with the GPZs and results have shown that the occurrence of sixth, seventh and eighth magnitude springs was located in predicted very high, high, moderate, and poor potential zone areas. The findings from this study were crucial for springshed management, indicating areas where artificial recharge structures may benefit spring discharge. Although the quality is good for drinking and agricultural purposes based on chemical parameters, adequate treatment of spring water is essential because of the microbial contamination. Considering seasonal variations in spring water discharge and quality, mapping groundwater and groundwater springs potential zones, constructing artificial recharge structures can contribute to effective water management in the hills of Dima Hasao and similar regions facing climate impacts. The study highlights the importance of regularly monitoring spring resources in Dima Hasao hills, artificial recharge to maintain spring discharge amidst climate change, aiding policymakers in crafting sustainable management plans to meet the UN's sustainable development goals XIII (climate change action).

Keywords: *Spring, groundwater, groundwater potential, springshed management, water quality indices*

SPRINGS WATER QUALITY EVALUATION USING WATER QUALITY INDEX AND GEOSPATIAL TECHNIQUES IN BHILANGANA BLOCK OF TEHRI GARHWAL DISTRICT, UTTARAKHAND, INDIA

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As natural sources of groundwater, springs have long been vital to human communities, particularly in mountainous and rural regions, offering a reliable and sustainable water supply. These water sources typically emerge from an aquifer, creating a visible flow on the Earth's surface. They are highly regarded for providing relatively pure water compared to other bodies such as rivers and lakes. In regions like the Indian Himalayan Region (IHR), the Western Ghats, the Eastern Ghats, and the Satpura and Vindhya Mountain ranges, spring water is essential for the survival of over 200 million people. In these areas, springs not only serve as a crucial drinking water source but also have cultural significance and serve agricultural and domestic needs. In particular, the Bhilangana block in the Tehri Garhwal district of Uttarakhand has a long-standing tradition of depending on springs for drinking water. Springs are often considered one of the most sustainable and reliable sources of groundwater due to their natural replenishment and relatively fresh water. However, spring water quality can vary significantly due to various factors, including the composition of the aquifer materials, local environmental conditions, and human interventions such as deforestation, urbanization, and contamination from agricultural runoff or sewage. Therefore, ensuring the safety of spring water for human consumption becomes critical, especially in the context of changing climate patterns, increased population pressures, and the potential deterioration of water quality over time. The Bhilangana block, located in the mountainous region of Uttarakhand, exemplifies these challenges, with spring water being the primary source for drinking and domestic use. This study aimed to assess the suitability of natural spring water for human consumption in the Bhilangana block of Tehri Garhwal district, focusing on the water quality of springs in Silyara, Holta, and Devlang villages.

Springs water samples were collected post-monsoon season when water quality is most susceptible to seasonal variations due to rainfall patterns and runoff changes. The study analyzed several key water quality parameters: temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), hardness, alkalinity, chloride, calcium, and magnesium. These parameters are crucial for understanding the chemical composition of spring water and assessing its safety for drinking. The results revealed notable differences in the water quality among the three springs, with varying concentrations of dissolved minerals that affect the water's taste and safety. For instance, the spring in Silyara village exhibited higher concentrations of EC (140 µS/cm), TDS (120 ppm), hardness (126 mg/L), calcium (34.4 mg/L), and alkalinity (120 mg/L), suggesting that the water had a higher mineral content. While this may impart a stronger taste to the water, the concentrations of these minerals remained within acceptable limits, making the water suitable for consumption. By contrast, the spring water from Holta village displayed moderate mineral content, with lower levels of hardness (42 mg/L) and alkalinity (32 mg/L). This made the water softer and palatable, likely appealing to people who prefer water with a lighter taste. In contrast, the water from the spring in Devlang village contained the lowest levels of dissolved minerals with values of 40 ppm for TDS, 24.0 mg/L for hardness, 6.4 mg/L for calcium, and 22.0 mg/L for alkalinity, making it the softest of the three. While the water from Devlang village is ideal for individuals who prefer low-mineral water, it may lack the characteristic taste associated with water that contains higher mineral content.

The study applied the Weighted Arithmetic Water Quality Index (WAWQI) method, a commonly used approach combining multiple water quality parameters into a single value, to understand overall water quality. The WAWQI assigns weights to different parameters based on their relative importance in determining drinking water safety. Using this method, the study classified the water from all three springs as falling within the 'Good' quality category, indicating that the water is safe for consumption and does not pose significant health risks based on the analyzed parameters. In addition to the water quality analysis, the study incorporated GIS techniques to understand the spatial distribution of water quality parameters across the study area. The Inverse Distance Weighted (IDW) interpolation method was employed to create spatial maps that visualize the distribution of temperature, pH, EC, TDS, hardness, alkalinity, calcium and magnesium for each spring. The study results provided valuable insights into the spatial variability of water quality. It helped identify potential areas of concern, such as regions where water quality may be slightly more compromised due to local environmental factors or human activities. By visualizing the data in spatial terms, the study enabled a more comprehensive understanding of the geographic patterns in water quality across the Bhilangana block, which could inform targeted water management practices. The findings of this study highlight the overall good quality of spring water in the Bhilangana block and suggest that it remains a viable and safe source of drinking water for local communities. However, the study also emphasizes the need for ongoing monitoring and sustainable management of these water resources to ensure their long-term viability. The combination of water quality indices and GIS-based spatial analysis provides a robust framework for assessing water quality in natural springs, offering valuable information for local authorities and communities engaged in water resource management. Furthermore, the results of this study can inform future strategies aimed at safeguarding the quality of spring water, addressing potential risks, and ensuring that these vital water sources continue to support the health and well-being of the dependent populace.

Keywords: *Drinking water, natural springs, GIS interpolation, spatial distribution, water quality index*

MODELLING STREAMFLOW DYNAMICS AND CLIMATE SENSITIVITY IN THE GANGOTRI GLACIER WATERSHED

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Glaciated watersheds are highly sensitive to climate change, with streamflow dynamics influenced by multiple factors such as glacier melt, snowmelt, rainfall, and temperature. Effective water resource management in these regions requires an understanding of the complex interactions between climate factors and hydrological processes. This study models the streamflow of the Gangotri Glacier Watershed, located in the Central Himalayas, which covers an area of 548 km², of which 48.4% is glacierized. The watershed is particularly important due to its contribution to downstream river discharge, which serves as a crucial water resource for the region. To model the hydrological processes of the watershed, the SPHY (Spatial Process in Hydrology) model was employed, which is capable of simulating the dynamics of water fluxes in glacierized regions. The climate forcing data, derived from NASA's Prediction of Worldwide Energy Resources (POWER) dataset were used. Due to potential biases in the climate data, temperature and rainfall data was corrected using observed meteorological records from Bhojwasa weather stations. Specifically, temperature data was bias-corrected using an additive scaling method, while rainfall data was corrected with a multiplicative linear scaling approach. This bias correction ensures that the model's inputs are more representative of the local climate conditions, allowing for more accurate simulation results.

A sensitivity analysis was conducted to understand the influence of various model parameters on the simulated streamflow. Sixteen parameters including the degree-day factor (DDF), recession coefficient (kx) and other parameters governing snow and ice melt were tested for their sensitivity. The analysis revealed that the DDF, which controls the rate of glacier melt, and the recession coefficient (kx), which governs the rate of flow recession during the dry season, were the most influential parameters affecting discharge predictions. This highlights the critical importance of accurately determining these parameters, particularly in glacierized catchments, where melt processes are key drivers of streamflow. For model calibration, observed discharge data from 2017 to 2019 were used. The model was calibrated by adjusting the key parameters until simulated streamflow closely matched the observed discharge values. The model was then validated using discharge data from 2022 to 2023. The validation process demonstrated that the model could accurately reproduce observed streamflow, with improvements in simulation accuracy during the validation period compared to the calibration period. This indicates that the model is robust and reliable for simulating streamflow in the Gangotri Glacier Watershed.

Using the corrected climate data and calibrated model parameters, a continuous simulation was performed from 2016 to 2023. The analysis revealed that approximately 90% of the streamflow occurred during the ablation period (May to October), which coincides with the primary monitoring period of this study. The model simulation showed that streamflow peaked during the months of July and August. This peak was primarily driven by the simultaneous contributions of increased glacier melt and rainfall during these months. This finding aligns with field observations, where significant glacier melts and intense rainfall

events were recorded in the region during this period. The contributions of different hydrological components were analysed for each month. Rainfall contributed significantly to streamflow from July to October, while snowmelt contributed mainly from March to June, coinciding with the melting of accumulated snow. The glacier melt contribution, which is heavily dependent on temperature was highest during the months of August and September, when both high temperatures and intense solar radiation cause rapid ice melt. The base-flow component, representing groundwater contributions, remained relatively constant throughout the year, providing a steady contribution to streamflow even during the winter months when glacier and snowmelt contributions were minimal.

The study also observed notable variations in streamflow across the years. The flow variability appeared to increase over the study period, with streamflow sustaining longer into the ablation season. This was particularly evident with more pronounced flow peaks observed in September, indicating a delayed discharge response due to increased glacier melt later in the ablation season. This suggests that warming temperatures and changing precipitation patterns are influencing the timing and magnitude of streamflow in the region. One of the most significant findings of this study is the increasing flow variability observed over the 8-year simulation period. This variability could be attributed to the complex interplay between glacier melt, snowmelt, and rainfall. The influence of localized intense precipitation events, which are becoming more frequent and severe due to climate change, may be amplifying flow variability. These extreme events contribute to higher peak discharges and increased sediment transport during the ablation period, further complicating hydrological dynamics.

The results of this study underscore the critical role of temperature in regulating streamflow in glacierized watersheds. Rising temperatures not only accelerate glacier melt, but also interact with precipitation patterns to intensify flow variability. These findings highlight the vulnerability of glaciated regions to the impacts of climate change, particularly in terms of water availability and flood risks. The increased frequency of extreme precipitation events may also lead to more frequent and severe flood events, posing challenges for water resource management and infrastructure in downstream areas. In conclusion, this study provides valuable insights into the hydrological processes of the Gangotri Glacier Watershed and the sensitivity of streamflow dynamics to climate change. The findings emphasize the importance of accurate climate data, appropriate model calibration, and understanding the role of temperature and precipitation in regulating streamflow. The results also highlight the need for ongoing monitoring of glaciated watersheds to better predict the impacts of climate change on water resources in regions dependent on glacier and snowmelt contributions. These insights are crucial for improving water resource management strategies in the face of a rapidly changing climate.

Keywords: *Streamflow, glacier, Himalaya, climate change, hydrological modelling*

ENVIRONMENTAL ISOTOPES FOR MANAGEMENT OF SPRINGSHED IN THE KHULGAD WATERSHED OF KOSI RIVER CATCHMENT, KUMAUN LESSER HIMALAYA, INDIA

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The springs are the external face of groundwater, which emerges through fractures or slopes, generally found in mountainous terrains around the world. In India, a total of 5 million springs are identified, out of which 3 million are located in the Indian Himalayan Region (IHR). Spring water is essential for mountain communities, especially those living at the mountaintop without direct access to river water to meet their drinking and domestic needs. Springs sustain the base flow of streams during the lean season. The spring discharges in the Kumaun Lesser Himalayan region are showing a declining trend. The cumulative effects of changing land use trends, anthropogenic activities, and climate change may trigger the dwindling discharge of the springs, leading to an acute scarcity of water. Therefore, it is indeed to delineate the spring recharge zones (i.e., Springshed) in order to rejuvenate the springs in the Himalayan regions. Hence, an attempt has been made to delineate the springshed in the Mattella village of the Khulgad watershed, Almora district, using stable isotopes of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) as well as to understand the recharge processes of the springs.

The stable isotopes (i.e., $\delta^{18}O$ and $\delta^{2}H$) have been widely applied in hydrological studies to trace water origins, movement, recharge source, and interactions within various hydrologic systems, offering crucial insights into these processes. The isotopic signatures of $\delta^{18}O$ and $\delta^{2}H$ in groundwater and precipitation are helpful in estimating the possible altitude of recharge zones. The altitude effect of the precipitation is an important factor which helps to estimate the recharge altitude of the spring water. As water vapor ascends and cools, heavier isotopes (^{18}O and ^{2}H) condense first, leaving the remaining vapor isotopically lighter, a process that leads to precipitation at higher altitudes or latitudes having lighter isotopic compositions. For instance, precipitation from higher elevations or specific seasons may exhibit unique isotopic compositions, which can be traced in groundwater to pinpoint the recharge sources, a critical step for water resource management, especially in regions heavily reliant on groundwater. To investigate these spatiotemporal variations, rain gauges were installed at three different altitudes within the study area for rainwater collection. Event-based rainwater sampling was collected from December 2020 to December 2021, with each sample collected in 15 ml high-density polyethylene (HDPE) bottles, securely capped with an inner lid and screw cap to maintain sample integrity. The regression line of the Local Meteoric Water Line (LMWL) was developed by the rainwater samples collected from the different altitudes. To understand the altitudinal variations of rainfall from different elevations, the isotopic characteristics of the monthly average rainfall have been analyzed for three different altitudes. Isotopic compositions of surface waters (rivers, lakes, canals) and groundwater (springs) often differ due to the unique sources and processes influencing them. By comparing $\delta^{18}O$ and $\delta^{2}H$ values, the interaction between these water bodies can be assessed; for e.g., a river significantly influenced by groundwater input will have an isotopic signature closer to that of the local groundwater. The identified spring of the Mattella village is located at an altitude of 1364 m above mean sea level (amsl) and serves as the sole source of drinking water and domestic needs for the local communities. Geologically, the study area comprises Schist rocks interbedded with the quartzite, which are fractured in nature. A total of 19 rainwater samples were collected from the three stations (Khoont, Sitlakhet, Nainital) at different altitudes. Similarly, the monthly spring isotopic signature was measured. The ^{18}O and ^{2}H signatures of the precipitation and spring are used to estimate LMWL. The monthly isotopic values of precipitation of $\delta^{18}O$ and $\delta^{2}H$ were plotted with the altitude to establish the rain altitude effect.

The altitude effect of $\delta^{18}O$ is 0.28 ‰ per 100 m rise in elevation, and the altitude effect of ^{2}H is 2.2‰ in the 100 m rise in elevation. Based on this analysis, the projected recharge area for the Mattella Spring is identified at an altitude of 1682.1 m amsl, which is approximately 318.1 m above the spring discharge site. Based on the hydrogeological and isotopic studies, it is recommended that recharge pits be constructed in the village of Mattella between the altitude of 1400 and 1682.1 m amsl. to ensure adequate rainwater recharge for the springs. Beside constructing recharge pits, several complementary measures can further augment spring discharge and ensure sustainable water availability for the community, such as contour trenches, additional percolation pits, and check dams that can be strategically placed within the recharge zone. Contour trenches help capture and infiltrate rainwater, while check dams slow down the flow of water, allowing it to seep into the aquifer. Similarly, Nala bunds and percolation shafts can increase the retention and percolation of rainwater. When implemented alongside the recommended recharge site, these additional measures can significantly enhance the spring discharge in the Mattella spring. Also, it is indeed important to involve the stakeholders in the awareness and need for rejuvenation and use their traditional knowledge for spring rejuvenation. A holistic approach combining scientific, ecological, and community-driven strategies ensures sustainable spring water availability for drinking and domestic purposes while preserving the recharge zone for future generations.

Keywords: *Springs, dwindling discharge, rejuvenation of spring, stable isotopes, recharge zone identification*

LAND SURFACE TEMPERATURE DYNAMICS IN A LESSER HIMALAYAN CATCHMENT

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Land Surface Temperature (LST) is a critical element of the Earth's weather and climate system, influencing energy and water exchanges between the land and atmosphere. It impacts glaciers, permafrost, vegetation, and crop water needs, serving as a key input for weather, climate, hydrological, and ecological models. Designated an essential climate variable by the WMO's in 2016, LST is widely used in weather prediction, evapotranspiration analysis, land use/land cover (LULC) change, drought monitoring and biodiversity research. LST represents the radiative skin temperature of the land, incorporating emissions from bare soil and vegetation canopies. Recognized as a key earth system data record by NASA, it reflects energy partitioning at the land-atmosphere interface and is sensitive to surface changes. Unlike air temperature, LST provides detailed insights into latent and sensible heat fluxes, vegetation density, surface roughness, and transpirational cooling, making it indispensable for understanding surface energy and water balances. The fragile Himalayan foothills, are witnessing abrupt shifts in seasonal patterns and extreme temperature variations, with recent years experiencing unprecedented LST spikes exceeding 49°C. These alarming trends necessitate a comprehensive investigation into the factors driving these changes. This study analyses spatiotemporal variations in LST across the Henval catchment, a minimally disturbed catchment spanning 254 km² in the Tehri Garhwal district of Uttarakhand. The catchment, comprising forested areas, agriculture, and the urbanized region of Chamba, serves as a benchmark for hydrological studies in the Lesser Himalayas. Using multi-temporal satellite (Landsat 8&9) datasets, processed on the Google Earth Engine platform, this study examines LST patterns w.r.t. elevation and longitudinal distance along the valley over four seasons (i.e., pre-winter, winter, summer & monsoon) between 2019-2024. Seasonal mean and 15-day interval LST data were analyzed across four longitudinal profiles mapped using ArcGIS: (i) valley, (ii) left ridge, (iii) right ridge and (iv) a road network connecting both the ridges and running adjacent to a right ridge. The study incorporated Sentinel-2-based LULC dynamics and ASTER-DEM-derived topographical attributes such as elevation and aspect or orientation to contextualize the observed temperature trends.

The annual mean LST shows a notable increase across all four profiles, with mean differences from 2019 to 2024 recorded as 10.24°C (valley), 6.13°C (right ridge), 4.35°C (left ridge), and 5.73°C (road network). The six-year mean LST highlights a ~1°C difference between the left and right ridges, while the valley is significantly warmer, exceeding both ridges by over 13°C. Despite representing valley slopes and a part of the right ridge, the road network's six-year mean LST also surpasses both ridges by nearly 10°C. Seasonal six-year LST averages reveal similar warming patterns for the ridges and road, following the order: winter, monsoon, pre-winter, summer. However, the valley exhibits a different sequence: winter, monsoon, summer, pre-winter. Notably, the difference between six-years summer and pre-winter LST averages is minimal for the valley (0.11°C) and road (0.67°C), but much higher for the left (7.37°C) and right ridges (10.55°C). The overall six-year seasonal mean LST difference is 6.46°C (valley), 14.83°C (left ridge), 12°C (right ridge), and 9°C (road), indicating that ridges and road are more sensitive to seasonal changes compared to the valley.

Additionally, the left ridge and road show a decreasing LST trend with increasing elevation, whereas the valley and right ridge display an opposite pattern over the 2019–2024 period. Abrupt temperature spikes in second half of May 2023 and 2024 indicate intensified summer warming. In May 2023, temperature fluctuation zones were observed: in the valley of 41 km in length (at 27.46–33.78 km from the outlet, elevation 922.32–1437.20 m), on the right ridge of 44 km in length (at 35.71–39.47 km, elevation 1368–1871 m), and on the left ridge of 43.5 km in length (at 2.52–5.37 km, elevation 1492–1513 m). By May 2024, these warming zones expanded, reflecting increased warming at both lower and higher elevations in the valley and left ridge, while shifting to higher elevations along the right ridge. The catchment elevation ranges from 379.83–1983.2 m above mean sea level (amsl) in the valley and 379.83–2673 m amsl for the ridges. To analyse LST fluctuations during the second half of May in 2023 and 2024, buffer zones were created, considering the extreme elevation points/width of identified fluctuations zones covering the area on either sides within a radius of 5 km for the valley (flat terrain) and 2.5 km for ridges (accounting for walkable distances in hilly areas). From 2019 to 2024, 15-day LST of second half of May 2023-24 data showed a consistent trend of decreasing temperatures with rising elevation in the valley and road profiles, with similar behavior on the right ridge, except in 2020 and 2024. However, the left ridge disrupting typical temperature-elevation relationships and exhibited a significant shift starting in 2021, with temperatures increasing with elevation, reversing the trend from 2019–2020. These variations may result from localized LULC changes such as deforestation, urbanization, the presence of water bodies/springs, or microclimatic factors like anabatic-katabatic flows, diurnal heating and nighttime radiative cooling. In contrast, the valley's stability suggests minimal climatic disruptions and efficient diurnal heat retention.

LULC dynamics was analyzed and assessed anthropogenic influences within defined buffer zones. On the right ridge, five LULC classes namely forest, agriculture, built-up, barren land, and range land were identified, whereas the left ridge and valley had four classes, lacking agriculture and barren land, respectively. From 2019 to 2023, the right ridge experienced a substantial 14.7% increase in built-up areas, rising from 18% to 32.7%, with the highest growth (3.8%) occurring between 2023 and 2024, reaching 36.5%. Similarly, the left ridge reflects built-up areas increase from 25% (2019) to 31% (2024). In the valley LULC changes are more prominent, as agriculture declined from 20% to 14%, built-up areas rose by 13.1% (28% to 41.1%), and range land decreased by 6% (44% to 38%). Other LULC classes on both ridges showed a consistent decline over the five years. These intensified anthropogenic activities and reductions in vegetative cover correlate with the temperature increases observed in 2023–2024: 2.59°C in the valley, 1.53°C on the right ridge, and 1.28°C on the left ridge. Analysis of aspect or orientation using DEM revealed that 52% of the right ridge area is sunlit, with 24% in the opposite direction. For the left ridge and valley, sunlit areas account for 39% and 38%, while shaded areas comprise 30% and 32%, respectively. Thus, by integrating LST trends, LULC changes, and topographical factors, this study identifies key drivers of regional warming and extreme temperature variations in the Himalayan foothills. These findings not only inform adaptive strategies and climate resilience efforts in this ecologically sensitive region but also provide a framework for future research. By connecting localized observations with broader climatic trends, the study highlights the need for proactive measures to protect vulnerable ecosystems and communities amid accelerating climate change.

Keywords: *Land surface temperature, Himalayan catchment, LULC*

SPRING REJUVENATION FOR WATER SECURITY IN HIMALAYA: A HOLISTIC APPROACH

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The Himalayan ecosystem is increasingly vulnerable to adverse impacts from changing climate patterns, intensified anthropogenic activities, land degradation, and shifting land use and land cover. These factors significantly threaten the region's natural water availability, particularly spring water resources, which serve as a lifeline for local communities. Over the years, these springs have experienced severe depletion, posing a critical challenge to water security in the region. To combat this issue, a study was undertaken in the Lohaghat block of Champawat district, Uttarakhand, with the primary goal of revitalizing drying springs in mountainous areas. These springs are essential for meeting the daily water needs of local communities, who rely heavily on them. The project adopted a participatory approach, actively engaging relevant line departments, organizations, and local communities. This initiative underscores the importance of community involvement and the integration of local knowledge and traditional practices and scientific methods to ensure sustainable water resource management in the area. The study began with a preliminary survey of the area, identifying nine key spring sources for detailed analysis. The methodology was organized into three primary stages: data collection, identification of potential recharge zones, and water augmentation interventions, supported by robust hydrological and statistical analyses. To monitor spring discharge, two methods were employed (i.e. the Bucket and Stopwatch Method and the Water Level Drop Method), enabling accurate yield measurement per minute for each spring. Additionally, three rain gauges were installed at varying elevations to gather rainfall data at regular intervals, resulting in a comprehensive three-year dataset that provided reliable insights into spring discharge and rainfall patterns. For identifying potential recharge zones, a combination of hydro-geological investigations, remote sensing techniques, and isotope analyses was employed. Geological studies involved detailed assessments of lithology, structural geology, topography, and geological contacts. Remote sensing techniques utilized the Analytic Hierarchy Process (AHP), integrating geological, hydrological, and catchment parameters to map groundwater recharge zones effectively. To corroborate these findings, isotope analysis of stable oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}D$) isotopes in spring and rainwater samples was conducted, enhancing the understanding of recharge processes and water sources.

Interventions for water augmentation were focused on improving groundwater infiltration and reducing surface runoff. Structures such as trenches, toe trenches, and percolation pits were constructed in identified recharge zones to capture rainwater and channel it into aquifers. The effectiveness of these interventions was assessed through a detailed analysis of spring discharge data before and after the interventions. Hydrological tools, including hydrographs, master recession curves, and flow duration curves, were combined with statistical approaches like bivariate and multivariate analyses, providing insights into changes in discharge patterns and aquifer health. Community involvement was integral to the project, with awareness programs and capacity-building initiatives conducted to promote sustainable water resource management. Para-hydrologists were trained to monitor spring discharge continuously, ensuring the long-term sustainability of the interventions. Through these multifaceted efforts, the study aimed to secure and enhance the water resources of the region effectively. The application of the outlined methodology to address water scarcity in the Manadunga villages delivered promising outcomes. The spring delineation studies identified that approximately 70% of the study area falls under moderate to good recharge potential, highlighting suitable zones for intervention. Based on these findings, over 500 recharge structures, including trenches, percolation pits, and ponds, were constructed in the identified zones with active community participation. These structures effectively captured surface runoff and directed rainwater toward areas ideal for groundwater recharge, significantly enhancing infiltration rates. The hydrological analysis demonstrated the success of these interventions. Despite reduced rainfall compared to the previous year, the average discharge of heavily utilized springs increased from 5.37 liters per minute (lpm) to 6.86 lpm. This improvement reflects the effectiveness of the recharge structures in maintaining and enhancing spring discharge. The results confirm the technical viability and impact of combining geological, hydrological, and community-driven approaches. It also emphasizes the importance of targeted recharge interventions in mitigating water scarcity and ensuring the sustainability of vital spring resources, even in fluctuating climatic conditions. Despite adverse rainfall conditions, the project demonstrated the effectiveness of rejuvenation efforts in enhancing spring discharge, particularly at the initial stage. This success underscores the potential for continued interventions to further improve water security in the region. Community involvement was central to the project's achievements, with capacity-building programs raising awareness about the importance of springs and their ecosystems. These efforts also trained para-hydrogeologists for long-term spring monitoring and sustainable water management. The integration of scientific techniques, such as hydrogeological studies, remote sensing, and isotopic analysis, with grassroots community participation, proved to be a promising strategy for spring rejuvenation. This approach ensures reliable water availability while promoting environmental sustainability. The study exemplifies a holistic method to tackle water scarcity challenges, offering long-term benefits for both the environment and the local population. Also, it sets a replicable model for similar regions facing water security issues.

Keywords: *Spring rejuvenation, Himalayas, mountain groundwater, water scarcity, hydrological assessment, remote sensing and GIS*

MORPHOMETRIC ANALYSIS FOR PRIORITIZATING SUB-WATERSHED OF KARLI RIVER BASIN USING GEOSPATIAL TECHNIQUES

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Watersheds are critical geographical units for understanding hydrological processes and planning sustainable water and soil resource management strategies. The present study investigates the Karli watershed, located in the Sindhudurg district of Maharashtra. The present study leverages GIS and Remote sensing tools to carry out a detailed morphometric and LULC analysis of the watershed for prioritizing its sub-watershed based on their susceptibility to soil erosion and surface runoff. Thirteen sub-watersheds were delineated and analyzed to provide insights into their physical characteristics and land cover dynamics, facilitating better decision-making for watershed management and conservation. The study aims to get a brief hydrological understanding of Karli watershed. The drainage area of watershed is approximately 778.3 km^2 and exhibits a dendritic drainage pattern. The linear, areal and relief aspects of morphometric parameters have been estimated for all the thirteen sub watersheds. The SRTM DEM (30 m resolution) was used to delineate the watershed and generate the drainage network. The morphometric characteristics of each sub watershed have been analyzed using GIS and remote sensing techniques. The parameters analyzed for linear aspect were stream order, stream count, stream length, stream length ratio, bifurcation ratio, average bifurcation ratio, mean stream length, average stream length, stream frequency, drainage density, drainage texture, length of overland flow, rho coefficient, drainage intensity, infiltration number, and constant of channel maintenance. The parameters analyzed for areal aspect were area of the watershed, perimeter of the watershed, basin length, circulatory ratio, elongation ratio, form factor, lemniscate ratio, shape index, and compactness coefficient. The parameters analyzed for relief aspect were maximum elevation, minimum elevation, relief, relief ratio, relative relief, ruggedness number, and hypsometric analysis.

Sub-watershed with higher relief and linear parameters, i.e. SW-3, SW-6, SW-8, SW-10 SW-11, and SW-13 were ranked as high priority due to their susceptibility to runoff and soil erosion. Conversely, SW-1, SW-7 and SW-9, with lower values, were ranked as low priority, indicating relatively stable condition with minimal vulnerability to degradation. The drainage density of the watershed was found higher at SW 4 (2.65) and lower at SW 9 (1.49), highlighting variation in runoff potential and infiltration rates across the sub-watersheds. Bifurcation ratios varied significantly, with the highest value (34.52) for SW-7, indicative of a structurally controlled drainage pattern, while SW-12 had the lowest value (4.29), reflecting a more stable drainage configuration. The ruggedness number, a key indicator of terrain ruggedness and soil erosion potential, was highest in SW-6 and lowest in SW-5, further emphasizing the diversity in geomorphological characteristics within the watershed. These variations underscore the importance of prioritizing conservation efforts in sub-watersheds with higher runoff and erosion risks. The study carried out for LULC characterization reveals that, the agricultural land constitutes significant portion of the watershed, particularly in SW-12, which is predominantly covered by crops such as cashew, coconut, paddy, and sugarcane. The extensive soil cover makes SW-6 highly susceptible to soil erosion, especially in the absence of adequate soil conservation practices. SW-8 has the highest forest cover (90%), which plays a critical role in stabilizing soils, enhancing infiltration, and regulating runoff. In contrast, SW-12 has minimal forest cover, exposing it to heightened vulnerability. Built-up areas were most prominent in SW-1, reflecting urban development pressures, while SW-8 showed the least built-up land, emphasizing its natural character. The findings further indicate that SW- 6 has substantially minimal forest cover, is challenged by its high ruggedness and steep slope, necessitating runoff management studies. Waterbodies are sparse across most sub-watersheds but played a crucial role in SW-9 and SW-11, where their presence mitigates runoff and supports groundwater recharge.

The integration of morphometry and LULC analysis provides robust framework for prioritizing sub-watershed and tailoring, management strategies. According to the data of morphometric analysis, SW 3, SW 6, SW 8, SW 10, SW 11 and SW 13 have the highest priority, and SW 2, SW 4, SW 5, SW 12 have the medium priority while SW 1, SW 9, SW 7 have the lowest priority among sub-watersheds. According to morphometric and LULC analysis, sub-watersheds, SW 3 is the common sub-watershed that fall within high priority. SW 4, and SW 5 has medium priority. Although morphometrically SW 6, SW 11, and SW 13 has high priority but as per LULC analysis it comes under the sub-watershed for medium priority. The present study highlights the significance of tailored land management practices. Sub-watershed with high agricultural activity, such as SW 5 and SW 12, should adopt conservation farming techniques, while heavily forested regions, like SW-8 required strategies to balance run-off control and ecological preservation. Urbanized area in SW-1 must incorporate green infrastructure to mitigate the impacts of the watershed and the socio-economic well-being of its communities. The integration of morphometry and LULC analysis in the study provides a holistic framework for prioritizing sub-watersheds based on their vulnerability to soil erosion, runoff and degradation. The results emphasize the need for targeted interventions in high-priority areas and proactive management in medium and low priority zones. By addressing specific vulnerabilities, this research contributes to sustainable watershed management, ensuring the ecological and socio-economic health of the Karli watershed. The study reinforces the value of GIS and remote sensing as indispensable tool for informed decision-making in environmental management.

Keywords: *Watershed management, morphometric analysis, GIS and remote sensing, LULC classification, watershed prioritization*

DEVELOPMENT OF SPRINGS IN HILLY TERRAINS – A CASE STUDY IN WEST SIANG DISTRICT, ARUNACHAL PRADESH, INDIA

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Since time immemorial, springs have emerged as the most dependable source of water in hilly areas. Spring water which is primarily a component of groundwater. However, it is difficult for storage logistically in hilly terrains. As spring water forms the lifeline of the hilly communities, revival of the age-old traditional source of this water is crucial for sustainable growth and development of the hilly areas. A large share of the groundwater flux ends up in springs and consequently in rivers. Therefore, it is imperative that river rejuvenation becomes immaterial without a clear focus on spring revival based on the fact that reinstatement of river waters throughout the year is due to their discharges received from groundwater as springs or seeps along their channels. The groundwater discharge from aquifers to river channels are recognized as the base flow of such rivers during lean period. Therefore, a depletion in spring water affects flows in rivers thereby revival of springs become tremendously significant in rejuvenation and restoration of the rivers. West Siang district in Arunachal Pradesh is predominantly hilly terrain. The 99% of the district is occupied by hills having maximum elevations of 5248 m above mean sea level (amsl). Out of this, 20% area remains permanently snow bound. The climate is sub-tropical humid in nature and the average rainfall recorded in the district is 2463.95 mm. The soils are fertile and suitable for paddy cultivation. Siyom river and its tributaries form the main drainage system of the district. The future irrigation and domestic water requirements in such hilly terrain can be met through systematic development of springs with a holistic approach and realistic awareness.

In this paper, a case study regarding development of springs in the hilly terrain of West Siang District of Arunachal Pradesh is highlighted based on field data. A preliminary study of these springs comprising spring inventory, classification of the springs, their discharges and preparation of a conceptual layout of the springs delineating their source of recharge, recharge area and their relationship with local aquifer system. The methodology includes both field and laboratory investigations. The field investigations include spring inventory and measurement of discharge of the springs and sampling of spring water while, laboratory investigations consist of chemical characterization of spring samples and desk analysis includes map preparation, making relevant diagrams, etc. Geotagging of springs done by using hand held GPS. Survey of India Toposheet of 1:50000 scale and satellite imageries downloaded from Google Earth have been used during mapping. Based on the various hydrogeologic data, conceptual diagram of the springs indicating recharge and discharge area were prepared. The discharge of springs was measured using a container of known volume and a stopwatch. Base line details have also been recorded through interaction with local people especially village heads. Puakghat Natural Calamities Welfare Society (PNCWS), Along, West Siang district, Arunachal Pradesh, one of leading organization was involved to make the villagers aware about the springs in an informal way.

It has been observed that the amount of discharge of the springs remain sufficient even during lean periods which can be harnessed efficiently for providing stable and low-cost water

supplies for domestic as well as irrigation purposes. Fifty (50) springs with varied discharges were recorded for detailed study. Discharge rate of springs have been found varied with the change in lithology. The discharge rate varies from 1.7 LPM to 57.77 LPM during pre-monsoon and it varies from 1.38 LPM to 55.63 LPM during post-monsoon period. Based on the hydrogeologic data of springs inventories and discharge data, thirty-three (33) springs were categorized as Perennial (66%) and seventeen (17) were as intermittent (34%) category. As per the Meinzers' classification, thirteen (13) springs have been classified under the 6th class-magnitude and twenty (20) springs in the 7th class-magnitude. In West Siang district, the existence of groundwater is found to be manifested in the form of springs. Storage and movement of springs are controlled by joints/fractures as secondary porosity. The discharge of springs varies between 1.38 LPM and 57.77 LPM in the district. All the chemical constituents of the springs were found within permissible limits of BIS for all uses. It is obvious that supply from single running water points of springs culminates in scarcity of water specially during lean period resulting in decline in spring discharges and sometimes even drying up. Obviously, sources of water supply go dry due to overload. It is necessary to develop springs systematically to meet the future requirements of the population. Scientific development of springs, diversion of stream water to reservoirs, storage and settling tanks are important. Inculcating regular practices to check the debris and mudflows during rainy seasons to get copious water throughout the year in such a hilly terrain is an important effort to be initiated. Cleaning the flow path of springs and construction of collecting tanks wherefrom the water should be drawn into the storage tank for distribution should be developed.

Keywords: *Springs, West Siang, hydrogeology, base flow, Meinzers' classification, spring inventory*

HYDROCHEMICAL ANALYSIS OF SPRINGS WATER IN PRATAPNAGAR BLOCK, TEHRI GARHWAL OF UTTARAKHAND, INDIA

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Groundwater-fed springs, locally referred to as *Naulas* and *Dharas*, serve as the primary water supply in thousands of mountainous villages of Uttarakhand state of India, where alternative sources are often limited due to the region's geomorphology and topographical constraints. Pratapnagar block, located in the Tehri Garhwal district of Uttarakhand, India lies between 30° 23'N to 30° 37'N latitude and 78° 24'E to 78° 34'E longitude, with elevations ranging from 800 m to 2,400 m, above mean sea level (amsl). The region experiences a monsoonal climate, with the majority of rainfall occurring from June to September. However, Pratapnagar is facing increasing water scarcity due to declining groundwater levels and drying springs, highlighting the urgent need for sustainable springshed management in the area. In the present study, 50 springs were identified within the boundary of Pratapnagar block in major settlement areas, and water samples were systematically collected for analysis. Key parameters, including spring location, dependency, usage, discharge rates, and historical data based on local perceptions were documented during field surveys. In-situ measurements of physical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), and oxidation-reduction potential (ORP) were recorded in the field. Samples for the analysis of major cations-anions, trace metals, and Alkalinity tests were collected and subsequently analyzed in the Water Quality laboratory of the National Institute of Hydrology, Roorkee. A key aspect in determining the main determinants of the water quality of the springs in the research region was the statistical analysis of the data that was gathered. Through the use of statistical techniques including regression modeling, analysis of variance (PCA), and correlation analysis; important connections between several environmental factors and water quality metrics were found. Both natural processes including geochemical interactions with underlying bedrock, and anthropogenic activities, like agricultural activities and waste disposal from the settlements, have an impact on the quality of water.

Concentrations of CO_3^{2-} and HCO_3^- were measured through the titration method by using unfiltered samples on an Auto-titrator with 0.02N H_2SO_4. Major ions such as Fluoride (F^-), Chloride (Cl^-), Sulfate (SO_4^{2-}), Phosphate (PO_4^{3-}), Nitrate (NO_3^-), Sodium (Na^+), Potassium (K^+), Ammonium (NH_4^+), Magnesium (Mg^{2+}), and Calcium (Ca^{2+}), were analysed using an Ion Chromatography (IC) calibrated with the standards, with results reported at an analytical precision of ±5%. Each sample was diluted 10 times with Milli-Q water (resistivity of 18.2 MΩ) to ensure ionic concentrations were within the instrument's sensitivity range. Aliquots of 60 ml samples were collected for trace metal analysis, focusing on major trace metals such as lead (Pb), zinc (Zn), arsenic (As), cadmium (Cd), nickel (Ni), boron (B), Aluminium (Al), Chromium (Cr), Manganese (Mn), and iron (Fe) by using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The springs in the Pratapnagar block are characterized as sixth-magnitude springs as per Mainzer's classification based on the average discharge of the spring, with discharge ranging from 1 to 10 gallons per minute (approximately 0.0063 to 0.063 liters per second). 85% of the springs are located at elevations above 1000 m, amsl while only 15% springs at altitudes below 1000 m.

It was observed during the survey that 68% of the surveyed springs are highly dependable source for the local populace, 27% as moderately dependable, and only 5% as low dependable. In terms of water quality, 85.5% of the springs exhibited a pH within the permissible range of drinking water i.e., 6.5 to 8.5, while 11.5% were slightly acidic (pH < 6.5), and 3% were slightly basic (pH > 8.5). Electrical Conductivity (EC) measurements revealed that 71.2% of the springs have EC values less than 150 µS/cm, 20.2% springs fell within the range of 150 to 300 µS/cm, and only 8.5% springs exceeded 300 µS/cm. EC measurements, a key indicator of dissolved ionic content, revealed that EC values below 150 µS/cm, signifying low mineralization and suitability for drinking. Additionally, higher EC values indicate higher mineral content potentially resulting from geological formations or anthropogenic influences such as agricultural runoff. Springs with higher EC levels may require additional treatment or monitoring to maintain drinking water standards. These findings provide valuable insights into the hydrological characteristics and water quality of the springs in the region. To evaluate the general health of springs, the Water Quality Index (WQI) is a numerical expression that condenses complicated water quality data into a single value. It is also useful to determine the suitability of springs water for drinking, irrigation, or other uses. The WQI offers a consistent method for evaluating the quality of water in various locations. Policymakers and environmental managers utilize it extensively to make decisions. Better water quality is indicated by a lower WQI score, whereas higher values suggest possible hazards and the need for corrective action. The estimated values of the WQI for the surveyed springs indicate the suitability of water for drinking purpose, with the present data categorized as excellent, yielding a WQI of 39.5. However, periodic measurements of the springs are to be needed to understand the effect of climate change and anthropogenic activities on the vital water resources of the mountainous area.

Keywords: *Spring, hydrochemical analysis, Pratapnagar block of Uttarakhand, Mainzer's classification, Water quality index*

PAST, PRESENT AND FUTURE OF SPRINGSHED MANAGEMENT IN INDIA

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Springs are critical and dependable sources of water security for the population of mountainous regions across world (e.g., India, USA, New Zealand, Ethiopia, Turkey, Spain and Greece). A gross estimate of nearly 200 million Indians depends on spring water mainly in the Indian Himalayan Region (IHR), Western Ghats (Sahyadri mountain range, traversing the states of Maharashtra, Goa, Karnataka, Kerala, and Tamil Nadu), Eastern Ghats (Northern Odisha, Andhra Pradesh, and Tamil Nadu) and Central India (Satpura and Vindhyas mountains). Springs are also one of the most cost-effective ways to provide relatively pure water in entire mountainous parts of the country as rivers are flowing in the deep valley and glacier are far flung, so water from these two sources is economically not feasible. In addition to this, these springs sustain several rivers, particularly in the lean season and there is hardly any river throughout the globe, which is not feed by a spring. However, climate change, deforestation, and unsustainable development practices are putting immense pressure on these springs. During 1961–2011, the Himalayan population grew by 250% with an annual growth rate of 3.3%, which is three times the world average growth rate. This rapid growth led to accelerated urbanization eventually causing the damage to recharge zones and degradation of water quality of the springs. Furthermore, this population surge has placed significant stress on these vital water sources. As a result, over the past few decades numerous springs have either dried-up or became seasonal.

In India, Govt. of Sikkim implemented a community-based programme i.e., Dhara Vikas Programme (first ever springshed management programme in the country) with the help of International Organization (ICIMOD, WWF, gIZ, UNDP) Central/State government Scientific Organization (BARC, ISRO, Land Resource), NGOs (ACWADEM, ARGHYAM, PSI, etc.) and other scientific institutes. Under this programme 50 springs, 5 lakes and 7 Hill top Forest was revived. Department of Land Resources, Nagaland initiated a one-year pilot programme to work on one spring in each of the State’s 11 districts involving the local communities. Programme has so far benefitted more than 600 households with increased availability of water, especially during the summers. National Institute of Hydrology (NIH) Roorkee, a Research and Development (R&D) organization under the Ministry of Jal Shakti, Govt. of India identify 40+ parameters, which are necessary for the successful implementation of a springshed programme. NIH has developed a digital data collection system named ISHVAR (Information System of Himalayan Springs for Vulnerability Assessment and Rejuvenation) using open-source technology for geotagging and survey of the springs through mobile. Spring mapping of high social relevance areas has been performed in Western Himalayan region. Till now, 981 springs of Ravi River catchment of Himachal Pradesh (drainage area 5400 km^2) and 469 springs of Tawi River catchment (drainage area 2100 km^2) have been mapped for 40+ parameters.

In year 2022, the Ministry of Jal Shakti, Government of India, constituted a steering committee of domain experts to initiate and monitor the systematic mapping/geotagging of springs across the mountainous regions of the country and develop a coordination mechanism among various stakeholders to expedite springshed management efforts in India. The committee, through stakeholder meetings and brainstorming workshops, gained an understanding of the tools and techniques employed by agencies working in the field of springshed management in the country. The committee compiled information on over 48,000 geotagged springs in India and identified potential districts for spring occurrence. Consequently, the Ministry of Jal Shakti, Government of India, initiated the First Spring Census of the Country in August 2023. The steering committee has also produced a resource book on springshed management to aid implementing agencies and encourage research on spring hydrogeology. CGWB has included the springshed management in its annual programme and monitoring discharge (four times in a year) of nearly 100 springs. The yield of these springs can be helpful to assess the ground water estimation resources in the hilly area. However, the final decision can be taken after long term measurements of the spring discharges in different mountainous region of the country. In the year 2023-24 CGWB has taken up 10 studies for springshed mapping and management under NAQUIM 2.0 studies. A Scheme has already been proposed for rejuvenation of 25,000 springs. On the recommendations of NITI Aayog, rejuvenation of Springshed has been incorporated as a new activity in the WDC-PMKSY 2.0 (Project period 2021-26). Under Springshed Development-Regeneration of springs, Springshed development is to be taken up as an activity under new generation watershed projects to mitigate spring water depletion in the Himalayas and other 'springscapes' of India. All state agencies particularly in hilly areas of the country are now giving springshed development adequate place in their Annual Action Plan (AAP) of the development. However, capacity building in the field of springshed management is still a major hurdle to upscale the springshed management programme in the country.

Keywords: *Spring, springshed management, Dhara Vikas programme, ISHVAR, Ministry of Jal Shakti*

DYNAMICS AND CLIMATIC CHANGES IN LARGE-SCALE EXTREMES IN THE NORTHWEST HIMALAYA: IMPLICATIONS FOR REGIONAL HYDROLOGY AND DISASTER RISK

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The Himalayan mountains serve as vital water reservoirs, sustaining millions downstream. However, in recent decades, the region has experienced unprecedented heavy rainfall, leading to devastating floods, landslides, and socio-economic losses. These events highlight the complex interplay between climate change and large-scale atmospheric systems. The northwest Himalayas, with their highly complex terrain and tropical-extratropical interactive atmosphere, are particularly prone to such extremes, especially during the monsoon season. They pose severe risks to the fragile ecosystem, traditional hydrological cycles and local communities. Research suggests that multiple factors driven by climate change contribute to extreme rainfall events. Interactions between deep westerly troughs, cross-equatorial Indian Ocean south-westerlies, and Pacific easterlies create large and intense monsoon troughs extending from the Philippines to the Indus Basin. These phenomena that involve confluence and convergence of huge air masses of contrasting characteristics are short-lived, resulting in rapid condensation and intense rainfall due to the confluence of contrasting air masses over the subtropical mountainous terrain.

The Himalayas exhibit distinct circulation dynamics between monsoonal and non-monsoonal weather systems, with significant seasonal variability. Even within the monsoon period, rainstorm dynamics differ across early, established, and withdrawal phases, complicating the identification of common patterns for extreme rainfall event occurrences. This study addresses these complexities through a comprehensive long-term analysis of large-scale extreme rainfall events (EREs) in the northwest Himalayas (NWH), covering Uttarakhand (UK), Himachal Pradesh (HP), and Jammu and Kashmir (JK). It focuses on three key aspects of these extremes: rainfall magnitude, spatial extent, and event duration using high-resolution (0.25° x 0.25°) gridded daily rainfall data. To explore the drivers of severe EREs, the study analyzes meteorological anomalies and physical processes using NCEP-CFSR-V2 reanalysis data of key atmospheric parameters such as temperature, pressure, geopotential height, wind fields, and absolute vorticity. Inter-annual variations in area averages of annual and seasonal rainfall are studied using Mann-Kendall (MK) test for its trend detection. Spatial variation in long-term trends in grid-scale EREs across the NWH states are also studied by using MK test. An objective criterion has been developed to identify the 1- to 5-day large-scale long-period extreme rain events (LS-EREs) for each year. The criteria use the daily mean rainfall (DMR) during a normal monsoon period as the threshold and the area under wet condition to determine areal extent. Anomalous meteorological conditions during LS-EREs are studied using composite analysis of top three EREs recorded during the study period.

The analysis reveals distinct rainfall trends across the NWH states over the period, with notable variations in recent decades: (i) In *UK*, no significant long-term trend is observed in the annual and monsoonal rainfall series. However, October–November (OND) rainfall exhibits a significant long-term decreasing trend. Over the past 20 years, OND rainfall has declined sharply by 35% compared to the preceding 51-year period. (ii) In *HP*, a significant

long-term decreasing trend is observed in annual rainfall over the 1951–2021 period. Seasonal rainfall patterns, however, remain mostly homogeneous and random. Over the last 20 years, annual rainfall in HP has decreased by approximately 13%, with declines of ~8.5% in monsoonal rainfall, ~33% in OND, ~17% in January–February (JF), and ~17% in March–May (MAM) rainfall. (iii) In *JK*, JF rainfall shows a significant long-term increasing trend over the study period, while annual and other seasonal rainfall series remain largely homogeneous and random. Over the past 20 years, however, monsoonal rainfall in JK has increased by approximately 18%. The LS-EREs intended to quantify the severity of persisting intense rains causing severe flood and damage. For NWH as a whole, while no significant change is observed in the rainfall amount (RA) of EREs, notable changes have occurred in other metrics over the past 20 years. The areal extent (AE) of 1- to 3-day LS-EREs has significantly increased by 28–43%, and the rainwater (RW) contribution of 1-day EREs has risen by 16%. At the state level the trend varies significantly: (i) In UK, RA of EREs of different durations increased by 10-23% and RW by 14-34%; (ii) In J&K, RA of 1-day ERE increased by 16% and RW by 23%, while AE of EREs of different durations by 19-23%; (iii) In HP, RA of EREs of various durations decreased by 10-20% and RW by 14 to 19%. Most of the year-wise most severe LS-ERE-RW events occurred during the monsoon season, however, surprisingly in some years, the severity of non-monsoonal extremes surpassed the monsoon extremes especially in HP and J&K.

The spatial analysis of long-term trends in grid-scale EREs reveals contrasting patterns across the NWH. High-altitude areas, particularly in J&K and northern UK, are experiencing increased rainfall amounts for short-duration (1–3 day) EREs. In contrast, mid- and low-altitude regions in HP and southern UK show significant decreases in rainfall amounts across most durations. Low-intensity EREs are widespread, with higher frequencies in J&K, while high-intensity EREs (>8 times the DMR) are less common and concentrated in northern J&K and high-altitude southern areas of HP and UK. These trends highlight a shift toward more frequent and intense short-duration EREs in high-altitude regions, particularly in J&K and northern UK, alongside a decline in moderate-intensity events in lower-altitude areas like HP and southern UK. Wintertime most severe LS-EREs are largely associated with deep western disturbances, significantly modulated by interaction with the south-westerly jet stream, however, persistence in temperature and circulation anomalies are observed to be strongly linked to the occurrences of LS-EREs during monsoon season. The unusual and abrupt warming of the upper troposphere in the Tibet and Turkey sectors promotes the development of deep troughs and reinforced ridges in subtropical westerlies. The abrupt intensification of the monsoon circulation connected to this warming causes catastrophic spatio-temporal rain events across NWH. This study provides insight into the changing patterns of large-scale extreme rainfall events in the Himalayas, which significantly impact river flows, groundwater recharge, and reservoir management. The results will be helpful for predicting flood risks, planning for sustainable water resource allocation, and improving the resilience of hydrological systems to climate-induced changes.

Keywords: *Large-scale extremes, extreme rain events, Himalayan extremes*

HYDROCHEMICAL ASSESSMENT OF WATER RESOURCES OF THE HENVAL CATCHMENT, TEHRI GARHWAL, UTTARAKHAND, INDIA

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Innumerable water resources of the Himalayan region, particularly natural springs, streams, and rivers, play a crucial role in sustaining water demands of local communities and ecosystems. Springs, as a primary and reliable year-round water source, are also vital for agriculture, especially in regions where irrigation is largely dependent on natural sources. In fact, these springs are the backbone of local livelihoods, providing water for both domestic use and crop irrigation. Streams and rivers, while important, play a secondary role in comparison to springs in maintaining the region’s ecological balance, supporting biodiversity, and ensuring water security in the region. These water bodies also hold significant cultural and spiritual values, with springs often revered in local traditions. The combination of springs, streams, and rivers are indispensable to the region’s agricultural, ecological, and cultural well-being, where springs being the most dominant and essential source. The Henval River watershed, extending up to Jijali in the Upper Ganga Basin, Uttarakhand, encompasses two paired catchments: a forested, undisturbed area and an agricultural watershed influenced by anthropogenic activities, including Chamba's semi-urban habitat. Spanning 102 km² between 30°17'N–30°26'N latitude and 78°16'E–78°25'E longitude, the area experiences temperate Himalayan climatic conditions with annual rainfall ranging from 1200 to 1800 mm and an elevation gradient of 999–2676 m, amsl. It transitions from subtropical forests to temperate mixed forests dominated by pine, offering diverse ecological features. The forested sub-catchment, covering 26 km², serves as a crucial drinking water source for 87 villages, while the 76 km² agricultural area highlights human-induced landscape changes, making the watershed a modal representative site for studying hydrological and ecological dynamics in the Himalayan region.

The physicochemical characteristics of water resources in the Henval catchment of Tehri Garhwal, Uttarakhand, were assessed by collecting and analyzing water samples. A total of 34 samples were collected. These included 21 spring’s samples, 10 stream’s samples, and 3 river’s samples. The study aimed to evaluate key parameters to understand the quality and dynamics of the region's various water resources. Spring water samples exhibited discharge rates ranging from 1.06 to 22.39 litres per minute (LPM), temperatures between 13.4°C and 25.3°C, electrical conductivity (EC) of 60.5-296 µS/cm, total dissolved solids (TDS) of 42.7-190 mg/L, salinity of 33.6-644 ppm, dissolved oxygen (DO) levels of 7.1-9.6 mg/L, and oxidation-reduction potential (ORP) values of 22-279 mV. Stream water samples were characterized by discharge rates of 150-12951 LPM, temperatures of 18.9°C-27.8°C, EC values of 84.5-469 µS/cm, TDS levels ranging from 60 to 333 mg/L, salinity between 44-225 ppm, DO concentrations of 7.1-10 mg/L, and ORP values spanning 46-151 mV. River water samples demonstrated higher values for all parameters, with discharge rates between 1500-36853 LPM, temperatures of 24.9°C-28.9°C, EC values ranging from 115-436 µS/cm, TDS levels of 82.5-308 mg/L, pH of 7.62-8.35, salinity of 59.1-211 ppm, DO levels of 7.2-7.3 mg/L, and ORP values of 99-108 mV. Water samples were analyzed for cation, anion, trace metal concentrations, and alkalinity in the lab of National Institute of Hydrology, Roorkee to

assess the quality of spring water in the study area. To identify the primary determinants of water quality, statistical techniques including regression modeling, principal component analysis (PCA), and correlation analysis were applied to the collected data.

Results indicated that both natural geochemical processes and anthropogenic activities, such as improper waste disposal and agricultural runoff, significantly influence water quality. Concentrations of CO_3^{2-}, HCO_3^-, and alkalinity were determined by titration using 0.02N H_2SO_4 and a Tarson Auto-titrator (Model: Titer Top 25). Major ions, including Fluoride (F^-), Chloride (Cl^-), Sulfate (SO_4^{2-}), Phosphate (PO_4^{3-}), Nitrate (NO_3^-), Sodium (Na^+), Potassium (K^+), Ammonium (NH_4^+), Magnesium (Mg^{2+}), and Calcium (Ca^{2+}), were analyzed using ion chromatography (IC), calibrated with Merck standards, and results were reported with an analytical precision of ±5%. Samples were diluted 10 times with Milli-Q water (18.2 MΩ resistivity). For trace metal analysis, 60 ml aliquots were analyzed for Pb, Zn, As, Cd, Ni, B, Al, Cr, Mn, and Fe using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The Water Quality Index (WQI) for the study was calculated using a weighted arithmetic method, where key water quality parameters such as pH, dissolved oxygen, turbidity, and major ions were assigned respective weights based on their relative importance. The individual parameter values were compared to standard water quality guidelines, and the WQI was computed by aggregating these weighted values. This method provided an overall index that categorizes water quality into various classes, enabling a comprehensive assessment of water health in the Henval catchment. The physicochemical analysis of 34 water samples from the Henval catchment in Tehri Garhwal, Uttarakhand, revealed overall good water quality across different sources. While, some spring water samples exhibited slightly higher concentrations of nitrate and sulfate, the majority maintained excellent quality, with WQI values typically between 0-50, indicating minimal contamination and largely natural processes. Stream water samples were also found to be of good quality, meeting key standards such as pH (6.5–8.5) and DO (> 5 mg/L), with only minor variations attributable to localized factors. River water samples similarly fell within the good quality range, with slightly elevated levels of nutrients such as nitrate and phosphorus, though these remained within a minor range that does not significantly impact overall quality.

Collectively, the findings demonstrate that the water quality in the Henval catchment is well-sustained, with only minor deviations, underscoring the region's generally favourable conditions for water resources. The water quality analysis revealed that the river samples exhibited acceptable levels of nitrate and phosphate, indicating effective natural filtration and limited anthropogenic impact. The relatively low turbidity, TDS and minimal contaminants reflect a balanced aquatic ecosystem, supported by sustainable land use and controlled discharge of effluents. These findings suggest that both natural processes and responsible human activities are contributing positively to maintaining the water quality within the catchment. This highlights the effectiveness of current management practices and emphasizes the importance of continuing integrated water management strategies to sustain and enhance these favourable conditions.

Keywords: *Spring, hydrochemistry, Henval catchment, Uttarakhand, water scarcity, water quality index*

ISHVAR – INFORMATION SYSTEM OF HIMALAYAN SPRINGS FOR VULNERABILITY ASSESSMENT AND REJUVENATION

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Springs are vital lifelines in the Indian Himalayan Region (IHR), serving as crucial sources of freshwater for biodiversity, local ecosystems, and human populations. These natural water outlets play a pivotal role in sustaining the region's rich biodiversity, providing essential hydration to flora and fauna. They are integral to the survival of numerous species, many of which are endemic to the Himalayas, thus maintaining ecological balance and supporting unique habitats. Springs also serve as a cornerstone for local ecosystems, replenishing soil moisture and sustaining streams and wetlands, which are critical for agricultural and forest health.

For local communities, springs are indispensable for daily needs such as drinking water, irrigation, and livestock rearing. Many Himalayan villages, lacking large-scale water infrastructure, rely exclusively on springs for their sustenance. In addition to their practical utility, these water sources hold cultural and spiritual significance, often regarded as sacred by the local populace. However, the overexploitation of spring water and climate change pose threats to their sustainability. Protecting and restoring these springs through community-driven management and scientific interventions is essential to ensure water security and preserve the delicate ecological balance of the Himalayan region. Springs are, therefore, not just natural resources but lifelines for both biodiversity and humanity in the IHR.

In Himachal Pradesh, a predominantly rural Himalayan state, water demand in rural areas surpasses that of urban regions. Traditional water sources, especially springs, are crucial for meeting water needs, particularly for marginalized communities, amid imbalances in water supply and consumption. Recognizing their importance, the Planning Commission (now NITI Aayog) emphasized the establishment of a traditional water resources cell to develop and safeguard these resources in light of climate change and anthropogenic pressures. NITI Aayog's report, "*Inventory and Revival of Springs in the Himalayas for Water Security*," called for a web-enabled database to map Himalayan springs. The development of a Web-GIS based Information System facilitates data visualization and analysis, empowering stakeholders with valuable information for decision-making. This tool enhances transparency, collaboration, and informed decision-making in water resource management efforts. In response, a Purpose Driven Study (PDS) titled "*Web GIS-based Spring Inventory for Vulnerability Assessment and Hydro-geological Investigation of Selected Springs in the Ravi Catchment, Himachal Pradesh*" was initiated in August 2017 under the aegis of National Hydrology Project (NHP).

Keeping the above discussion in view, a study was formulated for the Chamba district of Himachal Pradesh, which constitutes a significant part of the Ravi River Basin, to develop a digital database of springs. This paper provides a brief overview of the following three key objectives derived from the detailed study undertaken: i) Creation of web-enabled database of the springs emerging in the catchment based on extensive inventory of physical and hydro-

chemical characteristics, ii) Mapping of vulnerable springs using hot-spot analysis, and iii) To build capacity among the local stakeholders through creating para-hydrogeologists for conserving and managing the springs. A comprehensive digital database was developed as a WebGIS portal using ESRI ArcGIS Enterprise, named ISHVAR (Information System of Himalayan Springs for Vulnerability Assessment and Rejuvenation). This portal hosts data on over 900 springs across the Chamba district, encompassing more than 30 parameters that provide a detailed overview of the springs' characteristics, along with vulnerability assessments. The ISHVAR portal is designed to support policymakers and planners by providing critical insights to inform the design of future developmental activities. Furthermore, it facilitates the allocation of resources for spring rejuvenation initiatives, contributing to enhanced water security in the region. This digital platform serves as a vital tool for sustainable water resource management in the Himalayan context.

The exercise carried out in herein has laid a strong foundation for conducting a comprehensive nationwide census, demonstrating the feasibility and value of systematically collecting and analyzing large-scale data. The methodologies and frameworks established have not only streamlined data collection processes but have also highlighted the importance of detailed, region-specific insights for effective planning and management. Building on this groundwork, the forthcoming information from the national census will be hosted on a dedicated portal, ensuring accessibility and transparency. This platform will enable the general public, stakeholders, researchers, and decision-makers to utilize the data for diverse applications, ranging from policy formulation and academic studies to strategic planning and community-level interventions, fostering evidence-based decision-making across sectors.

Keywords: *Springs, ISHVAR, Indian Himalayan Region, Chamba, Ravi River basin*

HYDROGEOCHEMICAL CHARACTERIZATION OF HOT SPRINGS IN THE BHAGIRATHI VALLEY, UTTARAKHAND, INDIA: INSIGHTS INTO GEOTHERMAL RESOURCES AND RECHARGE MECHANISMS

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Hot or thermal springs are natural geological and geothermal phenomena, where water heated by the earth's internal heat emerges at the ground surface through the major faults and fractures. These hot springs form through the combination of geothermal, geological, and tectonic processes, where water seeps into the earth's crust through the fracture and porous rock formations, where it absorbs the heat from the surrounding geothermal sources before it emerges as thermal springs. The quality of heated water is influenced by several factors, including the rate/residence time of subsurface water circulation, the temperature of heat sources, rock alteration, and the degree of mixing with the cold groundwater from surrounding areas. Geological Survey of India (GSI) identified about 381 hot springs in different states of India in different geothermal provinces. Hot springs that occurred in the Himalayan geothermal province represent the areas prone for geothermal activity. The Himalayan geothermal belt extended from Ladakh to Arunachal Pradesh and spread over the length of approximately 1500 km. All the hot springs in the Himalayan region fall in the Central Himalayan geothermal belt of Northwestern Himalayan geothermal sub-provinces. Three main thermal occurrences in this belt are Punga, Chumatahng, Sidhu, and Nubra of Ladakh; Manikaran, Kosal, Bashist, and Tattapani of Himachal Pradesh; Tapoban, Yamunotri, Gangnani, and Gaurikund of Uttarakhand. GSI reports that eighty-two hot springs are located throughout Uttarakhand. The Ganga River Basin and the Kali River Basin are the two main basins where all of the hot springs are located. Forty hot springs identified in the various River valleys associated with the Ganga River basin are Tons, Yamuna, Bhagirathi, Bhilangna, Mandakini, Alaknanda, Dhauli, and Pinder valleys. Twenty-five hot springs were identified throughout many river valleys associated with the Ramganga Valley, Goriganga Valley, Dhauliganga Valley, and Darma Valley. The present study area lies in the Bhagirathi Basin from Chinyalisour to Harsil. Bhagirathi Valley is known for the occurrence of hot springs near Gangnani area. We identify a total of six hot springs in the study area namely in the places Joti, Gangnani, Jhaya, Bukki, and Matli in Uttarkashi district of Uttarakhand. Some physical parameters like Temp, pH, EC, TDS, etc. have been analyzed during the fieldwork in post-monsoon, 2024, while water samples of hot springs for Major ions, heavy metals, and isotopes were collected for analysis in the National Institute of Hydrology (NIH), Roorkee laboratory. These hot springs are visited by a large number of pilgrims every year as a part of religious belief. The hot spring at Gangnani occurs on the left bank of the Bhagirathi River. Its water emerges from sericite-biotite schist interbedded with granite gneiss from about 100 m above the river bed. Its water has a temperature of 59°C, a discharge rate is about 31 LPM, pH of 6.6, electrical conductivity of 1475 µS/cm and TDS of 950 ppm. Bhukki hot spring is located on the road to Gangotri about 25 km upstream of Aungi on the right bank of the Bhagirathi River, the temperature of the hot water is 34°C and the discharge rate is 15 LPM. It emerges through the gneiss belonging to the Central Crystalline. Its water has a pH of 6.10, Electrical Conductivity of 1118 µS/cm and TDS of

794 ppm. Two hot springs were reported in Jhaya towards 5 km upstream of Bhukki, these springs have temperatures of 48°C and 42°C, pH, EC, TDS are 8.00 and 8.14, 464 µS/cm and 545 µS/cm, 332 ppm and 387 ppm, respectively. These springs also emerge from the right bank of the Bhagirathi River. Joti hot spring is located 4 km upstream of Gangnani hot spring on the left bank of the Bhagirathi River. The temperature of thermal water is 57°C and has pH, EC, TDS, 6.67,1848 µS/cm, and 1200 ppm, respectively. Based on the water chemistry, hot springs can be grouped into three water types: Na- Cl, Ca- HCO_3 and Na- HCO_3. The majority of these six hot springs in the Bhagirathi Valley are categorized as Na-HCO_3 type of water based on the physical and chemical characteristics examined in this study. To understand the water recharge mechanism in the study area, isotopic samples of hot springs were employed. The finding highlights the importance of these springs as geothermal resources and cultural heritage places and also offers important insights into the hydrogeological processes.

Keywords: *Hot water springs, thermal springs, hydro-geochemistry, isotope analysis, Bhagirathi valley, recharge mechanism*

COMMUNITY LED SPRINGSHED MANAGEMENT IN MEGHALAYA, INDIA

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Springs are the primary water source in Meghalaya and 80% of its villages relying heavily on springs for drinking water and irrigation this reliance is threatened by anthropogenic activities like mining, unsustainable agriculture, and forest resource extraction, which have led to the drying up or reduced water discharge of about 50% of these springs. Rural communities perceive changes in spring quality as indicative of broader shifts in climate and land use patterns. Despite efforts to address these issues, comprehensive information on all springs in the state, which is under the 6th Schedule and where land is owned by communities, remains incomplete, highlighting the critical need for community involvement. Rainfall patterns have also shifted, showing increased overall rainfall within a narrower timeframe. This has led to the reduction in spring discharge and consequently the drying up of springs during the dry season. This in turn has led to significant challenges for women in these villages, forcing them to travel farther to fetch water. According to a rough estimate, almost all springs have witnessed a decline in discharge due to land use changes, including increased diversion, pumping, groundwater exploitation, pollution of surface and ground waters, degradation of natural recharge areas, and possibly climate change. The increasing demand for water and decreasing supply, attributed to these factors, underscores the necessity to comprehend the accessibility of water resources, specifically focusing on springs which have limited resources. Hence, the concept of springshed management was introduced with the intention of establishing a baseline data for future references and for identifying critical springs that require intervention also understanding their flow patterns, and developing management strategies to ensure that water resources are preserved for future generations. A holistic approach has been implemented to map, management, and monitoring of springs. This approach includes the development of a Spring Manual and the training to Village Community Facilitators, Green Volunteers, engineers, and GIS experts, along with additional master trainers. Advanced technologies such as GIS, Global Navigation Satellite System, and other mobile applications are also being utilized. Over 55,000 springs has been mapped under External Aided Projects (EAPs). Furthermore, a central dashboard has been developed to monitor spring-related activities in real time. The initiative of spring mapping and springshed management is regarded as the best approach for several reasons. Despite significant investments in natural resource management, the lack of baseline data was a major challenge. Spring mapping addressed this gap by providing crucial information on springs, enabling the development of sustainable management plans. Various parameters were captured, including discharge measurements, water quality indicators such as pH, TDS, EC, salinity and temperature, along with socio-economic factors. Monthly monitoring of critical springs supports Springshed Development activities aimed at enhancing spring discharge through recharge interventions. Community engagement played a key role in this approach with conducting Participatory Rural Appraisal (PRA) exercises followed by hydrogeological field survey and interventions. This involvement has empowered local communities in decision-making regarding conservation efforts. The approach is also cost-effective, ensuring efficient resource utilization while achieving significant benefits in water management. Furthermore, it provides government departments with a clearer understanding of on-the-ground realities, improving water management strategies and interventions. Geospatial Technology has incorporated to create a visual representation of spring locations, accessible via the Dashboards which enhanced accessibility to data on spring locations, water quality, and flow rates, aiding decision-making processes.

Spring mapping and springshed management was initially conceptualized by the Institute of Natural Resources, Meghalaya under the Meghalaya Basin Development Authority (MBDA). This concept was subsequently expanded through various externally funded projects, including the JICA funded MegLIFE, the World Bank-funded Meghalaya Community-Led Landscapes Management Project (MCLLMP), and the IFAD-funded Meghalaya Livelihoods and Access to Markets Project (MLAMP). The initiative has now been further advanced through the new EAP which is MegARISE project, funded by KfW, which focuses on the rejuvenation of two key catchments in the state: Umiew catchment in East Khasi Hills and the Ganol catchment in West Garo Hills. Within the MegLIFE project, under Meghalaya Basin Development Authority (MBDA) implementing comprehensive springshed management activities for more than 1700 springs across 500 villages in Meghalaya, aiming to enhance water security and sustainability through targeted watershed and recharge interventions under Soil and water conservation activity. The activity was built on extensive collaboration with various partners to achieve its objectives and ensure a comprehensive approach to springshed management. Key partnerships included those with CHIRAG, ACWADAM, PRASARI, and PSI, which provided essential technical expertise and support for springshed interventions. These training initiatives enhanced the knowledge and skills of participants across the water sector, fostering effective collaboration and cohesive implementation of springshed management efforts. In total 168 Detailed Technical Reports by MLSC partners and MegLIFE staff has further enriched the knowledge base required for future conservation efforts. Collectively, these initiatives have laid a strong foundation for ensuring the long-term viability of Meghalaya's springs and their critical role in sustaining rural communities.

Springs are a vital and irreplaceable resource for rural communities in Meghalaya, providing essential water for drinking, agriculture, and daily life. However, climate change, deforestation, over extraction, and pollution pose significant threats to their sustainability. Community-led initiatives for spring mapping and sustainable springshed management are critical to ensuring the long-term availability of these water sources. By leveraging collective action, traditional knowledge, and modern technology, rural communities in Meghalaya are taking ownership of their water resources and building a more sustainable future. This community-based water resource management model offers valuable lessons for other regions facing similar challenges in managing natural water resources. Springs are a vital and irreplaceable resource for rural communities in Meghalaya, providing essential water for drinking, agriculture, and daily life. Community led efforts to map springs and develop sustainable springshed management strategies are crucial to ensuring the long-term availability of spring water. Through collective action, community knowledge, and the integration of modern technology, rural communities in Meghalaya are taking ownership of their water resources and working toward a more sustainable future.

Keywords: *Community, springs, springshed, geospatial technology, Meghalaya*

Theme 4

WATER RESOURCES IN ARID AND SEMI-ARID REGIONS

ASSESSING GROUNDWATER VULNERABILITY WITH UPGRADED DRASTIC-LU MODEL IN SEMI-ARID BANASKANTHA DISTRICT, GUJARAT, INDIA

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Groundwater plays an essential role in meeting the water demands of various sectors, including agriculture, domestic consumption, and industry. However, the increased abstractions of groundwater, industrialization, intensive agricultural practices, and urban expansion have led to a significant rise in contamination levels, threatening both water quality and availability. The Banaskantha district of Gujarat, India, has been facing severe groundwater depletion and contamination issues, particularly in areas near the Rann of Kachchh and in talukas such as Vav, Bhabhar and Tharad. These regions are affected by saline water intrusion and higher fluoride concentrations due to over-extraction and industrial waste. The primary aim of current study was to assess groundwater vulnerability in Banaskantha district using geoinformatics and spatial analysis techniques. Groundwater vulnerability maps were generated to highlight the areas at risk of contamination based on the DRASTIC model (Depth to water table, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity). The research also incorporated Land Use Land Cover (LULC) data to improve the accuracy of the vulnerability assessment. By integrating groundwater quality data and spatial information, this study provides a detailed understanding of the zones that are most susceptible to contamination and offers recommendations for effective groundwater management.

The study area, Banaskantha district, lies in the north-western part of Gujarat, covering approximately 12,703 km^2. The district experiences a semi-arid climate, with hot summers observing maximum temperature up to 41°C, dry winters with minimum temperature 9°C and an average annual rainfall of 559 mm. The Banaskantha district features a multilayered aquifer system composed of Precambrian hard rocks, semi-consolidated Mesozoic and Tertiary formations, and unconsolidated Quaternary alluvial deposits. Groundwater occurs in both phreatic and confined conditions; however, its development is constrained by the geometry and yield capacity of the aquifers, as well as the groundwater's chemical composition within the geological formations. Groundwater level data and water quality data were obtained from the Gujarat Water Resources Development Corporation (GWRDC). Soil data was sourced from BISAG. Land use and recharge data were derived from remote sensing images (Resourceset LISS-III) and the USGS site for different years. The study utilized borewell data from 2010, 2015, and 2020 to create depth-to-water maps and recharge potential maps.

Groundwater vulnerability was assessed using the DRASTIC method, which is widely recognized for evaluating contamination risks based on hydrogeological factors. The model assigns ratings and weights to the seven parameters, with higher ratings indicating greater vulnerability. The DRASTIC index was computed for various locations across the district using GIS tools to prepare thematic maps for each parameter. Additionally, the LULC data was integrated into the DRASTIC model (resulting in the DRASTIC-LU index) to account for the impact of land-use patterns on groundwater vulnerability. GIS was used extensively for spatial analysis, creating maps for each DRASTIC-LU parameter and the final groundwater vulnerability map. IDW interpolation was used to generate continuous surfaces from discrete data points. Land use and land cover changes were also analyzed using remote sensing data for 2010 and 2020.

The study identified significant variations in groundwater vulnerability across Banaskantha district, with areas in the central and eastern parts showing the highest vulnerability due to shallow water tables, high permeability aquifers, and intensive agricultural activities. Agricultural activities accounted for 40% of the district's land, and the expansion of pasture land (by 5.57%) over the past decade indicated increased anthropogenic pressures. The LULC maps showed that urbanization had increased by 6.97% between 2010 and 2020, further exacerbating groundwater vulnerability in densely populated areas. These changes were reflected in the DRASTIC-LU index, which indicated that vulnerability increased significantly over the study period. The groundwater vulnerability maps were validated using historical water quality data, including parameters such as TDS, chloride, fluoride, and pH levels. The results showed a strong correlation between high vulnerability zones and areas with elevated concentrations of contaminants. The modified DRASTIC-LU index provided better results than conventional DRASTIC approach, with a higher R-square value which indicated that incorporating LULC improved the accuracy of the groundwater vulnerability assessment.

The study successfully delineated groundwater vulnerability zones in Banaskantha district, highlighting the area under risk of contamination. The integration of LULC data into the DRASTIC model improved the precision of the vulnerability assessment, making it a valuable tool for groundwater management. Further the research can be improved by implementing real-time groundwater quality monitoring systems and GIS tools can also provide early warnings of contamination to allow for timely interventions. Reducing the use of chemical fertilizers and promoting organic farming practices can mitigate the impact of agricultural runoff on groundwater quality. The vulnerability maps produced in this study can inform policymakers in developing targeted groundwater management strategies, including the regulation of groundwater abstraction and industrial waste disposal. The assessment of climate change impacts on groundwater recharge and contamination levels, particularly in semi-arid regions like Banaskantha should be further explored. In conclusion, the study underscores the importance of using advanced geoinformatics tools for groundwater vulnerability assessment and highlights the need for a multi-disciplinary approach to ensure sustainable groundwater management in Banaskantha district.

Keywords: *Groundwater vulnerability, DRASTIC-LU, Sensitivity analysis, LULC, GIS*

ASSESSMENT OF GROUNDWATER QUALITY AND IT'S IMPACT ON HUMAN HEALTH IN SOUTH WESTERN HARYANA, INDIA

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Groundwater is a critical source of drinking water in this semi-arid region and the quality of water resource has a significant impact over the human health. The contaminated groundwater and surface water can lead to a range of acute and chronic health issues depending on the type and level of pollutant or the presence of carcinogenic and non-carcinogenic elements. Due to contamination in the rural drinking water sources, around 38 million Indians suffer from waterborne diseases each year, with an estimated 1.6 million children dying from diarrhea alone; additionally, many Indians are at risk from excessive fluoride levels, and 10 million face dangers from excessive arsenic in groundwater. Haryana, primarily an agrarian state, faces significant water-related challenges including variation and depletion of groundwater and surface water, pollution, and inefficient water use practices. The semi-arid region of Haryana does not have sufficient quantity of water for domestic purposes especially in dry season. Due to the paucity of natural flowing water, the region is irrigated by shallow tube wells and a network of Bhakra Canal Systems and Western Yamuna Canal Systems along the Hand-pumps and bore-wells used for pumping out the groundwater. There is no natural drainage in this region. Dohan and Krishnavati rivers are the ephemeral streams in the area, flowing in direct reaction to precipitation. As a result, the people are compelled to use the groundwater by installing the tube wells and over-exploit the groundwater resource. According to the Groundwater level data (June, 2020), 1948 villages in Haryana are severely groundwater stressed (due to the over-exploitation) as the depth level is deeper than 30 mbgl . The major issues in the region comprised a persistent deficit of water resources and its quality deterioration due to the overexploitation, over-extraction and presence of various contaminants in water resources. The presence of alkalinity, hardness, salinity, fluoride, arsenic, mercury, chloride and various other elements are raising serious health concerns.

Primary data were obtained from collected samples of groundwater and drinking water. Secondary data were obtained from CGWB and Groundwater Cell, Department of Agriculture, Haryana. Instruments used are: ICP-MS and AAS, Hanna pH/TDS/ conductivity meter. Statistical analysis was done using Inverse Distance Weighting (IDW) Interpolation. Collection of groundwater and drinking water sample was carried out through the equally distributed stratified random sampling method from almost all villages in study area. Assessing the drinking water quality for different parameter like physical, chemical (major cations & anions), trace elements based on BIS & WHO standards. Water Quality Index (WQI) was calculated taking the year 2000 as base year. Mapping of Groundwater quality was done with the primary and secondary data from the monitoring and observation wells (piezometer) for groundwater collected by the CGWB and Groundwater Cell, Department of Agriculture, Haryana.

In this research, water samples were collected from multiple locations across the district from deep aquifer-based hand-pumps and bore-wells situated in various villages/town of southwest

Haryana region. Based on the results of analysis it is concluded that the groundwater in South-Western Haryana, is contaminated due to salinity, and high concentration of nitrate, and fluoride, making it unsafe to consume. The primary problem of the study area is the volumetric depletion of water resources, which is reflected by drying up of wells and decline in ground water levels. The average depth of groundwater table is approximately 7 m to 30 m. The groundwater quality indicates low potable rating for the drinking purpose. The areas of Behal, Kairu, Loharu, Tosham, fall under the category of over-exploited whereas Siwani, Bhiwani, Bawani Khera fall under the safe category as per GW extraction status. The poor groundwater quality is caused by agriculture, unplanned municipal growth, overexploitation and poor groundwater management which has led to various issues such as declining water tables, chronic health diseases, acute health risk etc. This location has the highest fluoride content ever reported in Haryana state which is far exceeding the permissible limits set by the WHO and BIS. As a result, water quality might pose a significant health risk to inhabitants of western Haryana.

Keywords: *Groundwater resource, Semi-arid region, Human health, water quality, chemical analysis*

EMPIRICAL EVALUATION OF WATER-SAVING IN IRRIGATION CANALS IN THE SEMI-ARID ZONE OF INDIA

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In the semi-arid region of Fatehpur Sikri Block, Agra district, India, water scarcity presents significant challenges for both irrigation and drinking water supply. This study explores the feasibility of improving water management in the Fatehpur Sikri Branch Canal (FSBC), which faces substantial water losses due to seepage and evaporation. Given the limited availability of groundwater and restricted access to surface water, the study evaluates potential water savings 4.60 million cubic meters (MCM) for drinking water and 9.10 MCM for irrigation by canal lining and improved distribution techniques. A total of 56 scenarios were analyzed, involving various combinations of full and partial lining of the FSBC and its distributaries. Empirical formulae were applied to calculate water savings, and the optimal solution was identified: lining the branch canal up to 32.960 km. This approach was found to be the most viable, as it preserves water for tail-end users and prevents water theft at upstream portion. In addition, a sensitivity analysis using CROPWAT software assessed the impact of climatic factors on irrigation demand. The analysis showed that maximum temperature had the greatest influence, significantly increasing evapotranspiration and irrigation needs. The study also evaluated ten empirical formulae for seepage estimation, with the Molesworth, Yennidumia, Ingham, and Egypt formulas performing the best. These findings offer valuable insights for sustainable water resource management in arid and semi-arid regions, promoting water-efficient practices and helping to mitigate the effects of water scarcity on agriculture. As water is an essential natural resource, critical for plant growth and daily activities. Over the past few decades, rapid population growth and increased agricultural demands have more than doubled water usage. Agriculture consumes 70% of global freshwater, and this demand is particularly pronounced in semi-arid regions where irrigation is necessary to sustain crop production. However, water scarcity, exacerbated by human activities and climate change, continues to challenge sustainable water management, especially in regions dependent on irrigation. In semi-arid zones like the Fatehpur Sikri, irrigation canals such as the FSBC are vital for water distribution. However, these unlined canals suffer from significant water losses due to seepage and evaporation, leading to inefficient irrigation, reduced water availability for downstream users, and negative impacts like rising groundwater levels and soil salinization. Globally, water conveyance losses in unlined canals can reach up to 70%, highlighting the need for effective water management strategies. This study explores the potential of canal lining to reduce water losses and meet the irrigation and drinking water needs of a 5000 ha water-stressed area in the Fatehpur Sikri Block. Additionally, the study evaluates 10 empirical models for seepage estimation, providing insights into their suitability for local conditions.

This study was carried out for a command area of Fatehpur Sikri Block. About 40 villages are facing acute shortage of water for both drinking and irrigation. Presently, this water-stressed area is not a part of any existing canal network system, and thus, agriculture

primarily relies on rainfall. The nearest potential source of water is the FSBC, completely unlined and is facing the problem of not only seepage but also water pilferage in its head reaches. The statistical survey of Fatehpur Sikri Block carried out in 2020 estimates the area of this Block as 397.24 km^2, population as 233128, and population density as 586 people per km^2. In field survey, the approximate forecasted population of the 40 villages falling in the water-stress high elevation area was revealed to be of the order of 250000 people for demand estimation purpose. The data of cropping pattern and net-sawn area for Fatehpur Sikri Block was taken from (CGWB, 2018-19). The long-term climatological data (38 years) of rainfall was collected from IMD. The study includes determination of domestic and irrigation demands of the water-stress area; seepage loss for unlined channels; water saving by lining of canal network involving branch, major distributaries, and minor canals; and economics of canal lining; and proposing a near optimal strategy for lining the FSBC canals selected such that the water demand of the water-stress area is fully met economically, the authorized tail-end water users are unaffected, and reasonably uniform seepage takes place in the FSBC command area for ground water recharge. In addition, Sensitivity analysis performed for the climatic factors using the base line scenario. Since the FSBC network comprises of fully unlined canals including branch canal itself, its major and minor distributaries, it is in order to identify a minimum number of canal-reaches for lining so that it enables stoppage of vandalism or water theft from upper canal (head) reach, uniform distribution of seepage, no impact on the authorised tail-end users, and lining cost is minimum. To this end, various scenarios were developed based on lining of bed and/or banks of the branch canal of FSBC system in its full/partial length, lining of bed and/or banks of minors and/or distributaries only, lining of bed and/or banks of minors only and so on.

The analysis led to capability of only six combinations to be effective in uniform ground water recharge, where the minors and distributaries are unlined, only 3 combinations are effective in stopping the water theft by lining in head reaches, and therefore, in these three cases, tail-end users will not be affected by lining. However, lining of the branch canal of FSBC system up to 32.960 km saves 17.355 MCM water with lining cost of INR 13.42 crores and it appears to be the most feasible option, for it meets all the constraints and is economically feasible as well, for the unit cost of water saved by lining is 0.773 INR crore per MCM, which is minimum of all the available options with sufficient water availability. Sensitivity analysis shows that the maximum temperature is the most sensible factor for irrigation demand. It can be inferred that an increase in the maximum temperature can raise the potential evapotranspiration rate rapidly, which results in a significant increase in irrigation water demand. This study concludes that saving water from seepage loss of the unlined canals by lining appears to be a feasible solution for developing countries to safeguard the people from water scarcity. Here, exists a potential of 50.578 MCM water saving by lining the whole FSBC system available for diversion for other uses, such as the water-stress area under study requiring 13.73 MCM. The lining of branch canal in partial length up to 32.96 km length is the one recommended for adoption. Sensitivity analysis shows that the maximum temperature is the most sensible factor for irrigation demand. This analysis contributes to informed decision-making for sustainable water resource management, encouraging water-efficient agricultural practices and mitigating the adverse effects of water scarcity in arid and semi-arid agrarian parts of India.

Keywords: *Canal irrigation, seepage loss, water scarcity, sustainable water management*

AN APPROACH FOR WATER RESOURCE MANAGEMENT IN THE SEMI-ARID REGION: A CASE STUDY OF KALAHANDI DISTRICT, ODISHA, INDIA

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At present the overgrowth of population and the climate change have led to water scarcity in many regions globally especially semi-arid regions. In semi-arid regions, generally precipitation cannot recharge the groundwater to meet-up the need of water-demand of the region for either agricultural, industrial, domestic or drinking purposes. Hence, water resource management is essential for survival of the economy and livestock. To address the acute problem of water scarcity in such a region, water resources should be analyzed in terms of relevant parameters, assessed and utilized with proper and scientific planning. The present study has been carried out in Kalahandi district of Odisha, India, which is a well-known a semi-arid region. Because of its semi-arid location, the Kalahandi district experiences irregular pattern of precipitation, which affects the replenishment of the subsurface water. Poor water management techniques combined with over-exploitation of groundwater for irrigation purposes make the problems worse. By defining priority zones for conservation and augmentation, the present work aims towards the sustainable management of groundwater resources by offering a thorough review of the factors controlling the groundwater recharge. The implementation of proper management plan of groundwater and surface water may address to the sufferings of the people in the area under study during dry season and improve their socioeconomic conditions too. Kalahandi has various mining industries, which suffer from water scarcity problems.

In this study, six different parameters have been selected to analyze the hydrogeological condition of the study area. The parameters are geomorphological aspects, rainfall, elevation, lineament density, drainage density and land use land cover. The AHP technique is used to assign relative weights to different criteria that affect groundwater recharge. To understand the rainfall pattern of the study area, an annual average rainfall map has been prepared based on the available rainfall data of the last 10 years. The topographic features and slope conditions of the study area have been analyzed in the spatial map presenting the geomorphological features along with percentage of slope which is generated using the SRTM DEM data. Hydrological conditions of surface and groundwater have been assessed with the help of map presenting drainage network and groundwater head map. To get the idea of the water demand of the Kalahandi district, available data of utilization of water, block wise and sector wise, has been used. Analytic Hierarchy process (AHP) has been applied for identification of the most suitable sites to conserve the water in the study area. In this study, these weighted layers are integrated using the Multi Criteria Decision Making (MCDM) technique to produce a suitability map for groundwater conservation. Five different zone have been identified and marked as excellent, good, moderate, poor and very poor. These zones depict the suitability level for conservation of water resources in the region to develop different action plan like rainwater harvesting, check dams, recharge pits, lake/reservoir etc. The ArcGIS platform facilitated the spatial analysis of data, allowing us to delineate the areas with different suitability zones. Based on the possibility for water conservation, the Kalahandi district has been identified as various zones using suitability map for conservation of water resources.

The most suitable areas are those with flat terrain, good soil permeability, and sufficient vegetation cover. These attributes make these areas perfect for conservation techniques like groundwater recharge. Although less permeable soils are prevailing in few patches of the areas, the regions with moderate to good permeability may be marked for the conservation of water resources. The regions with low and extremely impermeable soils and steep slopes, reduce the possibility for initiatives of water conservation. In these zones alternative methods and strategies may be can be effective. It is important to identify these zones for a number of reasons. Firstly, it provides policymakers and local authorities with an easy-to-understand, data-driven methodology for identification of the regions that require groundwater recharge. For efficient resource management in areas like Kalahandi, where water scarcity can negatively impact livelihoods and agriculture, it is essential to comprehend the spatial distribution of groundwater potential. In the present study, MCDM and AHP highlight the benefits of integrating geographical data analysis and interpretation. MCDM facilitates the amalgamation of diverse geographical elements, enabling the presentation of an all-encompassing and impartial land suitability map. When combined, these techniques provide a strong tool for resolving groundwater issues in semi-arid areas. This strategy may be applied to other semi-arid areas with comparable groundwater problems. The study may help for conservation of groundwater resources providing a scalable and replicable approach for evaluating groundwater potential in regions with high water demand and restricted supplies. Long-term water management strategies should include the imposition of restrictions on over-extraction, enhance groundwater recharging processes to lessen the effects of droughts. This study may provide Kalahandi district a direction towards the development of socio-economic planning of the area with the sustainable approach.

Keywords: *Groundwater, AHP, MCDM, water resource management, semi-arid regions*

LONG-TERM TREND ANALYSIS OF GROUNDWATER WITHDRAWALS IN A SEMI-ARID BASIN OF SOUTH INDIA

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Groundwater is essential for agriculture in arid and semi-arid regions, serving as a reliable, drought-resistant, and consistent source of irrigation, particularly where surface water resources are scarce. These regions are characterized by variable rainfall patterns and prolonged dry spells, which can significantly impede agricultural productivity. As a result, groundwater has become a critical resource for sustaining crop yields and maintaining food security in these areas. However, the over-extraction of groundwater poses significant risks to both the environment and agricultural sustainability. The consequences of excessive groundwater withdrawal can include aquifer depletion, land subsidence, lowered water tables, deteriorating water quality, and reduced surface water flow. These issues not only threaten agricultural productivity but also have harmful impacts on local ecosystems and increase the energy costs associated with water extraction. Given the interconnectedness of groundwater and surface water systems, comprehensive studies on groundwater are vital for improving our understanding of overall water cycles and resource management. Despite the importance of groundwater in agricultural systems, neglecting it in water availability estimates can lead to significant underestimations or overestimations of total water resources. While much research has focused on groundwater recharge, storage, and fluctuations, there has been a relative lack of studies addressing groundwater abstraction, which is crucial for effective water management and sustainability. The Intergovernmental Panel on Climate Change (IPCC) underscores the importance of studying groundwater withdrawals, particularly for irrigation purposes. In India, research on groundwater withdrawals remains limited due to a range of factors, including data gaps, funding constraints, the inherent complexity of groundwater systems, and a historical emphasis on managing surface water resources. These limitations hinder effective policy-making and management strategies aimed at promoting sustainable water use in agricultural practices.

This study focuses on the long-term trend analysis of groundwater withdrawals in the semi-arid Gundlu Basin of South India. This region serves as an important agricultural area that relies heavily on groundwater for irrigation. The analysis considers various time scales, including yearly, monthly, and inter-monthly data, to capture the dynamics of groundwater abstraction more comprehensively. To assess the trends in groundwater abstraction, the study employed several statistical methods, including the Mann-Kendall (MK) test, Sen's slope estimator, and innovative trend analysis techniques. The MK test is a non-parametric method widely used to identify trends in time series data, making it particularly suitable for analyzing groundwater withdrawal patterns. This method is robust in handling missing data and does not assume any specific distribution of the data, which is advantageous given the often-irregular nature of groundwater data. The Sen's slope method complements the MK test by providing a measure of the magnitude of the trend. Together, these methodologies enable a thorough and robust analysis of long-term changes in groundwater abstraction, allowing for a clearer understanding of the underlying trends and their implications. Additionally, groundwater abstraction was estimated using power consumption methods recommended by the USGS. This approach calculates the volume of groundwater extracted based on the energy consumed by pumping systems. This method is particularly useful when direct measurement data is sparse, as it leverages existing data on electricity consumption related to groundwater pumping, providing a reliable estimation of groundwater withdrawals. The data used for this study was sourced from a combination of databases on groundwater levels, irrigation practices, and power consumption for water extraction. The dataset included historical records of power consumption for groundwater withdrawals over the past thirty years, with a specific focus on the changes observed in the last decade. This long-term data set is crucial for understanding the trends in groundwater usage and its implications for sustainability. The findings of this study indicate a significant increase in groundwater abstraction in the Gundlu Basin, marking a tenfold rise over the past thirty years. Notably, the trend of groundwater withdrawals accelerated sharply after 2010. This increase suggests a rising demand for groundwater, potentially driven by several factors, including increased agricultural activities, changes in crop patterns, and depletion of surface water resources. As surface water becomes less reliable due to climate variability and over-extraction, farmers may increasingly turn to groundwater as a more stable source for irrigation, highlighting a growing reliance on this vital resource.

The trend analysis revealed that the rate of groundwater abstraction has outpaced the natural recharge rates in the region, raising significant concerns about the sustainability of these water resources. The statistical analysis using the MK test confirmed that the increasing trend in groundwater withdrawals is statistically significant, with the Sen's slope analysis indicating a rapid upward trend in abstraction rates. The results underscore the urgent need to address the sustainability concerns associated with groundwater resources in the Gundlu Basin. The rapid increase in groundwater abstraction poses substantial risks of over-extraction, which could lead to long-term ecological and socio-economic consequences, including increased competition for water, conflicts among users, and the degradation of water quality. This study highlights the importance of integrating groundwater abstraction data into broader water management strategies to ensure the sustainability of water resources in semi-arid regions. Comprehensive studies that consider both groundwater and surface water interactions are vital for improving water resource management. Policymakers must prioritize research on groundwater withdrawals, particularly in regions like India, where reliance on groundwater for irrigation is increasing rapidly. Addressing the existing data gaps and funding constraints will be crucial for developing effective management strategies that balance agricultural needs with the sustainable use of groundwater resources. In conclusion, this study aims to provide valuable insights into the trends of groundwater withdrawals in the Gundlu Basin, informing policy decisions and promoting sustainable agricultural practices. By enhancing our understanding of groundwater dynamics, this research contributes to the broader discourse on water resource management in arid and semi-arid regions, emphasizing the critical need for sustainable practices to ensure the long-term viability of this essential resource.

Keywords: *Groundwater abstraction, trend analysis, semi-arid regions, sustainable water management, groundwater depletion*

QUANTITATIVE ASSESSMENT OF CANAL WATER ALLOCATION FOR GROUNDWATER RECHARGE IN NORTH-WEST INDIA

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Groundwater is a major global source of freshwater resources and is essential for water management, governance, and strategic planning. Groundwater provides about 85% of the nation's drinking water and irrigation needs, serving as a critical resource for millions who lack access to alternative reliable water sources. The urbanized demand for groundwater due to population growth and agricultural expansion presents significant challenges. Over-extraction and pollution threaten groundwater quality and availability, creating a pressing need for comprehensive governance frameworks and sustainable practices. Punjab, having a geographical area of 50,362 km^2, is divided into 24 districts and 145 blocks. The state is predominantly agrarian, with agriculture playing a central role in its economy and land use. The state's 85% of land is under cultivation, with a cropping intensity exceeding 204%. Of this cultivated area, 71.3% is irrigated using groundwater, while the remaining 28.7% relies on the canal irrigation network. Over the past six decades, the area irrigated by canals has declined from 58.4% to 28%, while the area irrigated by tubewells has significantly increased from 41.1% to 71.3%. This shift reflects a major transformation in irrigation practices, with a growing reliance on groundwater resources as opposed to surface water from canals. Consequently, the state's total annual groundwater recharge is estimated at approximately 18.94 billion cubic meters (BCM), while the annual extractable groundwater resource stands at 17.07 BCM. However, the total groundwater extraction in the state reaches around 28.02 BCM. This shift is further reflected in the increase in the net irrigated area, which has grown from 54% to 99.2%. This expansion has placed considerable stress on water resources, particularly on groundwater reserves. The depletion is largely a result of the widespread cultivation of water-intensive crops, particularly paddy (rice), which requires significant amounts of water. Encouraged by government policies such as minimum support prices (MSP) and free electricity for farmers, the state's agricultural sector has prioritized high-yield but water-intensive crops, straining groundwater resources. As a result, Punjab's groundwater levels are dropping at an alarming rate, with the water table declining by nearly a meter each year in many regions. This unsustainable extraction has led to various environmental and social impacts. Deeper wells and increased pumping are needed to access diminishing water supplies, raising costs and energy demands for farmers. In some areas, the depth of groundwater has made it difficult for small-scale farmers to continue agricultural activities, impacting rural livelihoods and economic disparities. Additionally, deeper water tables reduce natural groundwater recharge and can lead to soil degradation and salinisation, further affecting crop productivity.

This research focuses on quantifying canal water allocations for groundwater recharge during seasonal releases as a means to strengthen agricultural resilience and improve water management in Longowal Rajwaha, Sangrur, Punjab. A region facing 320% of groundwater exploitation. Given the limited availability of comprehensive studies and data on canal water's role in groundwater recharge, this study introduces an innovative approach to minimise groundwater depletion through the strategic use of canal water during specific non-demand periods. By establishing recharge structures at canal tails and identifying opportune

periods for water release, this research aims to provide a solution that integrates surface and groundwater resources effectively, enhancing the sustainability of agricultural practices. The study investigates the imbalance between canal water supply and agricultural demand by analysing weekly non-demand periods where canal water could be reallocated for groundwater recharge. Detailed discharge data from 87 outlets along the Longowal distributary is used to quantify the canal water volumes available for recharge during these targeted periods. By assessing this discharge data, the study creates a strategic framework for optimizing water distribution that not only supports crop requirements but also ensures groundwater replenishment. This dynamic approach provides a pathway to balance water supply and demand by optimizing canal water flows, which are underutilized. A critical component of this framework involves AI-based analysis of crop water requirements and canal discharge patterns, allowing for predictive insights into the dynamics of canal water distribution. This enables a precision-focused methodology to optimize the release schedules for maximum recharge potential. The model aligns water availability with crop demand cycles, ensuring that water is utilized most effectively when canal demand is low and recharge potential is high. Through this model, the study delineates key intervention points, suggesting optimal timing for water releases that can be used to recharge groundwater without impacting irrigation requirements during peak demand periods.

Results from the AI-driven analysis show significant periods throughout the seasonal cycles where surplus canal water can be redirected to recharge aquifers without affecting irrigation needs. This approach highlights the potential for an integrated water management strategy that merges surface water and groundwater resources to meet agricultural demand while simultaneously addressing groundwater scarcity. By quantifying the available recharge volumes, the framework supports policy development and decision-making for water resource managers, emphasizing the importance of equitable distribution practices and the sustainable use of canal resources. The findings of this study are timely and impactful, offering valuable insights for policymakers, water managers, and agricultural stakeholders. This research highlights the importance of data-driven water distribution strategies that respond to regional challenges, including climate change impacts, increased agricultural water demands, and the need for resource equity. Promoting a balanced and optimized allocation of canal water for irrigation and groundwater recharge contributes to the resilience of local ecosystems and enhances agricultural productivity. In conclusion, it provides a comprehensive, science-driven framework that integrates canal water management with groundwater recharge, thus addressing the growing concerns of water scarcity in semi-arid regions. The proposed approach demonstrates a practical, scalable solution to enhance groundwater levels, supporting sustainable agriculture and advancing regional water security amid mounting environmental and economic pressures.

Keywords: *Groundwater recharge, semi-arid region, canal water, supply and demand, artificial intelligence*

AN INTEGRATED APPROACH OF GIS AND AHP FOR GROUNDWATER POTENTIAL ZONE MAPPING IN PARTS OF MIRZAPUR DISTRICT, UTTAR PRADESH, INDIA

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In India, the water demand is steadily rising due to population growth, agricultural needs and irregular and uneven distribution of monsoonal winds. Since monsoon serve as the primary source of water in India, contributing significantly to both rainfall and groundwater, its unpredictability leads to water scarcity across many regions. To address the rising water demand, groundwater resource mapping and replenishment of existing groundwater potential sites are the major concerns in recent years. The groundwater potential of a region is influenced by factors such as lithology, geology, hydrology, geomorphology, water quality and meteorological conditions. Geospatial techniques are widely used in water studies for estimation of surface and subsurface water, rapid groundwater mapping covering vast and unreachable areas, watershed management, identifying artificial recharge structures and hydrological modelling etc. The Multiple Criteria Decision Analysis (MCDA) provides an efficient approach to water resource management. Among the various MCDA techniques, the Analytic Hierarchy Process (AHP) is the most widely recognized and frequently applied, especially in groundwater prospecting research. The AHP, introduced by Tomas Saaty (1980), is a valuable tool for addressing complex decision-making scenarios related to groundwater. It simplifies intricate decisions into a series of pairwise comparisons and integrates the results effectively. Mirzapur district predominantly relies on agriculture, and the persistent challenge of inadequate groundwater availability poses a significant challenge. This study aims to identify and delineate groundwater potential zones through the integration of remotely sensed data and multi-criteria analysis, contributing to sustainable water resource development and planning in the region.

The study area, situated in the Mirzapur district, lies between latitudes 24º57'30" to 25º7'30" North and longitudes 82º47'30" to 82º55' East. It falls in the Survey of India toposheet no. 63K/16 and 63L/13, encompassing approximately 256.23 km^2. For this study, Survey of India (SOI) toposheet no. 63K/16, 63L/13 (1:50000 scale) and Sentinel 2A satellite imageries (10 m resolution), Shuttle Radar Topography Mission (SRTM) DEM (30 m) were utilized to generate various thematic layers. Thematic maps of geomorphology, slope, drainage density, lineament density and land use/land cover of the study region were generated using ArcGIS 10.5 software. All the thematic layers have been systematically compared to others through a comparison matrix. This matrix simultaneously evaluates two thematic layers based on their relative influence on groundwater development within the study area. Parameters assigned higher weights indicate greater influence, while those with lower weights reflect a lesser impact on groundwater potential. The relative ratings for each thematic layer were assigned using Saaty's scale of relative importance, which ranges from 1 to 9, where a value of 9 signifies extreme importance, and a value of 1 represents equal importance. The resulting pairwise comparison matrix is subsequently utilized in computing normalized weights. The weights assigned by the AHP method are derived from the normalized principal eigenvector. The Groundwater potential zone map was generated by integrating all thematic layers with

weighted index overlay analysis (WIOA) method in GIS platform. The groundwater potential zone map is categorised into very good, good, moderate, and poor zones. The final output was validated using available groundwater prospect map and yield zone range from Bhuvan bhujal (NRSC) portal.

The study area is characterized by sixth order drainage showing dendritic pattern and moderate to high drainage density. Based on slope of the terrain, most of the area comes under the very steep class while only small part of area comes under the gentle slope category. The study area is crisscrossed with lineaments with lineament density ranging from 0.31 to 3.5 km/km^2. The main geomorphic features of the study area include flood plain, dissected plateaus, alluvial plains, gentle slope regions and water bodies. Based on LULC map, the study area has been categorized into five classes- agriculture, plantation forest, built-up, waterbodies, and bare land. The findings of this study will be a guide for planners and local authorities, supporting the evaluation, management, and sustainable use of groundwater resources, as well as the identification of suitable locations for future exploration.

Keywords: *Remote sensing, GIS, groundwater potential zone, analytic hierarchy process*

HYDROCHEMICAL EVOLUTION OF GROUNDWATER IN THE ARID REGIONS OF NORTH-WEST INDIA

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In arid and semi-arid regions, groundwater is a vital resource. Absence of surface water in these regions induce extra stress on this vital resource. Groundwater serves as the primary source for drinking, agricultural and industrial activities. The hydrological character of these regions includes less precipitation, high evapotranspiration, and extreme temperature ranges. The chemical composition of groundwater in these regions differs significantly as compared to humid zones. The natural evolution of groundwater chemistry is dependent on geogenic processes such as intense evaporation, ion exchange and mineral dissolution etc. Apart from it anthropogenic factors also play a significant role in determining its quality and quantity. In India, arid zone covers upto 12% of the total land area encompassing large area of Rajasthan, Gujarat and Haryana. Over extraction of groundwater for irrigation has exacerbated the situation causing groundwater level to fall deeper than 50 m at many locations. Commonly observed geochemical character of groundwater in these regions include brackish type of groundwater, elevated concentration of sodium, chloride and Calcium and dominance of NaCl type of groundwater facie reflecting evaporative enrichment and silicate weathering as major process. Apart from groundwater quantity these regions also suffer contamination due to nitrate and fluoride. Understanding the chemical evolution of groundwater is crucial for addressing the broader socio economic and ecological system to promote United Nation's goal of sustainable water management in this climatically vulnerable region.

Data was procured from CGWB for the year 2015 and 2022. A total of 412 (2015) and 477 (2022) groundwater samples were analysed for groundwater chemical parameters. We have utilized pipers plot, gibbs plot, Bi-variate plots (Na/Cl vs Electric conductivity (EC), Na/Cl, Ca+Mg vs SO_4+HCO_3), Chloro Alkali Index and Saturation Index to understand groundwater chemical evolution. Utilized multivariate statistical methods like Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) to identify most influential chemical processes. Used ArcGIS v10.3 for creating spatial maps of groundwater level and quality, PHREEQC for calculating the saturation indices, and Origin v2024b for PCA, HCA analysis.

The result obtained from Gravity Recovery and Climate Experiment (GRACE) for NW India shows a decreasing trend in total water equivalence thickness from 2015 to 2023. The decline may be attributed to increasing groundwater and surface water usage. Spatial distribution of groundwater level indicates groundwater exists at deeper depth at Jodhpur, Bikaner, Sikar, Churu, Jaisalmer, Barmer, Kachchh, Pali, and Mahendragarh. Groundwater extraction is majorly for irrigation use followed by domestic and industrial uses. Groundwater recharge is primarily occurring through ephemeral streams during runoff events. Evaporation is more as compared to rainfall recharge, which significantly reduces the groundwater level in arid regions. Many aquifers are over-exploited for meeting daily demand of large population as a result, declining groundwater levels concentrated groundwater facies from mixed Ca-Mg-HCO_3 types to NaCl, due to increased evaporation, ion exchange and excessive groundwater

pumping. The highest EC values were observed in Jodhpur with 18670 µS/cm in 2015 at Bilara, and 24290 µS/cm in 2022 at Piparcity. The order of cation and anion abundance remained consistent across both years with Na > Ca > Mg > K for cations, and Cl > HCO3 > SO4 > NO3 for anions. The main reason behind elevated Na concentration is determined as silicate weathering and forward ion exchange. Absence of precipitation dominance in Gibbs diagram suggests limited freshwater recharge. Groundwater is affected by inland salinity, more than 60% of the samples classified into Brackish water and more than 80% of the samples are classified into very hard water. In arid zones, subsurface soil is affected from salinity and nitrate contamination due to irrigation return flow and long-term evaporation. From 2015 to 2022, the percentage of samples exceeding permissible limit increased for Fluoride, Chlorine, Nitrate and TDS highlighting a concerning decline in water quality. The average F concentration increases from 1.09 mg/L to 1.56 mg/L in 2015 and 2022 respectively which crossed the permissible limit. Groundwater is found to be oversaturated with calcite, dolomite causing more calcrete formation affecting soil health while it is undersaturated with gypsum. Principal Component Analysis and Hierarchical Cluster Analysis highlighted evaporitic enrichment and ion exchange combined with anthropogenic impact for groundwater evolution. The Intergovernmental Penal for Climate Change (IPCC) have identified climate change as key issue regarding the sustainability of groundwater resource. The CMIP6 projection in for Rajasthan shows increasing trend in precipitation, however its distribution will be will be unequal. With increasing precipitation groundwater storage change will be dependent upon land use practices and other factors.

Arid zones are climatically vulnerable region where limited and sporadic rainfall exacerbates the situation of groundwater recharge and quality. We have investigated the spatial and temporal variation in groundwater level and quality across the arid region of NW India between 2015 to 2022. TDS value often exceed potable limits, highlighting limited recharge and impact of salinity. Natural geochemical processes, such as carbonate weathering, gypsum dissolution, and cation exchange, continue to play a major role in shaping groundwater composition. The dominance of processes like silicate weathering, ion exchange, and evaporation, along with high nitrate contamination, underscores the urgent need for sustainable water management strategies. The findings emphasize the critical need for sustainable groundwater management in arid regions to mitigate salinization, preserve water quality, and ensure long-term resource availability.

Keywords: *Arid region, groundwater, hydrochemical evolution, water chemistry, NW India*

DIVERSITY OF PERCEPTION ON GROUNDWATER RISK FACTORS AND CONSERVATION PRACTISES: A MULTI-GROUP ANALYSIS FROM TAMIL NADU, INDIA

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Groundwater is an indispensable resource, serving as a primary source for consumption, agriculture, and ecological balance. In South India, over 85% of rural households depend on groundwater for drinking water, and it sustains 60% of agricultural irrigation needs. However, increasing demands from population growth, rapid urbanization, and erratic rainfall have intensified groundwater scarcity and quality degradation. Coastal areas face significant aquifer salinization risk while over-pumping of aquifers and contamination from pollutants threaten shallow groundwater reserves. This study was conducted at Sadhana Forest, an ecosystem restoration organization in Auroville, Tamil Nadu, focused on reforestation and water conservation. This research targeted four stakeholder groups—surrounding villagers, short-term and long-term volunteers of Sadhana Forest, and students offering insights into their water usage, groundwater representation, risk perceptions, and conservation strategies.

A structured survey was conducted to gather quantitative and qualitative data from 118 respondents across four groups: 39 villagers from Morattandi, Pattanur, and nearby areas; 29 short-term (up to 1 year) volunteers engaged in Sadhana Forest projects; 13 long-term (>1 year) volunteers with extensive ecological restoration experience; and 37 geology MSc students from Pondicherry University visiting Sadhana Forest. The survey was conducted as part of the project "Groundwater recharge and sustainable extraction through resilient forest communities", financed by Geoscientists Without Borders. The survey explored representations of the water table depths, seasonal scarcity trends, groundwater risks (contamination, over-pumping, salinization), well-location preferences, and knowledge of conservation practices. Key metrics included perceived water depths (m), scarcity prevalence (yes/no), and risk evaluations on a 3-point scale (low, medium, high). Statistical tools, such as descriptive statistics, Spearman correlation tests, and regression modeling, were employed to examine relationships between water scarcity perceptions, group membership, and risk awareness. Open-ended responses underwent thematic analysis to provide deeper qualitative insights into community-specific groundwater practices and challenges. Additionally, the survey investigated the adoption of water conservation practices such as rainwater harvesting and planting drought-resistant tree species, cultural attitudes toward groundwater use and management. Insights gained from the analysis aim to inform localized water conservation strategies and dissemination approaches, and foster sustainable groundwater practices tailored to each group's unique challenges and perspectives.

The results demonstrate a wide diversity of perceptions both among individuals and across groups. 70% of respondents describe groundwater as resembling a lake or river, while 30% associate it with being stored in mud, sand, or rock cracks. Regarding groundwater depth,

villagers perceived the deepest water table, with an average depth of 222 m, compared to 67 meters for university students and 54 meters for long-term volunteers. Among the respondents, 54% of villagers reported experiencing water scarcity, compared to 23% of long-term volunteers and 15% of university students. 80% of respondents perceived that the months of April and June are the most water-stressed periods of the year. Salinization was identified as a major concern by 64% of villagers, compared to 38% of volunteers and 25% of university students. Contamination risks were rated high by 52% of volunteers, 50% of villagers, and 35% of university students. Over-pumping risks were considered high by 45% of volunteers, 40% of villagers, and 30% of university students. Across all groups, 13.9% of respondents preferred “Low terrain, near a forest” as an ideal location for drilling a borewell, while 9.3% favored “Near a pond and monsoon river.” In an open-ended question about their preference for an ideal location for drilling a borewell, 65% of villagers used terminology such as "proximity to rivers and ponds," while 70% of university students used "recharge zones and low-slope areas." Volunteers used a mix of terminology, with 55% favoring terms like "recharge zones and forests" and 25% using "proximity to rivers and ponds." Conservation practices showcased diverse approaches. Villagers suggested traditional methods such as rainwater harvesting (28%) and tree planting (18%). Long-term volunteers emphasized greywater recycling (30%) and efficient irrigation techniques (20%), while university students focused on aquifer recharge techniques (35%) and reducing water wastage (25%). Regression analysis identified contamination risk and group membership as significantly correlated with the perception of water scarcity, explaining 48% of the variability in scarcity responses.

The study highlights significant disparities in groundwater perceptions, risks, and conservation practices among respondents and across the different groups of responders. Villagers, heavily reliant on deep aquifers, perceived the deepest water tables and reported the highest prevalence of water scarcity, particularly during the peak water-stressed months of April and June. Salinization emerged as a primary concern among villagers, while contamination and over-pumping risks were more pronounced among volunteers. Preferences for ideal borewell locations reflected diverse knowledge sources. Villagers relied on practical observations of natural water sources, such as rivers and ponds, while university students prioritized scientific concepts like recharge zones and low-slope areas. Volunteers demonstrated a blend of both approaches, integrating practical insights with ecological and technical considerations. Conservation practices also varied, with villagers relying on traditional methods like rainwater harvesting and tree planting, while long-term volunteers and university students emphasize adopting technical practices such as greywater recycling, aquifer recharge, and water-use efficiency. The data reveals how social roles and lived experiences shape perceptions of groundwater risks and conservation practices, with distinct patterns emerging across gender, knowledge sources, and community roles. Villagers' reliance on natural water sources reflects traditional ecological knowledge, while students' focus on recharge zones highlights academic influence. The integration of practical and scientific perspectives among volunteers underscores the potential for collective, interdisciplinary approaches to address water scarcity and quality issues. It paves the way for tailored communication strategies to effectively share groundwater knowledge with diverse groups. Such approaches can enhance understanding and support future watershed management interventions.

Keywords: *Groundwater, water scarcity, salinization, contamination, over-exploitation*

ON THE RELATIONSHIP BETWEEN GEOMORPHIC CONNECTIVITY AND PEIZOMETRIC SURFACE IN A SEMI-ARID REGION, LOWER CHAMBAL BASIN, INDIA

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Topography known as a major factor controlling the spatial patterns of water saturated areas and helps in understanding the variations in soils and hydrological processes. Topographic Wetness Index (TWI) measures the possibility of water buildup on a slope by taking into account the local slope gradient as well as the upslope contributing area. TWI is frequently used to map waterlogging-prone locations, locate possible groundwater recharge zones, evaluate the dynamics of soil moisture, and forecast vegetation patterns. High values in TWI and Wetness Index based on Landscape position and Topography (WILT) are considered to represent high potential recharge zones but the actual effectiveness of this indices falls short when it is noted that the regions with high TWI on slopes <5 degree does not improve water table depth over the years. The question remains still that these indices which highlight topographic wetness are interconnected to what extent, as it is assumed that the interconnectedness of these zones add to surface runoff in regions with low slope thus affecting depth of groundwater. This study deals with the interconnections of groundwater recharge zones in the semi-arid regions of the Lower Chambal River basin and explores the reasons of anomalous behaviour of water table in Lower Chambal River basin through use of indices such as TWI and Index of Connectivity and correlating with ground water table.

For this study, SRTM DEM data used to derive TWI and Index of Connectivity. There are multiple procedures involved in determining the TWI. First, determine the terrain's slope gradient, which is usually given in degrees or radians. Then, calculate the area from upstream that drains into each cell, which is known as the contributing upslope area. The formula TWI = ln(a/tan(b)) is then used to determine the TWI, where "a" represents the upslope contributing area and "b" represents the slope gradient in radians. Greater capacity for water buildup and saturation is indicated by higher TWI values, which can have an impact on a range of ecological and hydrological processes. For Index of Connectivity, we use SedInConnect tool by Crema and Cavalli (2018). The Index of Connectivity can be written as: $IC = \log_{10} (D_{upslope} / D_{downslope})$, where D_{up} and D_{dn} are the upslope and downslope components of connectivity. The upslope component (D_{up}) is a quantitative measure of the potential for sediment to be transported downhill from a specific area.

In this study, TWI is observed in the range from 3.47 to 20.81, whereas IC ranges from 1.88 to -13.43. It is found that the derived Index of Connectivity which is a degree to assess how the system facilitates flow from sources to sinks as proposed by the researchers is high in the south west lower Chambal basin. This duality in SW NW regions in connectedness provides information about the process which are surface driven but control both the surface and subsurface. Structural duality is observed to exist in SW-NE trends reflected in surface interconnectedness in the Lower Chambal Basin. It has been provided by the researchers that lateral disconnectors (two 25km lateral gorges) helped the terrain evolve differently resulting in this dichotomy due to which the SW part evolved with extreme ruggedness in terrain aiding the pathways to connectivity. This is one reason why after possessing high TWI in 95 % of SW Chambal basin the water levels are so low. These interconnectedness aid in runoff when these high TWI regions get interconnected through these pathways following climatic extremes, resulting in low groundwater recharge reflected in water table depth.

The important findings included in this study are: TWI is inversely proportional to IC which means more interconnected a region is the less it will recharge the groundwater and thus will impact the piezometric layer inversely. This is evident in the water level around Sheopur i.e. >40m which is about twice below the surface than its NE counterparts. Terrain ruggedness in the badlands of Chambal is an important factor which control the spatial variability of water resources as opposed to the slope. More than 95% of the SW regions are within 5 degree of slope which is significantly lower than the NE counterpart. Despite this low slope water table is twice below as compared. Sediment flux is more in SW region, thus highest Fe and Mn are recorded, this finding can be significant as regions where vertical connectivity is high (high TWI) will see significant concentrations of such elements in groundwater. It is assumed that vertical connectivity is secondary as compared to structural connectivity, thus the ongoing research to integrate both these types of connectivity will have to be seen from a different perspective, can be considered vertical connectivity originates as a result of differences between structural and functional connectivity. Lastly, this study can be a basis of theorising 4-dimensional connectivity (3D structural and 1D vertical), which will immensely help generalizing the complexities in a watershed.

Keywords: *Vertical connectivity, TWI, piezometric surface, lower Chambal basin*

IMPACT OF SEASONAL RESERVOIR DISCHARGES ON GROUNDWATER LEVELS IN SEMI-ARID REGIONS: A COUPLED MODELING APPROACH

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Reservoirs are integral to water resource management, serving functions such as flood mitigation, irrigation, and ensuring water supply. Despite their significance, their influence on downstream groundwater systems, particularly within semi-arid environments, remains inadequately investigated. This research examines the effects of reservoir operations on downstream groundwater dynamics through an integrated surface-groundwater modeling framework. The project employs integration of the Soil and Water Assessment Tool (SWAT) for surface water simulation and MODFLOW for groundwater modeling. By correlating reservoir discharge data with groundwater recharge processes, the study quantifies the spatial and temporal variability in groundwater levels across downstream regions in a semi-arid setting. Reservoir discharge data spanning 1987 to 2017, in conjunction with groundwater monitoring records, Digital Elevation Models (DEMs), and soil and land use maps, was utilized for model calibration. Various scenarios, including high-flow, low-flow, and seasonal fluctuations, were simulated to assess their influence on groundwater recharge.

The results reveal notable temporal and spatial variability in recharge dynamics, with regions proximal to the river exhibiting a rapid groundwater response to reservoir discharge events. Seasonal analyses indicate that monsoon (June-September) releases play a pivotal role in augmenting recharge to downstream aquifers. This research aims to address this research gap by examining the impact of reservoir discharges on downstream groundwater recharge and levels. Using a coupled modeling framework that integrates surface hydrology and groundwater flow, the study provides a comprehensive evaluation of surface-groundwater interactions. Emphasis is placed on quantifying the spatial and temporal impacts of reservoir discharges on groundwater recharge patterns over a 31-year period (1987–2017), delivering valuable insights for the management of water resources in semi-arid environments. This study focuses on Banas River basin, which is the largest river basin within the state of Rajasthan in India. The Bisalpur reservoir in the Banas basin plays important role in the economy of the region, providing water for drinking to various cities and irrigation to Tonk district of Rajasthan. As the climate pattern shifted, leading to increased risks of either water shortage or flooding. The findings will contribute to optimizing reservoir management strategies and the ground water levels to ensure better preparedness for both drought and floods under changing climatic conditions.

An integrated surface-groundwater modeling approach, combining hydrological simulations of surface water processes with groundwater flow dynamics. Surface hydrology, including runoff, river flows, and recharge, was simulated to evaluate the interactions between reservoir discharges and downstream aquifers. Groundwater flow was modeled to represent aquifer characteristics and capture the temporal and spatial dynamics of recharge. The methodology began with data preparation, where reservoir discharge records from 1987 to 2017 were collected to characterize reservoir operations. Groundwater monitoring data from wells downstream of the reservoir was utilized for model calibration and validation. Spatial datasets, including Digital Elevation Models (DEMs), soil maps, and land-use/land-cover (LULC) maps, were processed to support spatial analyses and hydrological simulations. In the model setup phase, the hydrological simulation was configured to calculate river discharge and recharge within the study area, while the groundwater model incorporated aquifer properties and boundaries to simulate groundwater flow. The outputs of surface hydrology, such as recharge and streamflow, were linked to groundwater dynamics, enabling an integrated analysis of surface-groundwater interactions. To assess the impacts of varying reservoir operations, different scenarios were simulated. High-discharge scenarios represented flood events, examining the rapid recharge of downstream aquifers. Low-discharge scenarios simulated drought-like conditions to evaluate groundwater depletion. Seasonal variations were also explored to compare recharge dynamics during monsoon and non-monsoon periods. This comprehensive methodology provided valuable insights into the complex interactions between reservoir operations and groundwater systems.

The coupled model effectively captured the interactions between reservoir operations and downstream groundwater dynamics. Areas closer to the river are expected to experience more rapid groundwater recharge in response to reservoir discharges, while regions farther from the river may exhibit slower or more limited recharge due to aquifer heterogeneity. Temporal trends indicated significant seasonal variability, with monsoon releases driving substantial groundwater recharge, while non-monsoon periods saw gradual declines in groundwater levels due to reduced discharges. Scenario simulations demonstrated that high-discharge events facilitated rapid aquifer recharge, stabilizing groundwater levels during peak flow periods, whereas low-discharge scenarios resulted in pronounced groundwater depletion downstream. Monsoon-season reservoir releases are expected to play a significant role in groundwater recharge, particularly in semi-arid regions, where they are likely to contribute substantially to annual recharge patterns. This highlights the importance of reservoir operations in maintaining groundwater sustainability.

This study highlights the substantial impact of reservoir operations on downstream groundwater levels within a semi-arid region. Through the integration of surface and groundwater modeling, the research provides a comprehensive analysis of the effects of reservoir discharges on recharge dynamics. The findings underscore the potential to enhance groundwater sustainability by optimizing reservoir operations, particularly during critical periods such as droughts. The outcomes present valuable implications for water resource managers and policymakers, advocating for the adoption of integrated surface-groundwater management strategies. Additionally, future research could expand upon this work by incorporating climate change projections and evaluating the long-term implications of reservoir operations on hydrological systems to support sustainable water resource planning. As such, these insights not only advance the understanding of reservoir-groundwater interactions but also contribute to the development of adaptive strategies for managing water resources in a changing climate.

Keywords: *Reservoir operations, groundwater recharge, surface-groundwater interaction, semi-arid regions, hydrological modeling*

SPATIO-TEMPORAL ANALYSIS OF RAINFALL AND GROUNDWATER: A CASE STUDY OF SEMI-ARID REGION OF RAJASTHAN, INDIA

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Groundwater is essential in arid and semi-arid regions, especially in Rajasthan, where surface water is scarce and rainfall is highly unpredictable. Understanding the relationship between groundwater levels and rainfall patterns is crucial for effective water resource management. The Nagaur district of Rajasthan is known for its arid climate and faces significant challenges in managing its groundwater resources. This study provides a spatio-temporal analysis of rainfall patterns and groundwater dynamics in the region at the block/sub-district level (11 blocks viz. Nagaur, Mundwa, Jayal, Merta, Riyan, Degana, Didwana, Ladnun, Parbatsar, Makarana and Kuchaman), emphasizing their interconnection and the implications for sustainable water management. The arid and semi-arid areas of Rajasthan are particularly susceptible to erratic rainfall and excessive groundwater extraction, leading to declining water tables and heightened water scarcity. Nagaur relies heavily on groundwater for both agricultural and domestic purposes. For the past few years, this district has consistently fallen under the over-exploited category of groundwater assessment conducted by the Central Ground Water Board. This research aims to analyze historical data to assess spatio-temporal variations in rainfall and groundwater levels, identifying critical trends and patterns necessary for effective groundwater resource planning.

This study extracted yearly gridded rainfall data for Rajasthan over 30 years (1994-2023) from the Indian Meteorological Department (IMD) in NetCDF format, with a resolution of 0.25^o. The data was subsequently downscaled to a sub-district level at a finer resolution of 0.1^o using Python programming. Pre-monsoon and post-monsoon rainfall were calculated for further analysis. Groundwater depth level data was obtained from the Water Resources Information System (India-WRIS) from 1994 to 2023. However, due to significant data gaps—over 90% missing data from 1994 to 2004—this study focused on 18 years of groundwater data from 2005 to 2023, specifically examining pre-monsoon months (March, April, May) and post-monsoon months (October, November, December). The data was pre-processed to ensure consistency, and ultimately, 13 monitoring stations were selected for trend analysis. The temporal analysis of groundwater levels and rainfall data was conducted using the Mann-Kendall (MK) test and Sen's Slope estimator. These non-parametric statistical methods are widely used for detecting monotonic trends in time-series data, minimising the influence of outliers and non-normal data distribution. The MK test was applied separately to pre-monsoon and post-monsoon groundwater level data and annual and seasonal rainfall data for a specified period. The test determines statistically significant increasing or decreasing trends by analysing the rank correlation between observed values over time. A p-value of less than 0.05 was used as a threshold for significance, indicating a strong trend. Sen's Slope method was applied to quantify the magnitude of the detected trends. Combining these methods ensured a reliable understanding of temporal dynamics in groundwater levels and rainfall, accounting for both magnitude and significance. Spatial patterns were examined using geospatial interpolation techniques, including Kriging and Inverse Distance Weighting (IDW), to generate detailed maps of groundwater levels and rainfall across the district**.**

The analysis of groundwater levels and rainfall data for the Nagaur district (2005–2023) at the sub-district level reveals a complex relationship between precipitation and groundwater fluctuations. In the pre-monsoon season, significant decreasing trends in groundwater levels were observed in several sub-districts, including Kuchaman (Sen's slope = -1.85), Merta (Sen's slope = -2.07), and Daulatpura (Sen's slope = -0.58), with Mann-Kendall tests indicating statistically significant declines (Z = -2.46 for Kuchaman, Z = -2.18 for Merta, Z = -4.83 for Daulatpura). These results suggest groundwater levels are steadily declining despite varying rainfall patterns. Notably, regions such as Kuchaman and Nawa showed increasing rainfall trends in the pre-monsoon season (Z = 2.46, p = 0.0138 for Kuchaman, Z = 2.14, p = 0.032 for Nawa). However, this increase in precipitation was insufficient to reverse the downward trend in groundwater. This could indicate that the increase in rainfall does not effectively recharge groundwater, possibly due to excessive groundwater extraction or issues related to soil permeability and water retention.

In contrast, groundwater levels remained relatively stable across most sub-districts during the post-monsoon season, with no significant trends detected (Z values between -0.17 and 0.78, p-values > 0.05), suggesting equilibrium conditions following the monsoon recharge. Similarly, post-monsoon rainfall showed no significant trend, with Z values ranging from -0.20 to 0.78 and p-values above the significance threshold. This stability in rainfall and groundwater in the post-monsoon period suggests that the monsoon season contributes to groundwater recovery. However, local hydrological conditions limit or constrain the recharge process in some areas. The findings emphasise that while rainfall influences groundwater recharge, particularly during the post-monsoon season, other factors, such as groundwater extraction rates and land-use practices, play a more significant role in shaping groundwater dynamics. Despite increasing rainfall trends in some areas, the ongoing decline in pre-monsoon groundwater levels highlights the limitations of natural recharge in offsetting the impact of excessive extraction and suboptimal land management. This underscores the urgent need for enhanced groundwater management strategies to ensure sustainable water resource use in the region. Key recommendations include implementing artificial recharge techniques, stricter regulation of groundwater extraction, and improved monitoring systems to address the challenges posed by changing precipitation patterns and escalating water demands.

Keywords: *Groundwater dynamics, semi-arid regions, rainfall variability, spatio-temporal analysis, water resource management*

ASSESSMENT OF TRENDS AND DECADAL CHANGES IN GROUNDWATER RESOURCES IN TAMIL NADU, INDIA

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Water is key to survival of life on earth as well as for national development. *All living organisms are predominantly made of water: human beings about* 60%, fish about 80%, plants between 80% and 90%. Water is necessary for all chemical reactions that occur in living cells. It is essential for food production and all living ecosystems. It is not only life sustaining, but also an integral input to the economy of our country and an important component in maintaining health and hygiene. Rapidly increasing population and urbanization have led to a considerable increase in the demand for water. Climate change is likely to have a further negative impact on water resources. Thus, conservation of this natural resource is vital. Groundwater constitutes an integral part of global water resources. It is used as the primary resource in different regions worldwide for drinking, domestic, agricultural, and industrial purposes. In the recent past, the population growth and overexploitation of groundwater resources have led to rapidly declining groundwater levels. The aquifers are under tremendous pressure and are vulnerable to depletion, particularly in semi-arid and arid regions where the natural recharge is not adequate to balance the withdrawals. Due to spatial unevenness in rainfall, groundwater dependency for irrigation has increased exponentially, which poses a challenge for its sustainability. Hence, the long-term behavior of groundwater level (GWL) fluctuations needs to be understood for better management of water resources and formulating a new action plan. One such decadal comparison has been attempted for entire Tamil Nadu State. Tamil Nadu being a tail end state, is devoid of any perennial rivers and major rivers flowing into the State are from the neighboring States like Karnataka, Kerala & Andhra Pradesh and the flow of water in these rivers depends entirely on the effect of monsoon, status of water requirement and geopolitics in these states. Due to these factors, Tamil Nadu is mostly dependent on ground water as a reliable source of water.

Ground water resources have been estimated based on the guidelines and recommendations of the Ground water estimation committee 1997(GEC-97) for 2013 ground water resource assessment and Ground water estimation committee 2015 (GEC-15) for the 2023 ground water resource assessment. The salient features of the methodology are given below. Ground water resources are estimated assessment unit wise. The assessment unit is watershed in the states occupied predominantly with hard rocks. This is because the ground water balance equations recommended in the methodology can be better applied in the assessment units with hydrologic/ hydrogeological boundaries. However, in the states covered predominantly with alluvium and/ or soft rocks, administrative blocks are chosen as assessment unit since in alluvial areas, it is difficult to identify watershed considering the possibility of trans-boundary aquifer system. In case of Tamil Nadu State, both hard rock and soft rock aquifers occur hence, firka is taken as an assessment unit. Further, within the assessment areas, the hilly areas (slope greater than 20%) are to be excluded as these are not likely to contribute to ground water recharge. The assessment units are to be divided into command and non-

command areas for the purpose of computation of ground water resources. The ground water resources in the poor quality (saline) areas are to be computed separately.

The ground water recharge is estimated season-wise both for monsoon season and non-monsoon season separately. The recharge and discharge components are assessed in the resource assessment - recharge from rainfall, recharge from canal, return flow from irrigation, recharge from tanks & ponds and recharge from water conservations structures and discharge through ground water draft [Groundwater Resource estimation – Principal Inflow – Outflow = Change in Storage].

The ground water resources for the state have been assessed firka-wise. Total Annual Ground Water Recharge has been estimated as 20.65 bcm and Annual Extractable Ground Water resources is 18.59 bcm. The Annual Ground Water Extraction is 14.36 bcm and stage of ground water development is 77%. 31% of the firkas are categorized as Over-exploited, 9% of the firkas are categorized as Critical, 19% of the firkas are categorized as Semi-critical and 37% of the firkas fall under Safe Category. Saline Firkas contributes about 3%. The ground water resources for the state have been assessed firka-wise. Total Annual Ground Water Recharge of the State has been assessed as 21.59 bcm and Annual Extractable Ground Water resources as 19.51 bcm. The Annual Ground Water Extraction is 14.42 bcm and Stage of Ground Water Extraction as 73.91 %. 33% of the firkas are categorized as Over-exploited, 5% of the firkas are categorized as Critical, 19% of the firkas are categorized as Semi-critical and 40% of the firkas fall under Safe Category. Saline Firkas contributes about 3%.

Decadal comparison of Ground Water Resources between 2013 sand 2023 shows an overall improvement in the resources. The Annual Ground Water Recharge improved from 20.65 bcm in 2013 to 21.59 bcm in 2023, while the Annual Extractable Ground Water resources improved from 18.59 bcm in 2013 to 19.51 bcm in 2023. The Stage of Ground Water Extraction improved from 77% in 2013 to 73.91% in 2023. The improvement in the overall ground water resource availability in the state is due to more than normal monsoon rainfall from 2015 onwards and more thrust on various ground water management aspects by Central and State agencies which lead to overall improvement. Migration of Critical firkas to Over-exploited category for the period of 2013 to 2023 is due to overexploitation of ground water resources made available to the public as a result of various conservation measures and also due to search for more resources.

Keywords: *Groundwater, assessment, Firka, extraction, category*

TREND ANALYSIS OF SELECTED HYDRO-METEOROLOGICAL VARIABLES FOR THE KOLAR BASIN IN MADHYA PRADESH, INDIA

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Earth's climate is undoubtedly warming, and there is growing agreement that the effects of climate change will have an impact on ecosystem services, food security, and water availability. The entire local agricultural sector may be at risk, and the effects of climate change may have an adverse effect on human health, particularly for the most vulnerable members of society. One of the most important problems in the study of climate change monitoring is analyzing long-term trends in climatic parameters. Precipitation and temperature are the two main physical elements affecting the climate. These factors establish the climate of a place, impacting agricultural productivity. Precipitation patterns and levels continue to be important factors influencing agricultural production, and agriculture and agribusiness are vital to the economic development and survival of the people of India. Researchers have continued to focus on the analysis of temperature and rainfall patterns to forecast their occurrence and manage water resources for a variety of purposes, especially in arid and semi-arid areas, which typically experience less precipitation and higher evaporation. Hydro-meteorological trends have been extensively studied using both parametric and non-parametric methods. When compared to non-parametric tests, parametric tests (such as the t-test for slope and linear trends) are seen to be more reliable at identifying trends, particularly in cases when the size of sample is small. Nevertheless, parametric tests are limited in their applicability since they rely on the assumption that the data are normally distributed, which is not a typical characteristic of hydro meteorological time-series data. However, as non-parametric tests do not depend on regularly distributed data and are unaffected by outliers, they are favored in the study of environmental and climatic data. Hence in this study non-parametric i.e. Mann–Kendall (MK) test and Sen's slope estimator was applied. Environmental time series analysis uses MK test because it enables us to quantify the significance of trends in time series. Using Sen's slope, a non-parametric method, the trend variation was quantified. The Sen Slope estimate is widely used for the study of hydro meteorological time series. Hence, the objectives of this study are as follows: (1) to examine the variability analysis of the overall annual and seasonal patterns of temperature and rainfall; (2) to identify trends in temperature and rainfall using trend analysis; and (3) to identify the trigger point of these trends.

One of the Narmada River's right-bank tributaries is the Kolar River. It flows through the state of Madhya Pradesh for 101 km in Narmada Basin. The study area is the Kolar basin which includes a dam with a 45040 ha annual irrigation potential, a 45087 ha cultivable command area, and a 62752 ha gross command area. It provides 61 MCM water to the Bhopal city which constitutes about 70% of Bhopal’s drinking purposes, also provides irrigation and inland fisheries. The MK trend test and Sen’s slope estimate were employed to find the nature of the rainfall and temperature trend and their significance level in the Kolar basin. Rainfall and Temperature datasets were downloaded from Indian Meteorological Department, Pune for the Kolar basin from 1981-2022(40 years) grid 0.25×0.25 and 1990-2022(30 Years) grid 1×1, respectively.

The MK trend test and Sen’s slope estimate provide insight into the data’s seasonal distribution and yearly trends. There is a significant increase in monsoon precipitation (4.39 mm per year) and a slight drop of 0.363 mm in winter months, while post-monsoon months witnessed slight decrease in rainfall over the years i.e. 0.589 mm and pre-monsoon indicated no trend. Due to an increase in monsoon precipitation, the yearly trend has also significantly increased over time, with an average rise of 3.165 mm per year. Sen's estimator, which calculates seasonal precipitation volume, was found to be 0.0, 4.394, -0.586, and -0.363, respectively, for the pre-monsoon seasons, monsoon, post- monsoon, and winter; and corroborates the abovementioned findings. Throughout the study period, rainfall exhibited both increasing and decreasing trends. A warming trend in temperature suggested that the local climate may be changing. The analysis reveals the evolving trends in rainfall patterns and temperature within the basin, which impacts the storage solutions and precautionary strategies that need to be implemented to guarantee the supply of water for future agricultural requirements and the rising demand for household water use. There is a trend of rising temperatures at the Kolar basin. This may be attributed to the effects of climate change, which can result in extreme weather conditions in the Kolar basin and also the capital city of Bhopal in near future located 25-30 km from Kolar reservoir and basin. Consequently, the study suggests that the fluctuations in temperature require additional monitoring methods, and it is essential to address the rising temperature trend to mitigate its impact on human health.

Keywords: *Mann-Kendall test, Sen's slope, climate change, trend analysis, temperature, precipitation*

EFFICIENT STORMWATER COLLECTION FOR SUSTAINABLE WATER RESOURCE MANAGEMENT IN SIKAR DISTRICT, RAJASTHAN, INDIA

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Rajasthan, India, grapples with acute water scarcity due to its predominantly arid to semi-arid climate, high evaporation rates, and erratic rainfall patterns. The Sikar district, situated in this semi-arid region, faces dual challenges: prolonged dry spells and intense monsoon rainfall, often leading to substantial runoff. This runoff, if effectively managed, presents a unique opportunity for water storage and recharge, mitigating water scarcity beyond the monsoon season. Addressing this duality, the present study focuses on designing an efficient stormwater drainage system that captures and manages excess runoff, contributing to long-term water sustainability. To achieve this goal, a robust methodology was devised combining hydrological, hydraulic, and spatial analyses. Intensity-Duration-Frequency (IDF) curves served as the foundation for assessing hydrologic risks, guiding the design of stormwater infrastructure to optimize runoff collection. The study utilized 35 years of rainfall data (1985–2019) obtained from the Water Resources Department, Rajasthan. Extreme rainfall intensities were modelled using Gumbel's distribution for return periods of 2, 5, 10, 25, and 50 years, with durations ranging from 0.5 to 6 hours. The IDF curves generated from these analyses offered a robust framework for understanding rainfall patterns and their implications for stormwater design.

Spatial analysis played a crucial role in delineating the study area into manageable units. Using ArcGIS, the region was subdivided into 10 distinct sub-catchments, with 7 junction nodes, 7 conduits, and a designated outfall. Each sub-catchment was characterized based on critical parameters, including slope, width, impervious surface area, conduit length, node elevation, soil type, and evaporation rates. These parameters were incorporated into a comprehensive hydrological model to simulate runoff dynamics under various rainfall scenarios. The Storm Water Management Model (SWMM) was employed to simulate the hydrologic and hydraulic behaviour of the stormwater drainage system. Five time-series datasets were established to represent critical rainfall intensities corresponding to the chosen return periods. Simulations conducted using SWMM yielded vital insights into sub-catchment runoff volumes, conduit flows, node depths, and outfall loading. The model outcomes provided a detailed understanding of how stormwater could be effectively captured, conveyed, and stored, offering solutions to mitigate the water shortages prevalent in Sikar district. Urban areas across the globe are grappling with the escalating challenges posed by urban flooding, a phenomenon characterized by the overflow or eruption of water over pathways not typically submerged. In countries like India, where tropical climates prevail, floods stand as the most common and widespread natural disaster. The ramifications of urban flooding are far-reaching, exacerbated by the insufficient carrying capacity of storm drains and blockages caused by solid waste. Such challenges can amplify flood peaks by up to 8 times and flood volumes by a staggering 6 times, leading to rapid flooding occurrences within minutes. While the challenges are evident, developing countries like India are still on the trajectory of reaching the peak of urban development. Therefore, addressing the adverse effects of storm water through resource optimization, proper modelling, and planning of drainage networks becomes imperative. The modelling of storm water in urban areas is a complex endeavour due to limited space availability and intricate landscapes.

The study's methodology can be broadly divided into three phases: data collection and preparation, model development, and analysis. Data collection was a foundational step. Long-term rainfall records (1985–2019) were sourced from the Water Resources Department, Rajasthan, and subjected to statistical analysis. Gumbel's distribution was applied to calculate extreme rainfall intensities for multiple return periods, forming the basis for IDF curve generation. SWMM was chosen for its ability to simulate stormwater systems with high precision. Input parameters for the model were prepared from the data collected. The sub-catchments were treated as hydrological units, with their areas, slopes, and imperviousness defining runoff generation. Rainfall, drainage network and hydraulic parameter of drain and soil were incorporated in hydrological modelling. The SWMM simulations were conducted for multiple scenarios, each representing different rainfall intensities and durations. Outputs of SWMM included runoff volumes, conduits flow, node depths and outfall loading. The simulations revealed critical insights into the hydrologic behaviour of the study area under varying rainfall conditions. Substantial runoff was observed in sub-catchments with higher impervious surfaces and steeper slopes. This indicated potential hotspots for water harvesting infrastructure. Node depths highlighted areas prone to waterlogging, offering guidance for targeted drainage improvements. The outfall was identified as a crucial point for water collection. By integrating storage tanks or recharge structures at the outfall, significant water could be conserved for post-monsoon use. By analysing IDF, for time of concentration of 45 min five rainfall intensity 32,51.5,64.4,80.7 and 92.8 mm/hr are generated for return period of 2, 5, 10, 25 and 50 years return period. The discharge at outfall for derived intensity are 142, 209, 241, 276 and 299 10^6 litre for 2, 5, 10, 25 and 50 years return period.

The IDF curve generated for different return periods showed high rainfall intensities for smaller durations and IDF curve generated by using IMD reduction formula gave better results as compared to CWC method. Sub catchment runoff, node depth, Node Inflow, Conduit flow, Node flooding and outfall loading computed for 5 time series corresponding to critical rainfall intensity of 2,5,10, 25 and 50 years return period shows that for return period of 2years and 5 years there was no major flooding in the initial nodes J1, J5 but as the return period becomes more than 10 years there was a significant flooding at all the nodes. Junction J7 and J4 were more prone to flooding. Sub Catchment S8 had the maximum runoff for every rainfall. The surface runoff and flow routing continuity errors does not exceed permissible value of 10% hence the analysis of results is valid. The results indicate that the drainage system of the study area does not have an acceptable capacity for rainfall of longer return period. The results also calculate the outfall loading that can be store and can utilized for off monsoon water requirement. This study demonstrates the potential of advanced hydrological and hydraulic modelling tools, such as SWMM, in addressing water scarcity challenges in semi-arid regions. By capturing and managing monsoon-generated runoff, the proposed stormwater drainage system offers a sustainable solution to Sikar's perennial water shortages. The methodology, which combines long-term rainfall analysis, spatial data processing, and hydrologic simulations, provides a replicable framework for other semi-arid regions facing similar challenges.

Keywords: *SWMM, IDF curves, stormwater management, hydrological modelling*

IN-DEPTH ANALYSIS OF THE HYDROECOLOGICAL SYSTEMS IN THE WATER-SCARCE LUNI RIVER BASIN IN NORTH-WESTERN INDIA

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The Luni River basin, located in the arid and semi-arid regions of Rajasthan, India, faces severe water scarcity due to a combination of climatic, geological and anthropogenic factors. The region is characterized by erratic and scanty rainfall, high evaporation rates and escalating water demands from many sectors. Climate change further intensifies these challenges by altering precipitation patterns, increased frequency of both droughts and flash floods. These hydroclimatic extremes significantly impact water availability, necessitating urgent sustainable water management interventions. This study provides a comprehensive assessment of the hydro-ecological and hydrochemical conditions of the Luni basin, evaluating groundwater and surface water quality, salinity and the impacts of industrial effluents on local water resources. The basin's geomorphology plays a crucial role in its hydro-ecological dynamics. The underlying hard rock formations predominantly host fractured aquifers with low discharge rates. Meanwhile, younger, coarse-textured alluvial sediments have better aquifer potential, although interbedded clay layers often hinder groundwater productivity. Older alluvial formations with granular zones function as productive aquifers under semi-confined to confined conditions. Groundwater recharge primarily occurs through flood events in the river channel and distant mountainous regions, contributing to varying groundwater potential across the basin. Yield rates fluctuate widely from as low as 5 liters per minute (lpm) to as high as 1340 lpm, depending on the underlying hydrogeological settings.

Utilizing GRACE data in conjunction with in-situ groundwater level monitoring from 2002 to 2023, this study observes significant fluctuations in groundwater storage, with notable depletion recorded in 2021 and recharge following the 2006 flood event. Despite the potential of groundwater resources in the region, contamination issues persist, particularly concerning fluoride enrichment. Approximately, 42% of the sampled groundwater exhibits fluoride concentrations exceeding the permissible limit. The natural geochemical weathering of fluoride-bearing minerals, coupled with anthropogenic influences such as industrial discharge, exacerbates this issue. The groundwater in the Luni basin exhibits distinct hydrochemical facies, primarily influenced by lithology, recharge conditions and anthropogenic activities. The dominant facies observed include Ca-HCO_3, typically found in areas with active recharge, particularly in shallow groundwater zones near floodplains; Na-Cl, common in deeper aquifers and areas with saline intrusion, reflecting long groundwater residence time and mineral dissolution; and Mixed-Type Facies, found in transitional zones where varying degrees of ion exchange, weathering, and anthropogenic contamination alter water chemistry. Salinity is a persistent challenge in the Luni basin, with high concentrations of TDS recorded in many areas. Groundwater salinity primarily arises from the dissolution of evaporite deposits, intensive agricultural irrigation with saline water, and poor drainage leading to accumulation of salts. The presence of non-meteoric fossil brines in deeper aquifers further complicates the region's groundwater quality, with some tube wells showing water ages exceeding 5,000 years, indicating minimal modern recharge. The intrusion of

brackish groundwater into freshwater zones, coupled with excessive groundwater extraction, exacerbates the salinity problem, reducing the usability of water.

Industrial pollution is a significant concern in the Luni basin, particularly affecting the Bandi and Jojri Rivers. These rivers receive large volumes of untreated or partially treated effluents from textile, dyeing, leather, and chemical industries, primarily concentrated in Pali, Balotra, and Jodhpur districts. Bandi River has been severely impacted by textile industry discharges, which introduce high loads of synthetic dyes, heavy metals, and chemical residues. The prolonged release of industrial effluents has resulted in severe water quality degradation, with elevated levels of chromium, lead, cadmium, and other toxic metals detected in the river water and adjacent groundwater. The accumulation of these pollutants not only affects aquatic life but also renders groundwater unsuitable for drinking and irrigation. Farmers in the region report declining agricultural productivity. Similarly, the Jojri River suffers from extensive industrial pollution. The discharge of highly alkaline effluents, along with a cocktail of organic and inorganic pollutants, has led to significant changes in the river's hydrochemistry. Elevated SO_4^{2-} and Cl^- concentrations in groundwater near the river indicate the infiltration of industrial contaminants, contributing to declining groundwater quality in surrounding areas. The long-term consequences of such pollution include the disruption of local ecosystems, deterioration of soil fertility, and increased health risks among communities relying on groundwater for daily consumption. Given the acute water scarcity and water quality challenges in the Luni basin, immediate and long-term measures are essential for sustainable water resource management. Key strategies include groundwater recharge enhancement through diverting excess floodwater into recharge zones, constructing check dams and implementing artificial recharge techniques; revitalizing traditional water harvesting structures such as tankas and step wells to improve local water availability; strengthening regulatory enforcement on industrial effluent treatment, promoting zero liquid discharge policies, and implementing advanced treatment technologies to minimize pollution loads; developing desalination techniques, promoting alternative cropping patterns that require less saline water and implementing fluoride removal technologies to improve drinking water quality; and encouraging participatory water management approaches, enhancing public awareness on water conservation, and involving local stakeholders in decision-making processes. The study basin exemplifies the challenges of managing water resources, where climatic variability, groundwater depletion and industrial pollution pose severe threats to water security. The basin’s hydrochemical complexity, characterized by varying facies, demands a multidisciplinary approach to water management. The findings of this study highlight the critical need for improved groundwater recharge, pollution control and adaptive water management strategies to ensure long-term sustainability. By integrating traditional knowledge with modern technological advancements, the Luni basin can move towards a more resilient and sustainable water future.

Keywords: *GRACE, Luni basin, hydrogeology, groundwater storage, salinity intrusion, fluoride contamination*

ANALYSIS OF CHANGING RAINFALL PATTERNS IN THE LUNI BASIN AND IT'S IMPACT ON GROUNDWATER TABLE DYNAMICS

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The Luni River Basin, situated in the arid and semi-arid regions of Rajasthan, is a critical water resource zone characterized by low and erratic rainfall with some parts receiving rainfall less than 250 mm annually. The basin primarily relies on monsoon rainfall, which contributes to surface runoff, soil moisture replenishment, and groundwater recharge. The basin supports diverse agricultural, industrial, and domestic water needs, making its hydrological balance a focal point for sustainability utilization of limited water resources. In recent years, significant shifts in rainfall patterns have been observed, attributed to a combination of local anthropogenic activities and global climate change patterns leading to the delayed, concentrated, or inclining monsoon rains disrupting this cycle. Anthropogenic factors, such as extensive groundwater extraction for irrigation, urbanization, increasing green covers from increased water quantiles through canal supplied waters, and land-use changes, further exacerbate the issue. Climate change-induced alterations, including increased temperature, low pressure zones, and shifting rainfall patterns, contribute to the complexities of managing water resources sustainably. These changes are causing profound impacts on the region's water resources, particularly the groundwater table, which serves as a key factor for agricultural patterns, drinking water, and other essential activities in the basin. The study focuses on the Luni River Basin, which spans an area of 70,550 km² across nine districts in Rajasthan. Among these, the districts of Pali, Jalore, Barmer, and Jodhpur collectively account for approximately 85% of the basin's total area. To assess long-term rainfall patterns, both ground-based observation data and satellite-derived datasets is utilized. Rainfall records for the Luni Basin, collected by state government rain gauges for the duration of 1957 to 2024 is considered. In addition, satellite & reanalysis datasets such as CHIRPS Daily, ERA5, and IMERG, which provide data from 1950 onward, is also used in the analysis. For surface temperature data, satellite & reanalysis climate products like ERA5-Land Daily Aggregated, NOAA CPC Global Temperature, and Terra Land Surface Temperature and Emissivity Daily Global, with varying spatio-temporal resolutions, is incorporated.

The aim of this study is to analyse the changing rainfall patterns in the Luni Basin and investigate it's direct and indirect impacts on the groundwater table dynamics. This study integrates the climate data, remote sensing technologies, and field-based observations for the detailed analysis on Luni Basin. This study investigates and highlights the relationships between rainfall variability and groundwater tables, offering insights into the implications for water resource management in the region. For achieving the aim of study, the following objectives are formulated (i) To analyse long-term trends and variability in rainfall patterns in the Luni Basin, (ii) Investigate variability in surface temperature patterns in the Luni Basin and its' long-term trends, and (iii) To assess the statistical correlations between changing rainfall patterns and groundwater table fluctuations. This study utilized rainfall and surface temperature datasets sourced from meteorological stations, reanalysis datasets, and satellite

platforms. Statistical methods, including the Mann-Kendall trend test and Sen's slope estimator, are applied to analyse trends and detect seasonal and annual fluctuations, and anomalies. Groundwater data, comprising historical and recent records, are obtained from the Central Ground Water Board (CGWB), with few field surveys, and piezometric readings which includes pre-monsoon and post-monsoon measurements dated since 2011. Similar statistical techniques are employed to analyse groundwater data, with a focus on comparing groundwater levels over decades to identify trends in depletion or recharge within the basin. Tools such as Quantum Geographic Information Systems (QGIS) and Google Earth Engine are used for visualizing the spatio-temporal variability of rainfall, surface temperature, and groundwater dynamics across the basin.

The analysis of rainfall patterns in the Luni Basin revealed notable temporal and spatial variations, assessed using statistical methods such as the Mann-Kendall Test, Rainfall Anomaly Index (RAI), T-Test, and Sen's Slope Estimator. The findings indicate a declining trend in annual rainfall across several spatial grids in the basin, with some localized areas showing an increase in rainfall. The high-resolution temporal dataset highlighted an increase in extreme rainfall events, which are concentrated over shorter durations. This shift has resulted in reduced infiltration and increased surface runoff, limiting groundwater recharge. The rise in the extreme rainfall events also elevates the risk of flash floods, presenting an opportunity for sustainable management of excess water through Managed Aquifer Recharge (MAR) to help restoring of the depleted groundwater table in the region. Additionally, the temperature trend analysis revealed a significant rise in surface temperatures, with noticeable increases in the frequency and intensity of heatwaves. The prolonged summer season has led to higher evaporation rates, further exacerbating the water scarcity issues in the region. The extended heatwaves and hotter summers place a considerable stress on agricultural systems, reducing crop yields and increase in the demand for irrigation water, further depleting groundwater resources.

The impact of changing rainfall pattern and fluctuations in groundwater levels have caused a significant drop in water tables, especially in the areas with intensive agricultural practices. Districts like Jodhpur and Barmer showed the highest groundwater levels, while some small, isolated areas experienced a rise in water tables, which needs further exhaustive analysis. This isolated pocket areas exhibited a rise in the water table, suggesting unique hydrological or land-use dynamics that require detailed investigation to understand their underlying causes. These findings emphasize the need for targeted groundwater management strategies that address regional disparities and focus on restoring the balance in areas that facing acute depletion while conserving resources in regions with favourable trends.

Keywords: *Groundwater table fluctuations, Luni River basin, rainfall pattern, statistical methods, surface temperature*

RISING GROUNDWATER LEVELS IN JODHPUR, INDIA: TRENDS, CAUSES, AND SUSTAINABLE MANAGEMENT STRATEGIES

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This study employs a multidisciplinary approach to investigate the causes and consequences of the rising groundwater table in Jodhpur. By integrating hydrogeological, climatic, and anthropogenic factors, the research aims to comprehensively analyse this phenomenon and propose actionable solutions. Understanding the underlying causes is essential for developing effective and sustainable management strategies to mitigate the impacts and ensure the city's long-term sustainability. The specific objectives of the study are i) Identify the reasons for the observed rise in the groundwater table in Jodhpur; ii) Examine rainfall patterns to evaluate their potential contribution to groundwater recharge; iii) Map groundwater quality to locate areas affected by contamination due to the rising water table and interactions with surface pollutants; iv) Determine groundwater recharge sources using isotopic techniques to trace origins and pathways, and v) Propose effective remedial measures to mitigate the impacts of rising groundwater levels and ensure sustainable water management.

This study integrates remote sensing, geostatistical analysis, and hadrochemical techniques to investigate the problem. Thematic maps were prepared using GIS to visualize Jodhpur's topography and hydrological settings. Long-term gridded rainfall data from the IMD spanning from 1901 to 2023 was analyzed, with a focus on the last 30 years (1992-2022). Statistical tools including the Mann-Kendall (MK) test and Sen's Slope Estimator, were employed to examine rainfall trends. Data from 40 groundwater monitoring stations across Jodhpur was analyzed to identify spatial and temporal trends in the water table. Groundwater samples collected from 40 locations during the pre-monsoon & Post monsoon period were analyzed for physico-chemical parameters and isotopic compositions to identify contamination hotspots and recharge sources. Analysis of groundwater level trends from 2011 to 2023 indicated that 70% of the study area is affected by rising water tables. The annual water table rise ranges from 0.25 to 0.75 meters, with the central and southern parts of Jodhpur experiencing the most significant increases. In some areas, groundwater levels rose by up to 9 meters during the study period, leading to severe waterlogging conditions.

The introduction of canal-fed water systems, such as the Rajiv Gandhi Lift Canal and reservoirs like Kaylana-Takhtasagar in 1997, drastically reduced groundwater extraction for domestic and agricultural use. This reduction in dependency on groundwater is a significant factor contributing to the rise in water levels. Long-term rainfall analysis revealed no significant overall increase; however, data from the last three decades indicates an increase in monsoon rainfall. Rainfall intensity has risen by 39.41%, 26%, and 21.45% over the past decade (2014-2024), two decades (2004-2024), and three decades (1994-2024), respectively with comparison to long term average rainfall. This increase, while notable, does not fully account for the rising groundwater levels.

Isotopic analysis is currently underway to identify the potential recharge sources contributing to groundwater levels. Preliminary findings indicate that seepage from canals, surface water storage structures, and leakage from old and clogged water pipelines are significant

contributors to groundwater recharge. However, these sources are also major contributors to contamination, highlighting the dual impact of these recharge pathways on the groundwater system. Preliminary analysis indicates that rising groundwater levels have intensified salinity and interactions with surface pollutants, heightening contamination risks. The findings suggest that the primary drivers of rising groundwater levels in Jodhpur are reduced groundwater extraction due to the canal-fed water supply, increased recharge from surface water systems, and leakage from aging water pipelines. Although changing rainfall patterns have played a role in recharge, their impact appears secondary compared to anthropogenic factors. The observed trends underscore the urgent need for groundwater management in Jodhpur, as rising groundwater levels threaten urban infrastructure and exacerbate contamination risks, presenting challenges to sustainable urban development. The remedial measures are suggested as: 1) Cleaning and repairing old pipelines to reduce leakage, and laying new pipelines for efficient wastewater discharge; 2) Identifying suitable sites for pollution waste disposal to prevent contamination of rising groundwater; 3) Promoting the use of groundwater for irrigation while restricting canal water usage to manage excess water levels; 4) Constructing subsurface tunnels to channel excess groundwater into the Jojri River, which is at a lower elevation than central Jodhpur, and 5) Pumping wells needs to be installed to extract excess water from waterlogged areas, which can then be utilized by industries or redirected to water-deficient regions. This study addresses the critical issue of rising groundwater levels in Jodhpur, integrating hydrogeological data, statistical analysis, and isotopic studies to identify key causes and propose practical solutions. It emphasizes infrastructural upgrades, pollution control, and sustainable water policies to mitigate the problem and ensure long-term water resource sustainability. The findings offer a replicable framework for tackling similar challenges in arid regions globally, positioning Jodhpur as a potential model for effective groundwater management in comparable settings.

Keywords*: Groundwater rise, isotope analysis, MK test, Sen's slope, waterlogging, urban hydrology, rainfall trends, sustainable groundwater management*

FORECASTING OF RAINFALL USING DEEP LEARNING ALGORITHMS FOR THE SEONATH RIVER BASIN, INDIA

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Rainfall forecasting is crucial for disaster relief, agricultural planning, and efficient management of water resources, particularly in areas like the Seonath River Basin, where hydrological variability poses a dual hazard of drought and flooding. The Seonath River basin is habitat to a wide range of rain-fed agricultural operations. Accurate rainfall forecasts reduce crop failures and optimize resource consumption by assisting farmers in properly planning their planting, watering, and harvesting practices. Traditional statistical models, which have proven helpful in earlier studies but usually fail in complicated scenarios, face significant problems due to the non-linear, dynamic, and multi-dimensional nature of rainfall patterns. Deep learning algorithms are a novel and revolutionary substitute that leverage their ability to process high-dimensional data, model intricate connections, and discover tiny non-linear correlations between variables. The implementation of modern deep learning frameworks for rainfall prediction in the Seonath River Basin is investigated in this paper. The study utilizes monthly rainfall time series data from the IMD, that forms part of a comprehensive dataset that spans the years 1981 to 2021. The reliability of the incoming data is made certain by the use of data preparation procedures, such as the elimination of abnormalities and missing values. After standardizing the dataset through a normalization scaling process, which yields consistent input parameters, the deep learning models are trained using monthly lagged data.

The study makes use of modern neural network architectures, including Long Short-Term Memory (LSTM) networks and Convolutional Neural Networks (CNNs), to enhance the accuracy and dependability of rainfall forecasts. LSTMs are powerful tools for rainfall forecasting, leveraging their ability to model temporal dependencies in complex weather systems. They provide a data-driven approach to predicting rainfall, overcoming many limitations of traditional models. With advancements in data availability, computational power, and hybrid modelling techniques, LSTMs have the potential to transform rainfall forecasting, supporting more accurate and timely decision-making in meteorology and hydrology. A CNN model for rainfall forecasting typically consists of an input layer to process structured data, followed by convolutional layers that apply filters to extract features, such as spatial patterns in rainfall distribution or atmospheric dynamics. These layers are complemented by pooling layers, which reduce the dimensionality of the feature maps, retaining essential information while minimizing computational costs. Fully connected layers then aggregate the learned features and predict rainfall intensity or probability for specific locations or times. The research methodology and findings, demonstrating the superior performance of LSTM models compared to CNNs for rainfall prediction, present significant opportunities for scaling and adaptation to other geographical regions and climatic conditions. The systematic approach to data preprocessing, model development, and performance evaluation provides a robust framework for similar studies in different contexts,

contributing to the growing body of evidence supporting the effectiveness of deep learning approaches in environmental and climatic predictions.

This data-driven strategy effectively addresses the limitations of traditional rainfall prediction methods, showcasing the power of deep learning techniques in processing complex, non-linear meteorological data. The study emphasizes the importance of selecting the appropriate algorithms based on the data characteristics and the specific goals of the prediction task. To assess the performance of the developed model, four key statistical metrics were employed: Nash-Sutcliffe Efficiency (NSE), Correlation Coefficient (CC), Coefficient of Determination (R^2), and Root Mean Square Error (RMSE). These metrics were carefully chosen to evaluate the model's accuracy, consistency, and reliability in predicting rainfall. The Long Short-Term Memory (LSTM) network delivered the better performance than the CNN. During training, the model achieved an R^2 value of 0.85, while in testing, it attained an R^2 value of 0.73, demonstrating a strong correlation between the observed and predicted rainfall. The training NSE value of 0.85 and the testing NSE value of 0.73 further supported the model's ability to replicate observed rainfall patterns effectively. The training CC of 92% and testing CC of 86% indicated a robust linear relationship between the predicted and actual values, showcasing the model's predictive strength. Additionally, the model's training RMSE of 0.3915 mm and testing RMSE of 0.4995 mm, both relatively low, highlighted its precision in minimizing prediction errors. Collectively, these metrics emphasize the exceptional performance of the LSTM model, making it the most accurate and reliable choice for rainfall forecasting. This study demonstrates the potential of the LSTM model in capturing complex temporal patterns and achieving high prediction accuracy, which is crucial for applications in hydrology, agriculture, and disaster management.

This study concludes by showing how deep learning algorithms, specifically LSTM networks, can significantly enhance the accuracy, dependability, and general dependability of rainfall prediction systems. The results demonstrate how the shortcomings of conventional forecasting techniques can be overcome by these sophisticated models, which can successfully represent the intricate temporal and non-linear correlations present in rainfall patterns. Through the demonstration of LSTM network’s exceptional performance, this study highlights their ability to tackle important issues related to climate variability and hydrological modelling.

Keywords: *Rainfall prediction, deep learning, LSTM, CNN*

WATER QUALITY ASSESSMENT AND HEALTH IMPACTS OF FLUORIDE IN RAJASTHAN'S CHAUKA SYSTEMS

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Groundwater is a critical resource for rural communities, particularly in semi-arid regions such as Rajasthan, India, where hand pumps and wells serve as primary drinking water sources. The Chauka system, a community-managed aquifer recharge method has been implemented in various locations to enhance groundwater sustainability. This study evaluates groundwater quality in three locations Antoli- Dethani, Balapura, and Lapodia by analyzing pre and post monsoon variations and assessing fluoride contamination levels and associated health risks.In the three study sites, water samples were collected from wells and hand pumps during pre- and post-monsoon seasons. 29 water quality parameters in all were examined: pH, electrical conductivity, temperature, total dissolved solids, total suspended solids, calcium, magnesium, sodium, potassium, dissolved oxygen, sulphate, chloride, fluoride, nitrate, alkalinity, hardness, and heavy metals (iron, lead, zinc, cadmium, aluminium, manganese, nickel, copper, silver). Additionally evaluated were biological criteria including Faecal coliform, chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Using the Weighted Arithmetic Mean approach, the Water Quality Index (WQI) was computed to evaluate the general fit of water for drinking needs.

The study found significant seasonal variations in groundwater quality across the three locations, primarily influenced by monsoon-related hydrological changes. In Antoli-Dethani, in pre-monsoon, 15.78% of samples were found good, 73.68% were poor, and 10.52% were unsuitable. These findings imply that most of the local water sources were unfit for direct consumption. Water quality improved following monsoon: 47.36% of it was rated as excellent, 31.57% as unsuitable, and 21.05% as poor. Rainfall diluting effects probably helped to improve things by lowering some pollutants concentration. Still, the persistence of inappropriate water samples following the monsoon suggests that groundwater quality may still be influenced by other sources of contamination, including runoff from surrounding farms. At Balapura region, groundwater quality was better than in the other two sites. Pre-monsoon data indicated that aquifer properties and natural filtration systems may have helped to improve baseline water quality as 72.73% of samples were excellent and 27.27% were unsuitable. The percentage of excellent samples dropped somewhat to 63.63% post-monsoon, while 27.72% were classed as poor, most likely from agricultural runoff and leaching of pollutants. The post-monsoon drop in water quality implies that although dilution takes place, the infiltration of contaminants from surface sources adversely affects groundwater in this area. To minimise these seasonal fluctuations, preventive actions and ongoing observation are required. In Lapodia, 54.54% were unsuitable pre-monsoon and just 36.36% were good or excellent. The high proportion of unfit water points to notable contamination, maybe from both natural and manmade sources. 45.45% of samples stayed poor or very poor post-monsoon, suggesting ongoing contamination issues even with efforts at recharging. Seasonal variations in water quality were ascribed to the combined actions of dilution and agricultural

runoff contamination. Fluoride contamination which exceeded allowed limits in all three sites was a big issue. Particularly dental and skeletal fluorosis, high fluoride levels seriously endanger health. Long-term exposure causes major health problems affecting adults as well as children.

Fluoride contamination in groundwater can lead to serious health problems, especially in vulnerable populations. The health risk assessment conducted in this study revealed that children are at the highest risk, followed by females, and then males. High fluoride levels most harm children since of their developing teeth and bones. Dental fluorosis marked by discolouration and pitting of teeth can result from prolonged exposure. Severe forms of skeletal fluorosis can cause bone defects, joint discomfort, and limited mobility. Women, especially pregnant and nursing mothers, are more prone to fluoride-related health problems. Increased fracture risks and osteoporosis can result from fluoride accumulation in bones. Although adult men are rather less sensitive than children and women, persistent exposure can nevertheless cause skeletal fluorosis, joint stiffness, and neurological problems. Combining occupational contact with contaminated drinking water increases these hazards.

To mitigate groundwater quality issues, the study suggests the following interventions: Implement activated alumina filtration, reverse osmosis, and community-based defluoridation systems among local water treatment solutions for fluoride removal. Establishing a systematic groundwater monitoring program would help to follow seasonal variations in pollution levels. Public education campaigns should teach locals about fluoride hazards and support different safe water sources. Support of sustainable farming practices that reduce chemical leaking into groundwater will help farmers to be environmentally friendly. This study highlights the seasonal dynamics of groundwater quality in community-managed Chauka recharge systems. While some improvements were observed post-monsoon, fluoride contamination remains a serious public health issue. Addressing these challenges requires an integrated approach involving technological solutions, policy interventions, and community participation. Effective groundwater management is essential to ensuring safe drinking water for rural populations in Rajasthan.

Keywords*: Aquifer recharge, Chauka systems, health risks, skeletal fluorosis, water quality index, water quality monitoring*

SPATIAL DISTRIBUTION OF ARSENIC, BORON AND LITHIUM AS KEY DETERMINANTS OF GROUNDWATER QUALITY INDEX IN THE LAUCA RIVER BASIN, BOLIVIAN ALTIPLANO

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In Bolivia, water contamination is often linked to mining activities, while only a few studies have highlighted the presence of naturally occurring arsenic (As) and other geogenic contaminants (GCs). The most significant research on geogenic As has been focused on small areas within the Bolivian Altiplano (BA), particularly in the lower Poopó Lake basin (Ormachea et al., 2013, 2016). Groundwater serves as a vital but scarce natural resource for drinking in arid regions like the BA. However, contamination of this essential resource with toxic substances poses serious threats to human health. Arsenic contamination in drinking water is a widespread issue, with reports from various regions highlighting this toxic element as a key factor in evaluating groundwater quality. However, studies related to the occurrence of As with the co-occurring GCs like boron (B), and lithium (Li) in areas with unusual geological characteristics like the Lauca River Basin (LRB), has remained scanty. This study aims to explore the natural occurrence of elevated concentrations of As, B and Li as key elements in assessing the groundwater quality index of the LRB. The research employs a comprehensive approach that integrates GIS-based mapping, geo-statistics, hydrochemistry, and a Groundwater Quality Index (GWQi) model. Groundwater contamination by As is a critical global issue, impacting millions due to its severe health effects, including skin lesions and cancer. Arsenic, a naturally occurring metalloid, is found in rocks, soils, air, and water, particularly in volcanic regions. Its presence in shared water sources, used for both drinking and agriculture, poses significant public health risks due to its high toxicity. WHO 2017 has established a maximum guideline value of 10 µg/L for As in drinking water.

Boron and lithium, lighter elements that are widely distributed in nature, enter water systems mainly through natural processes like the weathering of igneous rocks, hydrothermal activities, and the leaching of evaporative deposits. Human exposure to B primarily occurs through food and drinking water, and excessive intake can result in adverse health effects, such as male reproductive harm. The WHO 2017 recommends a maximum B concentration of 2.4 mg/L in drinking water. On the other hand, data on the health risks from Li exposure via drinking water remains limited. Some studies suggest that Li exposure may lead to thyroid function changes in women, potentially affecting fetal growth and newborn weight and kidney effects. In this context, guidelines from organizations like the United States Environmental Protection Agency (EPA) and the United States Geological Survey (USGS) recommend a maximum lithium concentration of 10 µg/L and a non-regulatory reference value of 60 µg/L, assuming drinking water is the sole source of lithium intake.

The present study is carried out in the LRB basin, within the BA, which covers an area of approximately 17,726 km² and is characterized by its high altitude, with a physiographic

barrier that features peaks exceeding 6 km above sea level, such as Mount Sajama. The basin is a longitudinal tectonic depression filled mainly with Tertiary and Quaternary sediments. Field and laboratory parameters of 96 groundwater samples collected from sources used for drinking and domestic purposes in the LRB were analyzed. Groundwater sampling followed standard procedures (EPA, 2017; ISO 5667-1) to ensure representative data. In-situ field parameters, including pH, water temperature, electrical conductivity (EC), and redox potential (Eh), were measured using HANNA-HI 98194 and HACH-HQ 40D multiparameter instruments. Alkalinity (as HCO_3^-) was determined in-situ by acid-base titration using a Hach digital titrator (model 16900). Laboratory analysis included major ions and trace elements by IC and ICP-MS.

Remarkably elevated concentrations of As, B, and Li and high correlation between these GCs were found in drinking water samples. Arsenic concentrations ranged from 2 to 615 µg/L, B from 77 to 9649 µg/L, and Li from 1 to 3049 µg/L. Groundwater pH values ranged from 6.10 to 9.80, while EC varied from 74 to 7222 µS/cm, with the highest EC observed near the Coipasa salt flat. Predominant water types included Na-Cl, Na-Cl-HCO_3, and Ca-Mg-Cl-HCO_3. Approximately 50% of the water sources exhibited elevated GWQi values, indicating a very high health risk. The evaluation of possible GWQi abnormalities caused by unacceptable levels of important ions and trace elements was carried out by comparing the concentrations with the drinking water standards recommended by the WHO and EPA. These unusual hydrogeochemical characteristics are consistent with extremely arid volcanic areas with high evaporation rates, containing evaporative deposits and geothermal fluids. The continuous monitoring of BA's water resources is essential not only to safeguard public health in rural communities that depend on untreated groundwater but also to promote the sustainable use of these water sources.

Keywords: *Bolivian Altiplano, geogenic contaminants, health effects, hydrochemistry, groundwater quality index*

STUDY OF GROUNDWATER DISCHARGE IN SELECTED AREA OF TAPI BASIN

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The Tapi Basin lies in between Satpura mountain in the north and the Tapi river in the south in elongated shape. The study area covers about 960 sq. Km and lies in the Tapi Basin. It comprises of Bhusaval, Raver and Yawal Talukas in Jalgaon district which is in the command area of the Hatnur Minor Irrigation Project. The area is covered by Deccan Trap and Tapi Alluvium. The alluvium thickness increases towards the Tapi river due south from the Satpuras. The area is divided into 9 Watersheds. The study area is well Known for cash crops viz. Banana, Sugarcane and Cotton. The heavy water required crops are located in the alluvial belt. The cash crops mainly depend on groundwater. Groundwater is the only major source which is extracted through deep dug wells and tubewells. The area receives 650 mm to 700 mm rainfall in the year. The discharge of groundwater is gradually decreasing year after year due to heavy pumping and increase in well density. It ultimately affects the yield per hectarage and lifting of groundwater from the existing groundwater structure. There is a competition in deepening of dug wells every year (2- 3m) by individual farmers. They have never bothered about the non-availability of groundwater for future. The groundwater quality is also deteriorating which leads to water borne diseases.

The area comes in the alluvial groundwater potential granular zone. The river Tapi is the major lineament which holds large quantity of groundwater. The summer Static Water Level ranges from 6.10 m to 43.60 m and the winter Static Water Level ranges from 0.30 m to 25.20 m. The fluctuation ranges from 5.80 m to 18.40 in the study area. According to groundwater assessment as of now there are 2 Number of Safe watersheds, 3 No. of Semi critical watersheds, nil Critical watersheds, 2 No. of Overexploited watersheds. The heavy discharge of groundwater leads to change in nomenclature. To study the trend of water level 11 No. of hydrographs are established to assess the trend of declining of SWL by 1 to 2 m per year. The discharge of groundwater is directly related to the annual recharge, as the annual recharge decreases there is fall in the groundwater discharge which ultimately affects the Water Supply and Irrigation sector based on groundwater. Many villages and big towns in the study area are facing drinking water scarcity during the summer and in non-summer months in case of deficit rainfall. The Scientific study reveals that water conservation structures like Cement Nalla Bandh, K.T. Weir, etc., are not feasible since they do not have foundation in the alluvial zone. The rainwater does not get recharge the groundwater as it flows on the soil and goes as a runoff flow to the Tapi River. New measures for artificial recharge, flooding of the water in intake dug wells and tube wells by using surplus water from the Hatnur canal and other measures like recharge shafts are suggested.

***Keywords**: Tapi Basin, watersheds, hydrographs, groundwater, aquifer discharge, decline, groundwater quality, water conservation structures*

ASSESSING DRINKING WATER SCARCITY IN SEMI-ARID HARD ROCK BASALTIC AQUIFERS USING GEOMORPHOLOGICAL SIGNATURES IN KARHA RIVER BASIN FROM WESTERN INDIA

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The importance of groundwater as a key resource in India lies in its critical role in meeting domestic, agricultural, and irrigation needs, particularly in semi-arid and drought-prone regions. Managing groundwater is challenging due to uneven rainfall distribution, which exacerbates drinking water shortages, especially in Maharashtra, where many villages rely on water tankers during the dry season. Government authorities face the ongoing task of implementing both short-term and long-term solutions to address this scarcity. The Karha River basin, located in Western India, exemplifies these issues. This semi-arid region depends mainly on groundwater, especially due to its basaltic hard rock terrain, which restricts groundwater availability. Irregular rainfall patterns further worsen water scarcity. Local populations access groundwater through large-diameter wells that tap into shallow aquifers, but these wells often dry up seasonally, making it difficult for local governments to sustain water supplies. The present study calls for an early warning system to improve proactive management. By analyzing geomorphological parameters, the study aims to model scarcity hotspots and vulnerable zones, thereby helping authorities address groundwater scarcity effectively.

Terrain analysis is fundamental to research and development, as land-surface topography strongly influences groundwater flow and water-table dynamics. Elevation data was accessed through the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). This data has a spatial resolution of 15 m and is organized in 1°×1° tiles. For the study area, two specific tiles, ASTGTM2_N18E074 and ASTGTM2_N18E073, were used to process the DEM. Groundwater fluctuations are also influenced by drainage patterns and density. Drainage density, especially in hard rock terrains, is crucial for groundwater availability and helps identify groundwater potential zones. Drainage analysis was conducted by integrating the vector drainage layer of the study area in GIS. A drainage density map was produced using ArcMap's 'Create Fishnet' tool. The catchment area was divided into 1 km² square cells, and the total length of streams within each cell was calculated and recorded in a database. This data was then joined to the 1 km² grid of the catchment area.

The study area is located on a moderately to gently sloping terrain (moderately dissected plateau). It is bounded by the hilly ranges towards northwest, whereas the rest of the area shows relatively plain surface. The elevation ranges from 418 m to 1353 m above mean sea level indicating dynamic groundwater system in the area (ASTER GDEM). The slope map has been derived from the ASTER GDEM reveals the general slope toward East. Thematic mapping technique has been used to highlight the relative variation of slope of the study area. About 80% of the area shows a slope up to 10%, except few hilly ranges in the north-western part. Drainage density (DD), determined as total length of streams channels per unit area, is vital in the groundwater movement. The study area is characterized by dendritic to sub-parallel drainage pattern. Such pattern is suggestive of same rock type with lineament structures and overall, more surface runoff. Moreover, the stream network is dense in the northwest part and becomes sparse, to some extent, in the southeast part along the Karha River.

Slope affects groundwater recharge and ranges from 0% to 152% in the study area. Classifying the slope into five categories (0-5%, 5-10%, 10-15%, 15-20%, and >20%) reveals that approximately 80% of the study area has a slope of up to 10%. Observation wells indicate that areas with slopes greater than 10% have reduced groundwater recharge, while slopes up to 5% account for most recharge. Therefore, slopes above 5% suggest vulnerability to water scarcity as they facilitate groundwater movement via hydraulic gradient. The relationship between slope and groundwater level fluctuation is complex and spatially variable. Generally, areas with steeper slopes have lower groundwater recharge potential due to increased surface runoff. A plot of groundwater recharge (measured from May 2024 to October 2024) across different slope classes shows that recharge decreases as slope increases (R^2 = -0.735). Drainage density in the catchment area varies from 0.00 to 7.44 km/km². Classified into three zones—low (<2 km/km²), moderate (2-4 km/km²), and high (>4 km/km²)—moderate drainage density is prevalent in the study area. Low drainage density promotes infiltration, whereas high density increases surface runoff. Groundwater fluctuation across these categories shows a negative correlation with drainage density (R^2 = -0.943). As drainage density is a critical indicator of groundwater availability in hard rock terrains, it supports effective water management decisions.

Drinking water scarcity is a multifaceted issue influenced by various factors. Effective mitigation in Maharashtra, India, requires real-time information on the location, intensity, and duration of scarcity. Successful management of this recurring issue hinges on accurate predictions. Accordingly, this study suggests that incorporating drainage density and slope into groundwater management can improve early warning systems, mitigate the risks of groundwater depletion, and inform strategic water management in basaltic hard rock regions. The study also shows that drinking water scarcity is closely linked to spatial and temporal variations in groundwater recharge. Groundwater availability, or recharge, is significantly impacted by slope and drainage density, both key contributors to scarcity conditions.

Keywords: *Drinking water, scarcity, basaltic aquifer, geomorphology, Karha River, Maharashtra*

Theme 5

GROUNDWATER CONTAMINATION AND REMEDIATION

CHITOSAN AND CHITOSAN-GRAPHENE OXIDE NANO-BIOADSORBENTS FOR EFFICIENT FLUORIDE REMOVAL FROM WATER: PROCESS OPTIMIZATION AND ADSORPTION MECHANISMS

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Fluoride contamination in water poses a significant environmental and health problem, particularly in regions reliant on groundwater. Excess fluoride concentrations (> 1.5 mg/L) in drinking water can lead to adverse health effects such as dental and skeletal fluorosis. Thus, it is crucial to efficiently reduce high fluoride concentrations before water is used for drinking purposes. Various technologies, including ion exchange, oxidation, coagulation, electrocoagulation, and adsorption, have been employed to remove fluoride from water effectively. However, most of these methods, except adsorption, are not ideal for removing contaminants from very dilute solution and may not completely eliminate pollutants from treated water. Further, adsorption stands out due to its simplicity, low energy consumption, feasibility, and higher effectiveness in achieving complete removal of contaminants like fluoride from water. Numerous adsorbents have been explored for fluoride removal, including biochar, alumina, clay, zeolites, fly ash, activated charcoal, nano-adsorbents and nano-bio-adsorbents. Among these, nanomaterial-based adsorbents stand out due to their high surface area and surface energy, which enhance their adsorption potency. In recent years, the integration of nanoparticles into or onto porous polymeric matrices has led to the development of nanocomposite adsorbents, which demonstrate superior performance. Polymer nanocomposites are particularly effective because they combine the extensive surface area and high reactivity of nanomaterials with the structural flexibility, durability, and enhanced stability of polymers. This synergy results in greater adsorption capacity, improved stability, and enhanced selectivity for a wide array of contaminants. Chitosan, a naturally abundant, eco-friendly, and biodegradable polymer, has gained significant attention as a matrix for constructing nanocomposite adsorbents for removing harmful ions such as fluoride, nitrate, and heavy metals from water. However, in its unmodified flake or powder form, chitosan is less stable and has limited adsorption performance in field applications. To overcome these limitations, modified or composite forms of chitosan have been developed, offering a more promising solution for fluoride removal. In the present study, we evaluated fluoride adsorption capacities using two adsorbents: chitosan (CTS) beads and chitosan-graphene oxide (CTS/GO) nano-bio-adsorbent beads. Bead-shaped adsorbents made from CTS and CTS/GO are particularly effective for pollutant removal due to their higher regeneration capacity after treatment. The adsorption process involved evaluating factors such as pH, initial fluoride concentration, contact time, and adsorption capacity (mg/g). Response Surface Methodology (RSM) with a Box-Behnken Design (BBD) was used for process optimization, helping identify the optimal conditions for fluoride removal. The adsorbents were thoroughly characterized using a suite of spectroscopic and microscopic techniques including UV-Vis spectroscopy, SEM-EDX, TEM, and FTIR, confirming the successful incorporation of GO into the chitosan matrix.

RSM-BBD was utilized to optimize the operating conditions, achieving maximum fluoride removal efficiencies of 44.72% for CTS and an impressive 74.31% for CTS/GO under optimal parameters. The adsorption behavior was further analyzed by evaluating the effects of key variables, with equilibrium data fitting well to the Langmuir isotherm model. The maximum adsorption capacities were 7.29 mg/g for CTS and a significantly higher 45.32 mg/g for CTS/GO, showcasing the superior performance of the composite. Kinetic studies indicated that the pseudo-first-order model best described the adsorption kinetics, with rate constants of 0.059 min^{-1} for CTS and 0.038 g/mg/min for CTS/GO. Thermodynamic analysis revealed that the adsorption process for CTS/GO was spontaneous and exothermic, with a Gibbs free energy change (ΔG) of -5.89 kJ/mol, while CTS exhibited a non-spontaneous process (ΔG = +2.31 kJ/mol). It was also demonstrated that the adsorption rate was dependent on the number of available adsorption sites on the adsorbent surface, and was eventually controlled by the binding of fluoride to the surface. Furthermore, the adsorption capacity of CTS/GO was higher than that of CTS indicating that the number of available adsorption sites increased when CTS is modified but GO nanoparticles. Desorption studies highlighted the reusability of the adsorbents, with CTS/GO maintaining an 80.56% desorption efficiency after three cycles, further enhancing its potential as a sustainable solution. Applied to real wastewater, CTS/GO consistently outperformed CTS, reinforcing its promise as a highly effective material for fluoride de-fluoridation. This study positions CTS/GO as a viable and long-term solution for efficient fluoride removal from water resources. The incorporation of GO into the CTS matrix not only enhanced adsorption capacity but also improved adsorption kinetics and regeneration potential. The CTS/GO composite exhibited higher desorption efficiencies over four cycles compared to pure CTS beads, making it a promising candidate for reusable and cost-effective fluoride removal from water. Future work will focus on further optimization and scale-up of the CTS/GO composite synthesis process in column studies to ensure its practical application for large-scale wastewater treatment.

Keywords: *Fluoride, chitosan, chitosan-graphene oxide, adsorption isotherm, adsorption kinetics*

ASSESSING GROUNDWATER QUALITY: VARIABILITY AND DISTRIBUTION OF MAJOR AND TRACE IONS IN CHHATTISGARH, INDIA

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Groundwater is considered as safest source of freshwater for drinking and domestic purposes. The quality of groundwater is an important aspect to be considered for use of water. Globally, only 2.5% water can be ascertained as fresh water. The fresh water sources are being contaminated due to anthropogenic activity, agriculture practices and industrialization. Also, the quality of groundwater can be ascertained to geogenic origin, i.e. role of geology on groundwater quality. The objective of this study is to understand the groundwater quality in terms of major and heavy metal concentration across the Chhattisgarh state. The purpose is to ascertain the variability and distribution of the chemical constituents of the groundwater, thereby helping to understand the status of groundwater quality in Chhattisgarh. It will also enable to identify freshwater and contaminated zones. Also, it will help to identify the sources of contamination, and comment on the role of geology on groundwater quality. This paper is a review of literature to understand the variability and distribution of major and trace ions in groundwater in the northern, central and southern region of Chhattisgarh. CGWB has published district hydrogeology reports, which has helped to understand groundwater occurrence, movement and groundwater quality of Chhattisgarh. The work includes compilation of previous work on geochemistry of groundwater, thus ascertaining the status of groundwater quality in Chhattisgarh. The status of groundwater quality is demonstrated by compilation of analytical data of work on groundwater quality in the northern, central and southern regions of Chhattisgarh.

Korba coal field area is the major coal mining area in the northern part of Chhattisgarh. According to CGWB, the groundwater geochemistry reports concentrations of barium, iron, nickel, manganese and aluminum exceeding a desirable limit in groundwater sample. Also, a high concentration of lead, cadmium and chromium is reported in Korba. The Balrampur, Korba, Koriya, Raigarh, Surajpur, Sarguja and Jashpur has fluoride above permissible limit (above 1.5mg/l). In the Korba, Jashpur and Raigarh regions, elevated level of nitrate (above 45 mg/l) is reported. Also, elevated level of iron is reported in Koriya, Raigarh, Surguja, Korba, Jashpur, Surajpur areas. In the central region of Chhattisgarh, salinity, arsenic and fluoride are the major contaminants. In Bemetera distict, high concentration of sulfate, magnesium, calcium, chloride and fluoride is found in groundwater. The elevated level of arsenic and fluoride is observed in Ambagarh chowki of Rajnandgaon district. Water Quality Index (WQI) of Raipur reported, 76 % area comes under good category while 24 % is classified as poor or unfit for consumption. It has also found elevated levels of lead, chromium and calcium in the Arang block. Rapid extraction of groundwater has raised concern on groundwater quality particularly nitrate, fluoride, manganese in Kasaridhi village of Durg, and that of iron and manganese in Durg-Bhilai region. In the Janjgir-Champa region, copper, cadmium, chlorine, zinc, lead, nickel, chromium, calcium, manganese and iron has been reported at higher levels due to fly ash dumping. According to CGWB, the groundwater in Balod, Bemetera, Durg, Kanker, Dhamtari, Mahasamund, Bilaspur, and

Raipur region contains fluoride concentration above the permissible limit. In the central region high concentration of nitrate is observed in Bilaspur, Dhamtari, Kanker, Kawardha, Mahasamund, and Raipur. Iron is reported in the regions of central Chhattisgarh namely, Kanker, Raipur, Durg, Bilaspur, Dhamtari, Kawardha, Mahasamund, Rajnandgaon, and Jhanjgir-champa. In the southern region of Chhattisgarh, 50% of groundwater samples are found to be contaminated with fluoride in Bijapur district due to geogenic process. Bastar, Bijapur and Kondagaon also contain fluoride above permissible limit. Nitrate and iron are reported above desirable limit in Bastar and Dantewada districts. This review highlights the variation in groundwater quality across the state. The quality of groundwater is a serious issue as the groundwater is the sources for drinking and agriculture practices for overall population.

Keywords: *Groundwater, groundwater quality, groundwater contamination, groundwater analysis, Chhattisgarh*

STRATEGIC ANCHORING OF CERIA ON GRAPHITE SURFACE FOR OPTIMAL GROUNDWATER ARSENIC REMOVAL

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Arsenic (As) contamination is a significant environmental pollutant largely resulting from human activities through mining, industrial processes, agricultural practices and geological disturbances. Prolonged exposure to arsenic-contaminated water poses serious health risks, leading to diseases like cancer and skin lesions. Groundwater arsenic concentrations are notably varied, with studies reporting levels ranging from less than 0.005 ppm to 5 ppm across different regions. In arid and semi-arid areas, developing nations heavily rely on groundwater for irrigation and drinking due to its relative availability. However, this water often contains trace elements that exceed safe drinking standards established by the Bureau of Indian Standards (BIS), Indian Standards (IS), and the World Health Organization (WHO). Contaminants such as lead (Pb), selenium (Se), chromium (Cr), cadmium (Cd), nickel (Ni), aluminum (Al), As, fluoride (F-), and nitrate (N) present substantial health risks that challenge the achievement of Sustainable Development Goals (SDGs) focused on clean drinking water. More than 200 million individuals are exposed to water that has an As content greater than standards. More than 105 nations have reported having arsenic in their water. Over 200 million individuals worldwide are exposed to water with arsenic concentrations exceeding safety standards, with more than 105 nations reporting arsenic contamination in their water supplies. This widespread issue underscores the urgent need for effective solutions to mitigate the health risks associated with arsenic exposure in affected populations. In the present study, synthesized ceria particle demonstrates exceptional effectiveness as an adsorbent for arsenic removal, offering unique advantages over conventional adsorbents through its superior efficiency, cost-effectiveness, and minimal need for pre-treatment processes. This research establishes ceria as a leading candidate for practical applications in community water purification systems, enhancing overall accessibility and safety in arsenic-affected regions.

Ceria particles were synthesized using a micellar route, employing cetyltrimethylammonium bromide (CTAB) as a surfactant to stabilize the process. Ammonium oxalate and cerium (III) nitrate served as precursors, facilitating the controlled formation of the ceria structure. Additionally, graphite was incorporated to provide a high surface area for effective adsorption, enhancing the overall efficiency of As removal from water. This methodology not only ensures uniform particle size but also optimizes the interaction between ceria and targeted contaminants. The synthesized cerium oxide (CeO_2) particles were characterized through PXRD, revealing Bragg reflections at specific angles (2θ) of 20.8°, 30.3°, 40.8°, and 50.6° indicating the formation of a pure phase of cubic cerium dioxide with space group Fm-3m (225). The enhanced intensity of the diffraction peaks in sample confirms its higher crystallinity. To investigate the morphology of the prepared samples, FESEM analysis was conducted, which revealed a flake-like morphology with an average flake size of 1.2 µm. Furthermore, the surface area of the ceria was determined through BET analysis, yielding a substantial surface area of 50.380 m^2/g. This significantly high surface area enhances interactions between As and the CeO_2 surface, providing a greater number of active sites for arsenic molecules to contact, thereby facilitating their conversion into degraded products. The pore volume and average pore radius were measured at 0.096 cc/g and 18.873 Å, respectively.

In the present study, cerium oxide (CeO_2) colloidal particles were synthesized using a micellar route and subsequently anchored onto graphite for the removal of As from groundwater. The effectiveness of these ceria particles in removing As through adsorption was investigated across various parameters, including contact time, pH (ranging from 2 to 8), and adsorbent dose (from 1% to 5% w/v) .The results indicate that nearly complete removal of As, achieving 98% efficacy, occurs within 30 minutes at an optimal adsorbent dose of 50 mg for an initial arsenic concentration of 10 ppm. This process demonstrates remarkable effectiveness across a wide pH range, specifically from pH 2 to pH 8. Furthermore, in the presence of competitive ions, the ceria-based adsorbent exhibited substantial adsorption capacity, effectively removing various pollutants such as aluminum (Al), chromium (Cr), nickel (Ni), copper (Cu), selenium (Se), cadmium (Cd), mercury (Hg), lead (Pb), uranium (U), and iron (Fe), with removal efficiencies ranging from 60% to 90%.

In this study, CeO_2 particles were successfully synthesized. The findings can be summarized as follows (i) Kinetic analysis demonstrated that arsenic removal occurred rapidly, with approximately 98% elimination within the first 30 minutes; (ii) The adsorption data were well-fitted to the linear forms of Freundlich, Langmuir isotherm models, indicating that the adsorption process followed first-order kinetics; (iii) The presence of other ions, including Al, Cr, Ni, Cu, Se, Cd, Hg, Pb, U, and Fe influenced adsorption dynamics. Nonetheless, the high adsorption capacity of CeO_2 particles suggests significant potential for the removal of arsenic from water. This work highlights the efficacy of CeO_2 particles as a promising material for arsenic remediation in aquatic environments.

***Keywords**: Groundwater, ceria, graphite, arsenic removal, adsorption, environmental pollutant*

GROUNDWATER QUALITY ASSESSMENT IN SEMI-ARID REGION OF NORTH-WESTERN PART OF ODISHA, INDIA

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Groundwater as a vital resource is being utilized by human beings since the dawn of civilization. The utility of groundwater for both drinking and irrigational purposes demands constant scrutiny of its quality. Increase in mining activities, improper use of wastes on land, excessive use of fertilizers and pesticides in agricultural field and other anthropogenic activities have challenged the purity of groundwater. Other than human involvement, geogenic actions such as degree of chemical weathering of various rock types, quality of recharge water and inputs from resources other than water rock interaction influences the chemistry of groundwater. The alarming increase in rate of groundwater pollution throughout the world has imposed serious health hazard to humans and hampered agricultural productivity. The present study encompasses the geochemical characterization of groundwater and its suitability in north-western part of Odisha for domestic and irrigational purpose. Around 15 samples of groundwater were collected from tube-wells, bore-wells and dug-wells during the month of January, 2023 (post-monsoon period). The physico-chemical parameters such as total dissolved solids (TDS), total hardness (TH), Calcium, Magnesium, Sodium, Potassium, Sulphates, Fluoride, Bicarbonates and Nitrates were determined using standard analytical methods. The concentration of Ca^{++}, Cl^{-}, HCO^{-} and TH were determined through standard titration. The concentration of Mg^{++} was calculated from the concentration of Calcium and Total Hardness. The concentration of Na^{+} and K^{+} were estimated with the help of flame photometer. The concentration of SO_4^{2-}, F^{-}, and NO_3^{-} were determined using UV Spectrometric method. The parameters such as pH, EC were measured insitu. The estimation of pH and EC revealed that the groundwater is generally fresh water but slightly alkaline in nature. The presence of hydroxides, carbonates and bicarbonates affects the alkalinity of groundwater. From the analysis, it was found that the concentration of major cations such as Na^{+} ranges between 2.8-56 mg/l, K^{+} ranges between 2.6-37.5 mg/l, Ca^{++} ranges between 25-165 mg/l, Mg^{++} ranges between 6.09-40 mg/l. The concentration of major anions are as follows: SO_4^{2-} is between 6-84 mg/l, NO_3^{-} is between 5.51-105 mg/l, Cl^{-} ranges from 20-180 mg/l, HCO^{-} ranges from 54.9-311.1 mg/l and F^{-} ranges from 0.008-1 mg/l. The TH ranges between 60-530 mg/l and reveals the water can be classified as moderately hard to very hard water. Hardness in groundwater makes it undesirable to be used as drinking water. The high concentration of K^{+} in the post-monsoon period is likely the cause of leaching of silicate minerals such as orthoclase, microcline, hornblende, muscovite and biotite in igneous and metamorphic rocks. Agricultural activities might also escalate its concentration in the groundwater. Furthermore, high concentration of potassium might cause significant disorder to people suffering from kidney diseases, coronary artery disease, high blood pressure and diabetes. High concentration of potassium in irrigation water can affect the hydraulic conductivity of the soil. The increase in alkalinity of groundwater affects the alkalinity of the soil and this might play a significant role in crop failure. The concentration of all the other ions falls under the permissible limit determined by BIS (2012) and WHO (1993). TDS ranges between 105.4- 658.5 mg/l indicating non saline water and that the groundwater is suitable for human consumption. The suitability of groundwater for agricultural purpose is determined using sodium ratio, Kelly's ratio, sodium adsorption ratio (SAR) and Wilcox diagram. Salts like sodium, potassium, calcium and magnesium affects the growth of plants as they can modify their osmotic processes and metabolic reactions. These salts also affect the structure, permeability and aeration in soil. The sodium concentration is basically expressed in terms of Na%. The Sodium Adsorption Ratio is defined by SAR and Kelly's Index is calculated as KI. The Wilcox diagram is used to determine the viability of groundwater for irrigation. It is a graphical representation in which EC is taken along X-axis and Na% along the Y-axis. The sodium ratio ranges between 0.020-1.80. According to the sodium adsorption ratio, 80% of the sample falls under the excellent category while 20% of the samples falls in the good category. As per the Kelly's index it has been found that around 60% of the sample are recommendable while the rest 40% show slight increase in alkalinity of the water. From the overall study, it is concluded that almost all the water samples of this area are suitable for irrigational practices as well as for human consumption. The hardness in groundwater can be eliminated by lime-soda process, reverse osmosis, ion exchange method, distillation etc. Water softeners can be used for elimination of potassium in groundwater and can be made desirable for susceptible individuals before consumption.

Keywords: *TDS, agriculture, Na%, Wilcox diagram, Kelly's ratio, SAR*

ARSENIC CONTAMINATION IN GROUNDWATER AND HEALTH RISK ASSESSMENT IN PARTS OF THE BRAHMAPUTRA FLOODPLAINS IN ASSAM, INDIA

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Arsenic (As) is a toxic metalloid that can contaminate groundwater posing significant health risk to humans and as such is a growing global concern. As occurs naturally in rocks and soil on the earth surface and can leach into water through geogenic or anthropogenic sources. The As concentration in the groundwater of many parts of the world, notably South Asian countries like Bangladesh, India and Nepal, have far exceeded the safe drinking water standard leading to widespread public health issues. Previous studies in India, have reported that more than 20 states have been affected with As (>10µg/l) in the groundwater including Assam. As in groundwater of Assam was first reported in 2004 and thereafter several studies have been undertaken to understand the sources, distribution and release mechanism of As. Various As release mechanism has been discussed in the studies globally, however, reductive dissolution of Fe oxyhydroxide is widely accepted. The present study has, thus, been undertaken in parts of the Upper Brahmaputra floodplains in Jorhat and Golaghat districts of Assam, India to assess the distribution of geogenic contamination of As in groundwater and its health risk on exposed population. Groundwater samples (n=100) were collected from shallow (<30m) aquifers covering the two districts. Major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}, NO_3^{-}) along with the heavy metals (As, Fe, Mn) were analyzed for the present study. The heavy metals and cations were analyzed in ICP-OES with precision of nearly ~2%, whereas the anions were analyzed following the procedure of APHA 2017. Potential health risk associated with arsenic contamination, focusing on human exposure through drinking water was evaluated for 6 administrative blocks (where As>10µg/l). The population was divided into children (2-14 yrs), adult male and female (>18 yrs). Hazard quotient (HQ) was calculated to determine non carcinogenic risk. HQ <1 signifies the absences of detrimental effects on human health, while, HQ>1 depicts the possible chance of non-carcinogenic health risk. The cancer risk was determined where cancer slope factor for arsenic was considered as 1.5 per mg/kg/day as given by USEPA and Cancer index (CI) was calculated.

The average cations and anions concentration in groundwater of the southern bank of the Brahmaputra River are in the order of $Na^{+}>Ca^{2+}>Mg^{2+}>K^{+}$ and $HCO_3^{-}>Cl^{-}{}^{-}>SO_4^{2-}$. The trilinear piper plot indicates Ca-Mg-HCO_3 as the primary water type followed by Na-Ca-HCO_3-Cl. In addition to it, Gibbs plot indicates rock water interaction as a dominant process that controls the groundwater chemistry of the region. As concentration in the groundwater of the study area ranges from 0.07 to 480µg/l with a mean value of 54.5µg/l. 71% of samples have exceeded the WHO permissible limit of 10 µg/l while 41% samples have As concentration >50 µg/l. 97% and 69% of samples are observed to have exceeded the permissible limit of 0.3mg/l and 0.4 mg/l for Fe and Mn with their mean values of 12.41 mg/l and 0.73 mg/l respectively. Elevated As is mostly found in the aquifers adjacent to the foothills of Naga hills, while low As (<10 µg/l) is found near the Brahmaputra floodplain. The subsurface study reveals the presence of thick clay layer capping the aquifers near the

Naga foothills, whereas mostly sandy layers are found near the river Brahmaputra. XRD peaks indicates the presence of illite and kaolinite minerals in the clay sediments which might have acted as an adsorbing site for As and these clay layers might have behaved as a host for As in the region. Upon receiving the conducive environment, the adsorbed As is released into the groundwater, thus contaminating the aquifers. Health Risk assessment indicates that the HQ values of children (range 1.86 - 25.45) are higher than the HQ values of adult male (range 1.12 – 19.33), and adult female (range 1.09 – 17.03), making them highly vulnerable for non-carcinogenic risk. Moreover, the cancer risk ranges from 1.1×10^{-3} to 8.7×10^{-5} which is much higher than USEPA limit 10^{-6} making the entire population at high risk of cancer.

The present study concludes that the groundwater of the study area is highly contaminated with heavy metals particularly As, Fe and Mn, raising concerns regarding safe drinking water. The evaluation of health risk assessment indicated that the entire population is at potential risk of both carcinogenic and non-carcinogenic risk, while children are most vulnerable as compared to adult male and female. The results of the study will facilitate in understanding the As distribution and its adverse impact on human health in the southern bank of the Brahmaputra floodplains and will also be helpful for stakeholders to take evidence based decision that aims in providing safe drinking water and protect human health.

Keywords: *Arsenic contamination, health risk assessment, sediment chemistry, hydrogeochemistry, Brahmaputra floodplains*

HEAVY METAL CONTAMINATION IN GROUNDWATER OF THE GUWAHATI CITY, ASSAM, INDIA

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Assessing groundwater quality is crucial for ensuring safe drinking water, as it is the primary source of drinking water. Groundwater quality is progressively worsening due to population growth and subsequent urbanization. Groundwater is contaminated due to lack of proper management and protection, mainly in urban centres. Preventing groundwater from contamination is a major concern as it can cause dangerous health problems. Heavy metal contamination in groundwater causes a serious health impact on human beings causing various cancers and some neurological issues. Therefore, proper research on the sources of groundwater pollution is essential for sustainable development. Many researchers have assessed groundwater quality in urban areas throughout the world. In urban areas, heavy metals like Mn and Pb contamination in groundwater is increasing. Lead in groundwater is like a curse for humans since it is a carcinogen and can affect every system and organ of the human body. Groundwater in Guwahati City, Assam, India is already contaminated with the heavy metals Cu, As, Mn, Pb, Ba, Cu and Fe. Therefore, proper research on the sources of groundwater pollution is essential for the protection of the source.

This study's objective is to evaluate the groundwater quality of rapidly urbanizing Guwahati city, Assam, emphasizing heavy metal contamination. The study focuses on evaluating the groundwater quality in Guwahati City, Assam emphasising six heavy metals (Fe, As, Cu, Zn, Mn and Pb). The study also aims to delineate the spatial distribution pattern of the different parameters and establish the relationship between the parameters and the geology of the area. Sixty-three groundwater samples were collected from ring wells in 250 ml HDPE bottles. Samples were preserved with HCl for As, Fe and HNO_3 for Cu, Zn, Mn and Pb in two different bottles for heavy metal analysis. Physical parameters pH, Temperature, Total dissolved solids (TDS) and Electrical Conductivity (EC) were measured in the field using a Hanna handheld instrument (HI98129 pH/conductivity/TDS tester). Samples were well-preserved at 4°C at the laboratory prior to analysis. Heavy metals (Fe, As, Cu, Zn. Mn and Pb) were analysed in Atomic Absorption Spectrophotometer (PG Instruments AA8000) following standard protocols provided by the American Public Health Association (APHA). Heavy Metal Pollution Index (HPI) and Metal Index (MI) were computed using MS-excel and spatial distribution maps were prepared using ArcGIS 10.8. The heavy metals analyzed for the samples revealed that Cu and Zn metals are below the detection limit (bdl). As concentration exceeds the WHO limit of 10µg/l in only one sample out of 63. Mn concentration exceeds the WHO guideline value of 0.4mg/l in 39.68% of samples indicating serious health concerns for the exposed communities, whereas the concentration of Pb exceeds the permissible limit of WHO i. e. 10µg/l in 100% of samples. Based on the analysis of the six heavy metals in the city inferred that it is in a critical position where groundwater is polluted with poisonous contaminants like Pb, Mn, and Fe. The groundwater in the entire city is heavily loaded with Pb.

The spatial distribution pattern of the metals inferred that the city is contaminated with Fe and Mn except in small pockets, whereas the entire city is contaminated with Pb. As

contamination occurred only in a small area in the northwestern part of the city. The plot of the concentration in the geological map indicates the contribution of geology in As and Fe contamination as their concentration is highest adjacent to the Archean group of rocks, while no coordination has been found between Mn and Pb concentration with geology. This contamination may be attributed to the anthropogenic contribution through the leaching of urban sewerage load. HPI computed for six metals (Fe, As, Cu, Zn, Mn, and Pb) ranges from 95.84 to 1467.18 with a mean of 795.86. The HPI value greater than 100 in 98.41% of samples indicates the unsuitability of groundwater for consumption. The spatial distribution of HPI reveals groundwater only in a small area in the extreme northernmost portion of the city is suitable for human consumption. Metal index (MI) calculations also reveal that groundwater is seriously affected (>6) by heavy metals, and 4.76% of samples are strongly affected (4 – 6). This insight allows for a targeted intervention in the city to prevent further water quality degradation. HPI and MI computed for the metals also suggested that there is a need for another source of drinking water in the absence of a proper mitigation plan. The spatial distribution pattern and the distribution with geology are suggestive of the anthropogenic influence on groundwater contamination. Therefore, preventing and mitigating these groundwater problems are necessary by intervening in the resource with a systematic scientific approach.

Keywords: *Heavy metals, heavy metal pollution index, metal index, spatial distribution, Guwahati*

IMPACT OF MUNICIPAL SOLID WASTE LEACHATE ON GROUNDWATER QUALITY AND ITS POTENTIAL PUBLIC HEALTH RISK

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The efficient waste management is a global challenge, with a direct public health effect. The global solid waste generation rate is rising quickly due to the result of ongoing urbanization and industrialization. According to the CPCB 2020-21 report, India produces 160038.9 tonnes per day (TPD) out of which waste collected only 152749.5 TPD, further 79956.3 TPD of waste is treated, 29427.2 TPD is landfilled and the rest 50655.4 TPD of total waste remains omitted. A major global environmental and public health concern is the inappropriate handling of municipal solid waste (MSW). Among the numerous issues, the leachate produced by MSW landfills poses a serious risk to groundwater supplies and, by extension, public health. Highly concentrated dark brown color leachate is generated from landfill, which contaminates both groundwater and soil as well. The leachate properties are often characterized by high concentrations of Biological Oxygen Demand (BOD), Ammoniacal nitrogen (NH_3-N), Chemical Oxygen Demand (COD), COD/BOD_5 ratio. It also contains persistent organic pollutants (POPs) like dioxins, which impair immune function and upset hormonal balance, and volatile organic compounds (VOCs) like benzene, a known carcinogen. These substances have extensive negative effects on health, including harm to reproduction and problems with development in infants. Many of these compounds are very soluble, which makes it easier for them to migrate through soil into nearby groundwater, degrading sources of drinking water and posing serious health concerns to people.

In order to synthesize information on the effects of landfill leachate on groundwater quality and human health risk assessment, 118 selected studies from the Google Scholar database were reviewed. Leachate from unlined or insufficiently lined landfills percolates into groundwater, which is the primary contributing factor to groundwater contamination. Water quality is severely degraded when leachate migrates into groundwater, introducing a wide range of contaminants. Vital organ damage is negatively impacted by the high concentration of heavy metals found in leachate, which seeps through the soil to groundwater near dumpsites. In geographical areas with permeable soils, broken bedrock, or poorly managed landfills without sufficient containment measures, leachate has a very negative effect on groundwater. Because of the subterranean flow of contaminants and the sluggish natural recharge rate, cleaning up contaminated groundwater is difficult and expensive. This emphasizes the significance of stringent landfill design guidelines, frequent inspections, and efficient leachate treatment systems to protect groundwater resources from contamination.

Groundwater quality is impacted by MSW leachate, which emphasizes the importance of sustainable waste management techniques. In addition to endangering essential water resources, leachate pollution causes serious health dangers to the general public. Children exposed to lead and cadmium suffer from developmental problems, kidney failure, and brain impairment. Mercury and arsenic have been connected to organ damage, immunological

system inhibition, and cancer. Elevated nitrate and ammonia concentrations in leachate can contaminate drinking water, causing nitrate-induced oxygen depletion in the blood, which causes blue baby syndrome (methemoglobinemia) in infants. Adults exposed to ammonia may experience respiratory discomfort and other systemic consequences. Human health is also at risk from biological pollutants found in leachate. Pathogens include bacteria (like Salmonella and E. Coli), viruses (like Hepatitis A), and parasites (like Giardia) that can cause serious liver infections, gastrointestinal disorders, and in rare situations, potentially fatal dehydration. Although leachate can produce toxic gases and aerosols when exposed to air, it also presents a risk to human health. Methane and carbon dioxide are produced by decomposing organic matter in landfills, and volatile chemicals that irritate the skin, eyes, and respiratory system can be released by leachate. Due to the presence of airborne contaminants and unpleasant odors, communities close to landfills frequently complain of headaches, respiratory issues, and stress-related diseases. Additionally, exposure to polluted soil or agricultural water can cause toxins to bioaccumulate in crops, which can have an indirect impact on human health by way of the food chain. People who live close to landfills, landfill employees, and vulnerable populations like children and the elderly are the most in danger since they are more likely to suffer negative consequences from hazardous exposure. The long-term effects of landfill leachate, such as neurological harm, reproductive issues, and cancer risks, highlight how urgently appropriate waste management and leachate treatment are needed to safeguard public health. For groundwater resources to be sustainable over the long run and to protect public health, MSW leachate must be managed effectively. This study provides a comprehensive review of the impact of leachate generated from landfill sites on groundwater quality and its possible human health risks. An integrated strategy that incorporates better landfill management, cutting-edge leachate treatment technologies, regulatory enforcement, and community involvement is needed to address the issue of municipal solid waste (MSW) leachate. Communities may minimize the threats leachate poses to the environment and public health by enhancing landfill infrastructure, using cutting-edge treatment technology, reducing trash production, and encouraging cooperation. These actions will save essential water resources for future generations and open the door for sustainable waste management systems when paired with proactive monitoring and public involvement.

Keywords: *MSW leachate, dumping site, groundwater, human health, leachate management*

USE OF HYDRO CHEMICAL INDICES FOR MINERAL DISSOLUTION AND POLLUTANT IDENTIFICATION IN THE MIDDLE GANGA BASIN, INDIA

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This study aims to characterize the parameters (cations, anions, pH and EC) and factors (Geology, Water-rock interactions, and the degree of chemical weathering**)** controlling groundwater geochemistry using various hydro chemical indices, and a comparative analysis of data. The spatial distribution of the points from where the groundwater samples have been extracted for the estimation of the nine parameters is not the same. Rather the number of points as well as the location of the points is different for all the nine parameters. However, at some places there is common point where all or more than one parameter has been estimated for the groundwater samples. The number of points or stations for pH, Electrical Conductivity (EC), Chloride (Cl^-), Bicarbonate (HCO_3^-), Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sulphate (SO_4^{2-}), and Nitrate (NO_3^-) are 134, 190, 4, 353, 11, 10, 10, 9, and 10 respectively. In the case of pH, EC, and Cl the distribution of points is more towards north rather than southern portion of the basin. In statistics, control charts are the tools in control processes to determine whether a process is in a controlled statistical state or not. This chart is a graph which is used to study process changes over time. These charts are also known as Shewhart charts or process-behavior charts. The control charts are used for monitoring the quality of the groundwater that can easily tell about the lower and upper limits of the water quality parameter from the center lines. Control charts are essential tools for monitoring groundwater quality by tracking variations in key water parameters over time. The X-bar chart is used to monitor the average concentration of a parameter, such as nitrate levels or pH, across multiple subgroups of samples, while the I chart tracks the average performance of individual measurements without subgroups. The R chart and S chart help assess variation, with the former measuring the range within subgroups and the latter focusing on the standard deviation, both important for understanding the consistency of water quality. The MR chart is used to observe variation between consecutive individual measurements, while the C chart tracks the number of defects or exceedances of a threshold in a subgroup, such as contamination levels exceeding safety limits. The P chart monitors the proportion of defective samples exceeding a predefined threshold, and the U chart tracks the number of defects or exceedances per unit of water, helping to ensure the water remains within safe quality standards. These charts enable water quality managers to identify trends, shifts, or anomalies, ensuring timely intervention to maintain safe and sustainable groundwater resources. In this study, a total of 117 control charts (all nine types for all nine parameters for different groups) have been prepared.

In other studies, the principal component analysis (PCA) has been widely applied to assess major geochemical processes in aquifers and to choose hydro chemical indicators to address each geochemical process. When PCA is conducted using the isometric log-ratio (^{i}lr) transformed hydro chemical parameters, the ^{i}lr coordinates of a sub composition can be recommended as a method to integrate the selected ions. This process is cumbersome. Hence, for this study, traditional hydro chemical indices are used to classify groundwater according to flow path to evaluate groundwater salinity problems to assess the impact of microbial activity and chemical fertilizers, and the impact of anthropogenic activities, and quantify the impact of landfill on groundwater quality used hydro chemical indices to promote sustainable development and effective management of groundwater resources. For the development of hydro chemical indices, hydro chemical indicators should be so selected as to determine the dominance of rainwater. Then the hydro chemical indicators (as Ca^{2+}/Mg^{2+}) should be coupled to provide a single index. A number of hydro-chemical indices are available such as Sodium Absorption Ratio (SAR), Percentage Sodium (%Na), Permeability Index (PI), Kelly Ratio (KR), and Magnesium Hazard (MH). These indices can help analyze the quality of the groundwater for as large area as the middle Ganga basin. Apart from these indices, Total Dissolved Solids (TDS), water hardness, nitrate to chloride ratio, and nutrient pollution index (NPI) have been used to identify the source of pollution (i.e, industries, agriculture, manure etc.). The use of Empirical Cumulative Distribution Function (ECDF) in our study tells the probability of occurrence of certain quantity (ppm) of the chemical parameters in the groundwater for the entire study area. Hence, a comprehensive statistical analysis of groundwater in the entire basin has been done to gain valuable and crucial insights for the assessment of the groundwater quality. The groundwater quality in Uttar Pradesh (middle Ganga Basin) was investigated by collecting samples and analyzing key geochemical parameters, including pH, Electrical Conductivity (EC), Chloride (Cl^-), Bicarbonate (HCO_3^-), Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sulphate (SO_4^{2-}), and Nitrate (NO_3^-) with values varying from 6.9 to 8.7, 130 µS/m to 1620 µS/m, 0.32 ppm to 549 ppm, 0 ppm to 557 ppm, 7.8 ppm to 729 ppm, 23 ppm to 175 ppm, 4 ppm to 155 ppm, 11.9 ppm to 946 ppm, and 0 ppm to 174 ppm respectively. The spatial analysis of these quality parameters can identify the route of the mineral dissolution (anions like chlorides, bicarbonates, sulphates, and nitrates of cations like sodium, calcium, and magnesium along with many others) along with the pollutant (sources could be from industries, agriculture, and domestic waste) discharge into the aquifers. The geochemical analysis (using Ion Chromatography, Titration, pH Meters, and Conductivity Meters) of the study area can give information about the soil, agriculture, rocks (Carbonate Rocks, Sulfide Minerals, and Silicate Weathering), non-point and point sources of pollution, and chemical reactions causing changes in pH and EC. This study can be useful for various domains like geology, health department, and water resources development.

Keywords: *Hydro-chemical indices, groundwater quality, mineral dissolution, pollutant discharge, water resources*

CO-TRANSPORT OF ENGINEERED NANOPARTICLES AND BACTERIA IN WATER SATURATED POROUS MEDIA

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Expanding manufacture and widespread use of engineered nanoparticles (ENPs) in several industries such as medicine, personal care, food, energy storage, and site remediation leads to the unavoidable release of ENPs into the environment, thereby contaminating the soil and groundwater resources. Thus, introduction of ENPs into the soil and water occurs through release of untreated industrial nano-waste, waste water treatment plant discharges, landfill leachates, agricultural discharge and stormwater runoff. Among the metal oxide ENPs, ZnO is one of the most widely used ENPs in the world due to advancement of nanotechnology. Therefore, understanding the transport pathways, and related retention mechanisms of ZnO nanoparticles in the subsurface is critical for protecting drinking water sources from contamination and minimizing possible ecological consequences. Soil is inhabited by diverse bacterial communities of which *Escherichia coli* is ubiquitously found everywhere which is associated with the occurrence of water borne diseases. Bacteria have been found to significantly affect the transport behavior of engineered nanoparticles and other colloids. Profound research has been undergone on individual transport studies of nanoparticles and bacteria, however studying the cotransport behavior of nanoparticles and bacteria needs more vivid investigation. Modeling the cotransport of nanoparticles and bio-colloids in an efficient way is also lacking in the literature which has been addressed here efficiently.

For understanding the cotransport behaviour of ZnO nanoparticles and *E. coli*, lab scale column experiments have been performed to understand the fate and transport of ZnO nanoparticles and *E. coli*, both in the absence and presence of each other. Interactions between ZnO nanoparticles and *E. coli* along with the interference of one on the transport of the other has been studied here as well. In this work, we have observed higher retention of ZnO nanoparticles onto soil when present alone, in comparison to its retention in presence of *E. coli* during its co-transport. In contrast, we have observed retarded transport of *E. coli* in the presence of ZnO nanoparticles in comparison to its individual transport. The contrasting transport behaviour of ZnO nanoparticles and *E. coli* during their cotransport is attributable to their competition for attachment sites on the grain surfaces and due to nZnO-*E. coli* hetero-aggregates formation. Our developed model well supported our experimental results, accounting for ZnO nanoparticles and *E. coli* deposition in soil, hetero-aggregation kinetics, and hetero-aggregate retention in soil. We have observed the formation of hetero-aggregates during the cotransport which has introduced a new entity in the transport pathway, thus interfering in the transport of both ZnO nanoparticles and *E. coli* by effecting the interaction energies within the nanoparticles, bacteria, and the porous media. The hetero-aggregates formed were found to have higher tendency of transport than deposition.

Altogether the upshot of this work explains that ZnO nanoparticles and *E. coli* transport behaviour gets altered in the copresence of each other, which help to understand the risks posed by releasing wastewater rich in ZnO nanoparticles into the subsurface inhabited with bacteria. In both natural and artificial systems, the transport of microorganisms through

porous media (such as aquifers and sand filters) is also a significant problem along with groundwater contamination by engineered nanoparticles like ZnO nanoparticles. We have seen in our study that the bacterial transport in saturated porous media is severely hampered in the presence of ZnO nanoparticles. Thus, by incorporating these nanoparticles into the sand beds, presents the opportunity to create an efficient bacterial barrier, either as a preventative measure, an enhancer for drinking water filters, or for retaining active bacteria and inhibiting biofilm growth during bioremediation processes within the contaminant plume boundaries. However, this addition of nanoparticles should be designed carefully, considering the potential risks which can arise due to sudden release of the previously retained bacteria, once the nanoparticle input is hindered. Also, we have observed facilitated transport of ZnO nanoparticles in presence of *E. coli*, which increases the risks of groundwater contamination by ZnO nanoparticles when co-present with *E. coli*. Altogether, our results provide comprehensive understanding of the mechanisms underlying the transport and deposition of engineered nanoparticles and bacteria in ground water environments. These findings suggest a significant likelihood of bacterial aided transport of engineered nanoparticles in the subsurface, increasing the risks of groundwater contamination by engineered nanoparticles in presence of bacteria and also showcases retarded bacterial transport in the subsurface in the presence of ZnO nanoparticles which works as a filter for bacteria, thus reducing bacterial contamination of groundwater.

Keywords: *ZnO nanoparticles, bacteria, soil, cotransport, modeling*

FLUORIDE TOXICITY AND ITS IMPACTS ON HUMAN HEALTH IN WAZIRGANJ BLOCK, DISTRICT GAYA, BIHAR, INDIA

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There are many elements which are important for the healthy growth of human body and fluorine is one such element whose presence in small quantity is important for good dental health and bone structure. But, when it finds its way in excess, it becomes a problem leading to adverse impacts. The presence of excess fluoride ion in groundwater is one of the major toxicological environmental hazards worldwide. In groundwater, the natural concentration of fluoride depends on the geological, chemical and physical characteristics of the aquifer, the porosity and acidity of the soil and rocks, the temperature, the action of other chemical elements, and the depth of the aquifer. Fluoride is a naturally occurring substance found in some igneous and metamorphic rocks. These rocks often contain fluoride-bearing minerals such as fluorite, biotite, apatite, hornblende etc. Fluoride commonly occurs in groundwater due to the weathering and leaching of these minerals and also through overuse of phosphate fertilizers. It has been observed globally that fluoride is one of the most abundant anions in groundwater. The surplus concentration of fluoride in groundwater has a direct implication on human health leading to issues like dental and skeletal fluorosis. In this concern, a study has been conducted in Wazirganj block, Gaya district, Bihar, India to understand the geochemical processes and mechanisms responsible for the release of fluoride contaminant in groundwater, its health implications in the study region and to suggest some mitigation measures.

A total number of 50 groundwater samples were collected from different locations in Wazirganj. The samples were collected in one litre high-density scientific polyethylene bottles. The physical parameters such as pH, EC and TDS were measured in the field itself. These samples have been further analyzed in the water testing laboratory using a UV Spectrophotometer to determine the concentration of fluoride. Apart from water samples, rock samples were also collected from the vicinity. After doing the thin-section preparation of the rock samples, petrographic study was undertaken to understand the petrography of the rocks present in the study area. Electron Probe Microanalysis (EPMA) of the rock thin sections was also performed at IIT Bombay to fathom the elemental composition of the common rock-forming minerals. All the data have been pieced together to trace the potential source of fluoride contamination in groundwater. Additionally, health risk assessment was carried out based on field survey comprising of discussion with the villagers and empirical study based on the obtained data.

The chemical analysis of water samples has shown that the highest value of fluoride was recorded at Budhaul village (2.40 mg/L) whereas the lowest value was found to be 0.85 mg/L at Dharampur village. The petrographic study and EPMA of rock thin sections have yielded that there are fluorine-bearing minerals present in the rocks of the study region. The major rock types are quartz-mica schist, phyllite, slate, quartzite and granite. Minerals that have fluorine in their composition are biotite, muscovite, apatite, hornblende etc. Long-term weathering of the rocks has a potential bearing on presence of fluoride in water. Since groundwater flows at a considerably low rate, there are high chances of the contaminants being persistent in the groundwater system once it gets contaminated as evident from the analysis results. In addition to the chemical and petrological studies, field-based survey has revealed that many villagers are suffering from several health issues such as dental fluorosis and deformed bones (sign of skeletal fluorosis) present in the study area due to excess of fluoride in water and its consumption. There are several factors that lead to fluoride toxicity, some of them being doses, exposure, age and genetics. People of different age groups are differently susceptible to fluoride contamination as the instances of dental fluorosis and skeletal to some extents were observed frequently among the children.

The maximum permissible limit of fluoride in groundwater is 1.5 mg/L as per the World Health Organization (WHO) and Bureau of Indian Standards (BIS), 2012. Thus, Public Awareness Programmes are indeed a need of the hour in the region affected by high fluoride pollution and also about the associated health risk. There are some De-fluoridation techniques/measures that could be followed to reduce the level of fluoride in drinking water. These include membrane filtration process such as Reverse osmosis and Electrodialysis, Adsorption using activated alumina, Distillation, Ion Exchange etc. These must be adopted in regions with high fluoride concentration in groundwater (International Groundwater Assessment Centre). It will be helpful for the local people to mitigate the fluoride toxicity and to ensure the availability of clean and safe drinking water.

Keywords: *Fluoride, groundwater, toxicity, health risk, de-fluoridation*

ASSESSMENT OF GROUNDWATER AND SURFACE WATER QUALITY IN THE SOUTHERN BRAHMAPUTRA FLOODPLAINS, ASSAM, INDIA: INSIGHTS FROM HYDROCHEMICAL ANALYSIS AND ISOTOPE STUDY

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Groundwater is a vital resource. Globally the hydrological and hydrochemical conditions of groundwater are significantly anthropogenic activities. Thus, it has arrived at a point where restoration is required as a result of environmental degradation. In the past few year's studies have found a notable decline in the quality of water, used for drinking and irrigation purposes raising concerns across various regions of the world. (Bhunia et al. 2018). Therefore, this study seeks to evaluate the quality of groundwater and surface water in the Brahmaputra floodplains in Assam by utilizing the Water Quality Index (WQI) along with relevant statistical methods. This research investigates the quality of the surface water and groundwater in the Southern bank of the Brahmaputra River floodplains in Assam, India which covers the area between 94° 25' to 95° 22' east longitudes and 26° 45' to 27° 15' north latitudes bounded by the Disang river to the east and Jhanji to the west. To the South, it shares border with Tirap district of Arunachal Pradesh and is bounded by Naga-Patkai Hill Range while the Brahmaputra flows to the North.

Forty groundwater and ten surface water samples were systematically collected during pre-monsoon and post-monsoon seasons during the year 2023. The analysis comprises twelve physico-chemical parameters, covering a variety of cations and anions, including pH, EC, hardness, TDS, HCO_3^-, Na^+, SO_4^{2-}, Ca^{2+}, Cl^-, Mg^{2+}, K^+ and F^-. Sampling was done following standard methods proposed by APHA, 2017 (23rd Edition). Piper, Gibbs plot, box plots and various statistical methods were generated to illustrate the variations in the data. Stable isotope analysis ($\delta^{18}O$ and δ^2H) of groundwater, surface water and rainwater were done to find the primary source of groundwater recharge. All the physico-chemical parameters fall within acceptable limits, with the exception of Mg^{2+}(15%), Na^+(12%), K^+(1%) and F^-(2%) which exceed the permissible thresholds of WHO and BIS. Among the four blocks investigated under the present study, Nazira block shows the highest concentrations of Mg^{2+} (15%) and Na^+ (12%) followed by Sivasagar, Amguri, and Demow blocks. High amount of K^+(1%) and F^- (1%) were found in Demow block followed by Nazira block. Water Quality Index (WQI) indicates that the overall water quality in the area is good. The Piper diagram reveals that the predominant facies for groundwater during the pre-monsoon season is Ca^{2+}-Mg^{2+}-HCO_3^-, whereas surface water is classified as Ca^{2+}-Mg^{2+}-Cl^--HCO_3^-. In contrast, post-monsoon groundwater shifts to a Na-HCO_3^- type, while surface water is characterized by a Na-Cl^- type. The Gibbs plot illustrates that the chemical composition of the samples is largely influenced by atmospheric precipitation, underscoring the significant impact of rock weathering on water chemistry. Additionally, stable isotopes ($\delta^{18}O$ and δ^2H) from groundwater, surface water, and rainwater suggest that local precipitation is the main contributor to groundwater recharge in the area.

The study concludes that the quality of groundwater in the region is generally good, exhibiting neutral to slightly alkaline characteristics. Groundwater recharge primarily occurs through local precipitation which can be inferred from the stable isotopes ($\delta^{18}O$ and δ^2H).

Elevated levels of sodium (Na^+) and magnesium (Mg^{2+}) are attributed to geogenic processes, while the presence of higher fluoride (F^-) and potassium (K^+) concentrations is linked to anthropogenic activities. This interplay between natural and human factors shapes the overall water quality and highlights the need for ongoing monitoring and management although according to the WHO it is not considered an issue of health concern. Analysis of stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) from rainwater, surface water & ground water indicates that the local precipitation acts as the primary source for the recharge of GW in the region. Thus, this study provides valuable insights for effective planning and management of water resources intended for household and consumption purpose.

Keywords: *Groundwater, water quality, water quality index, isotope, Piper diagram, Gibbs Plot*

SEASONAL ASSESSMENT OF GROUNDWATER QUALITY AND PRACTISE OF WATER USE MANAGEMENT IN CHAMPHAI AND MAMIT DISTRICT OF MIZORAM, INDIA

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Surface water and ground water suitability for various purposes is largely determined by the kind and composition of dissolved substances in the water. Surface water is more easily accessible than groundwater and also more prone to contamination than groundwater. The contamination of groundwater has been caused by human activities, growing population growth, industrialization, urbanization, and other human activities. This is despite the fact that groundwater is often better protected than surface water. When groundwater is contaminated, it becomes a challenging endeavor to locate and remove the substances that have caused the contamination. As a result, it is essential to conduct regular evaluations of the quality of groundwater in order to ensure its protection. This makes it possible to quickly identify all of the possible sources of contamination, which in turn makes it easier to carry out the measures that are necessary to safeguard groundwater from future contamination. Groundwater is an essential resource that is found all over the globe and plays an important part in the maintenance of ecosystems, agricultural operations, and the well-being of people. Assessing and protecting the quality of groundwater is particularly important for maintaining life in areas that have limited access to water resources, such as the Champhai and Mamit Districts in the Indian state of Mizoram. A location that is facing challenges with water scarcity is the impetus for this study since there is an urgent need to find solutions to water quality concerns. In some regions where there is a scarcity of surface water, groundwater is an essential source of drinkable water that may be used for drinking. As a consequence of human activities, contaminants are introduced into the groundwater, which leads to an imbalance. The objectives of the present study are (i) enhancing the management and quality control of regional groundwater resources, (ii) addressing current groundwater quality challenges while providing stakeholders with insights into future patterns, and (iii) improving operative groundwater protection and management techniques.

A seasonal evaluation of physicochemical features, heavy metal analysis, and microbiological analysis is performed in order to get an understanding of the quality of groundwater and to identify the degrees of contamination according to the guidelines set out by the WHO and BIS. In each of the two groundwater samples, the presence of faecal coliforms as well as total coliforms was found. Both of the groundwater samples were found to contain trace amounts of heavy metals such as arsenic, cadmium, chromium, and iron. Through the use of the Weighted Arithmetic Water Quality Index (WAWQI) methodology, the study endeavors to determine the Groundwater Quality Index (GWQI), which is used to assess the quality of groundwater for drinking purposes. The use of a consistent index makes it possible to identify changes in the trends of water quality and to identify potential areas of concern or improvement in relation to drinking water systems. In light of the consequences of climate change and the expanding population, the need of protecting groundwater resources has become even more pressing. Due to the fact that there is a lack of water, the hilly topography of Mizoram provides further evidence of the critical need of conserving the

quality of groundwater. The results help to improve the management and quality control of regional groundwater resources. The use of the results will be a significant advancement that not only tackles the existing problems with groundwater quality but also offers stakeholders insights into the patterns that may emerge in the future. The study helps to lead sustainable groundwater resource management in the area, which paves the way for a future in which the availability of safe and clean groundwater has a significant impact on quality of life. This, in turn, enables decision-makers to design policies for the preservation of groundwater quality. In this particular setting, it is of the utmost importance to emphasize the need of increasing awareness about the degradation of the quality of groundwater. Furthermore, the local authorities in the water-scarce regions of Champhai and Mamit District in Mizoram, India, are interested in implementing preventive measures in order to improve the overall quality of the groundwater resources situated in these areas.

Keywords: *Climate change, contaminants, groundwater, sustainability, pollution, water quality*

GEOCHEMICAL ASSESSMENT OF GROUNDWATER CONTAMINATION WITH SPECIAL EMPHASIS ON FLUORIDE CONCENTRATION IN SONO RIVER BASIN, BALASORE DISTRICT, ODISHA, INDIA

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Groundwater rich in fluoride is well-known in aquifers of granitic terrain in India. Nevertheless, a detailed investigation is essential to explain the behavior of fluoride in natural water resources, taking into account regional hydrogeological conditions, climatic influences, and agricultural activities. This study examines the content of fluoride in groundwater of Sono River Basin in the Balasore district, Odisha, with the aim of understanding the spatial distribution of fluoride and identifying the geochemical parameters contributing to its dissolution. Balasore district is one of the thickly populated districts of the Odisha state in Eastern India. The study area falls under Survey of India toposheet no 73K/10, 11 and 14. Climatic condition is tropical to subtropical with hot summer, high and well disturbed rainfall during monsoon and cold winter. The drainage is controlled by Sono River and its tributaries and distributaries. The drainage pattern is mostly dendritic to sub-dendritic. The groundwater generally occurs through fracture, fissure and consolidated basement rock formations with shallow levels during pre and post monsoon period. Nilgiri granites of Archean age are the primary rock types in the study area. These rocks are weathered moderately in the valley areas of the terrain. For 2,321,419 residents in that area, groundwater serves as their primary supply of drinking water. The study area belongs to Balgopalpur industrial estate. A total of 35 groundwater samples were collected during pre-monsoon season of 2024. The quality of water was evaluated by estimating pH, EC, total dissolved solids (TDS), total hardness (TH), major cations like sodium (Na^+), potassium (K^+), calcium (Ca2+), magnesium (Mg2+) and anions like Bicarbonate (HCO3-), chloride (Cl-), sulphate (SO42-), Fluoride (F-) and Nitrate (NO3-). Measurements of physical parameters like pH, EC and TDS were carried out in-situ by pH and EC meter. The groundwater samples were analyzed using standard techniques (APHA 2012).

Chemical analysis results reveal that the groundwater is severely contaminated with fluoride ions and 45% of samples have higher content than prescribe WHO standards (≤1.5mg/l) for domestic uses. The fluoride content ranges from 0.5 to 5.90 mg/l with an average of 2.34mg/l. The higher concentration is seen near Kuanpur, Chakulia, Hatiagand, Balipal and Bhimeswar villages. The pH of the groundwater samples varies from 7.1 to 8.5 with an average of 7.8 which indicates alkaline character of groundwater. Besides that, most of the samples with respect to TDS, calcium, magnesium, chloride, sodium, potassium, nitrate, sulphate and iron have values of more than the acceptable limit of BIS (2012) rendering them unfit for drinking purpose. From the statistical analysis cations shows dominance of Na> Ca> Mg> K and anion dominance is in the order of HCO_3> Cl> NO_3> SO_4. From the statistical analysis it is observed that fluoride has positive correlation with bicarbonate and pH and negatively correlated with calcium. Sample location, geological, geomorphological, structural, LULC, spatial distribution maps of different chemical parameters and iso-concentration maps were prepared in ArcGIS10. From this application the spatial variation of fluoride content has assessed that helped in demarcation high fluoride areas. Also, GIS is used to delineate the groundwater potential zone. The Gibbs diagram reveals that the chemistry of groundwater is principally influenced by weathering characteristics of rocks. The groundwater samples are plotted in the Piper Trilinear diagram. Higher concentration of fluoride is observed in Na-HCO_3 facies of groundwater. The important processes responsible for transportation and mobilization of fluoride into the groundwater are decomposition, dissociation, and dissolution. The study indicates that fluoride ions predominantly originate from the dissolution of fluoride-bearing minerals such as fluorite, apatite, biotite, and hornblende present in the granitic bedrock, particularly under alkaline conditions. Secondary sources contributing to fluoride contamination include domestic and industrial effluents, as well as return flow from irrigation, which contains components of phosphate-based fertilizers. Communities consuming non-potable water with elevated fluoride levels may experience health issues such as dental fluorosis, skeletal disorders, and accelerated aging. Groundwater being the sole source of drinking water, high fluoride causing obstruction in water supply schemes. De-fluoridation based on latest technology i.e. reverse osmosis system and adsorption technology should be provided in the area having higher concentration of fluoride in drinking water. Also, rainwater harvesting and artificial recharge structure will achieve the dual purpose of resource augmentation and quality improvement. Alternate defluorination methods include passage of water through a matrix where the fluoride ions are selectively trapped inside the bed. It is suggested that people living in the study area should use activated alumina domestic de-fluoridation filters to remove fluoride.

Keywords: *Fluoride, water quality, hydrochemistry, geochemical, Sono River basin, groundwater*

ANALYSIS OF THE QUALITY, AND IDENTIFICATION OF THE SOURCES OF IONS IN THE GROUNDWATER- A CASE STUDY IN SILIGURI AND MATIGARA BLOCKS, DARJEELING DISTRICT, WEST BENGAL, INDIA

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A systematic study of groundwater quality has been carried out for the areas of Siliguri and Matigara Blocks of West Bengal, India. Groundwater samples were collected from thirty-three wells and analyzed for various physio-chemical parameters such as conductivity, Total Dissolved Solids (TDS), pH, salinity, Na^+, Ca^{2+}, K^+, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, and NO_3^- in the laboratory to determine the quality of the groundwater in the study site. All the physio-chemical analysis of the samples was carried out according to the standard procedure of APHA. TDS, pH, salinity, and conductivity have been analyzed using a portable water analyzer. Ca^{2+} and Mg^{2+} were analyzed using the EDTA titration method, Na^+ and K+ were measured using flame photometry, and Cl was analyzed using the argentometric titration method. $SO_4^{2-}$and NO_3^- were analyzed using UV Photospectrometer. The analytical results indicate significant cations as $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$, and anions as $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$. To know the suitability of water for drinking purposes, all the analytical parameter results were compared with WHO and BIS drinking water standards. The highest and lowest values of the salinity were noted at Mathapari and Pradhan Nagar, which are 0.05 ppt and 0.45 ppt, respectively, with an average value of 0.17 ppt. The minimum and the maximum pH values have been noted for the places of Dagapur and Subhas Pally with values of 5.77 and 7.0, respectively, with an average value of 6.26. The maximum value of TDS was observed as 421 mg/l at Pradhan Nagar, and the minimum value as 55 mg/l at Subhas Pally, and its mean value is 167.24 mg/l, which is indicated within the permissible limit of drinking water standards. The concentration of Ca^{2+} ranges between 4 (at Mathapari) and 32 mg/l, (at Champasari) with an average value of 13.14 mg/l. Mg^{2+} concentration ranges from 2.4 (at Mathapari) to 24.8 (at Pradhan Nagar) with a mean value of 9.73 mg/l. The concentration of Na^+, which is more predominant than Ca^{2+} and Mg^{2+}, has the lowest value of 2 mg/l, which was observed at Uttarayon twp, and the highest value of 68 mg/l is observed at Pradhan Nagar and its mean value is 22.82 mg/l. The results of the bivariate plot and coefficient correlation show that the K+ contamination might be from both anthropogenic (such as pesticide usage in agricultural lands) and geogenic sources. The minimum (16.8 mg/l) and maximum (100.8 mg/l) amounts of HCO_3 were obtained at the sample locations of Mathapari and Pradhan Nagar, respectively with mean values of 49.68 mg/l. NO_3^- ranges from 0.0268 mg/l to 2.61 mg/l at the places of Champasari and Bara Gharia, respectively, with an average value of 0.4 mg/l.

Based on the Piper diagram, the maximum number of samples fall under Na-Cl type (16 samples), followed by Ca-Cl_2 type (9 samples), and the mixed type (8 samples). Gibbs plot exhibits that most of the samples (24 samples) belong to the evaporation-precipitation domain, and few samples fall under the rock-dominance domain. To know the irrigation suitability of the waters, the following indexes as Residual Sodium Carbonate (RSC), Kelly's Index (KI), Total Hardness (TH), Sodium percentage (Na%), and Sodium Adsorption Ratio (SAR) were used and results were obtained from the analytical data. According to RSC, all the samples fall under the safe class (less than 1.25) and Kelly's Index, the sample ranges from 0.025 (Champasari) to 3 (Shanti Nagar) with a mean value of 0.08; most of the samples (except 11 samples) having a value of less than 1. It reveals that the groundwater is suitable for irrigation. The range of total hardness varies from soft to hard, where most of the samples (23 samples) fall under the class of soft, a few samples (9 samples) falling in the moderate class, and one sample falls in the hard class. The samples of the study region showed a wide range of variation in terms of Na% with 2 samples falling under the excellent category, 7 samples under the good category, 15 samples under the permissible category, 8 samples under the doubtful category, and 1 sample was noted as falling under the unsuitable category. The Sodium Adsorption Ratio (SAR) value varies from 0.095 (Champasari) to 4.85 (Shanti Nagar) and indicates that all the samples belong to the excellent range. Based on GWQI (Ground Water Quality Index), the groundwater quality of the study region was categorized as excellent to good water quality.

Keywords: *Groundwater quality, water quality index, irrigation suitability, hydro-geochemical facies, Darjeeling district*

A HYDROGEOCHEMICAL APPROACH TO EVALUATE THE GROUNDWATER QUALITY IN THE COASTAL AQUIFERS OF NORTH EASTERN PART OF ODISHA, INDIA

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Odisha, a coastal state in eastern India, has significant coastal aquifers that supply freshwater to various regions. The coastal aquifers of Odisha encounter severe threats from urbanization and pollution, compromising their quality, quantity and sustainability. There is a high population density and significant agricultural activity in these regions, and the need for freshwater is always rising. They are extremely vulnerable to various natural processes locally and regionally such as climate change, sea level changes, storm surges, coastal erosion, floods, etc. The coastal aquifers are also vulnerable to groundwater pollution due to anthropogenic activities, reflecting in seawater intrusion, depletion of the static water levels, and infiltration of industrial and agricultural pollutants. Coastal aquifer systems have unique geological and hydrogeological settings posing difficulties in managing groundwater supplies. Therefore, an attempt has been made to evaluate the groundwater quality and to identify the probable zones of contamination on the eastern coastal regions of Odisha.

The present study focuses on Matei River Basin, a part of Bhadrak district, situated in the north-eastern part of Odisha along the stretch of Bay of Bengal. Bhadrak is bounded by Jajpur district on its south, Keonjhar district on its west and by Bay of Bengal on the east. There are 4 major distinct geomorphic units in the study area- inter tidal zone, coastal plain, alluvial plain and flood plain (CGWB,2017). It experiences humid tropical climate with an average temperature of 27ºC (CGWB,2017). The study area receives an annual rainfall of 1431 mm with a maximum rainfall during southwest monsoon (SWM). Agriculture is the main occupation and maximum area comes under agricultural landuse. Paddy is grown as main crop in Kharif. Due to high population density, there is enormous stress on groundwater resources. Few aqua culture ponds are also present the northern most part of the study area. The vast alluvial deposits form the main repository of groundwater in the study area. Alluvium of recent deposits forms the main rock type of the study area. These deposits consist of clay, sand, silt and gravel. A total of 80 groundwater samples were collected during pre-monsoon season (April, 2024) from the study area. Using mobile pH and EC meters, the physical variables, such as pH and electrical conductivity (EC), were measured on-site. Further the pH and EC of each sample were analysed in laboratories for accuracy and precision. The electrical conductivity (EC) in µS/cm was multiplied by 0.65 to determine the total dissolved solids (TDS) (Subba Rao, 2017). Murexide and Eriochrome black T solution as indicators, titration techniques were used to measure the concentration of calcium (Ca^{2+}) and total hardness (TH) using standard EDTA solution. $TH = 2.5 \times Ca^{2+} + 4.1 \times Mg^{2+}$ was the formula used to calculate magnesium (Mg^{2+}) from the total hardness and Ca^{2+} values (Todd, 1980). Using potassium chromate, bromocresol green, phenolphthalein, and methyl orange indicators, respectively, titrations with silver nitrate solution and sulfuric acid were used to quantify the levels of chloride (Cl^-), total alkalinity (TA), and bicarbonate (HCO^{3-}). A flame photometer was used to measure the amounts of potassium (K^+) and sodium (Na^+). A UV-visible was used to measure the levels of sulphate ($SO_4{}^{2-}$), nitrate (NO_3^-), and fluoride (F^-). The major cation and anion analysis was done following the standard procedure maintaining an ionic balance error between 5 to 10%.

Statistical analysis of all physico-chemical parameters and its comparison with WHO (World Health Organization) and BIS (Bureau of Indian standard) drinking water standard was carried out to identify the number of samples exceeding the standard and the suitability of groundwater for drinking purpose. Considering the average value of chemical constituents (Table 2), the order of dominance is identified for cations as $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and for anions as $HCO_3{}^- > Cl^- > NO_3{}^- > SO_4{}^{2-} > F^-$. The Domestic Water Quality Index (DWQI) was calculated to understand the suitability of groundwater for drinking water purpose, and it is inferred that most of the samples represent under bad category and groundwater is unfit for drinking in the central part of the study area. Irrigation water quality index (IWQI) was calculated using five parameters namely SAR, RSC, EC, Na% and Kelly’s ratio (KR). The weighted overlay analysis was performed by compiling parameters like SAR, EC, Na^+, Cl^- and $HCO_3{}^-$ to identify the regions suitable for irrigation water quality. It is identified that most of the samples are suitable for irrigation purposes, except for a few in the central part of the study area (Fig.3). Further, it is confirmed by Wilcox diagram that most of the samples fall under permissible to doubtful category. Three major water types were identified from the Piper’s Plot (Piper 1944) such as Ca-Na-HCO_3 type, Na-Cl type and Mg- HCO_3 type. Geo-statistical analysis was performed to identify the factors influencing the groundwater composition. Factor 1 is represented by loadings of EC, magnesium, sodium, chloride and sulphate which infers saline water ingression along the coastal tract of the study area. Factor 2 has high positive loadings of sodium, potassium, bicarbonate and pH reflecting the process of weathering. Factor 3 has high positive loading of fluoride which might be due to anthropogenic activities. Thus, it is concluded that saline water ingression, weathering and anthropogenic activities are the major factors influencing the groundwater chemistry of the study area.

Thus, the study infers that the groundwater is not suitable for drinking purpose but could be used for irrigation with caution in certain places. Further the major factor controlling the chemistry of the region is seawater intrusion. To accomplish the sustainable development goal, more research into the fit for purpose could improve groundwater's utility for other uses.

Keywords: *Groundwater quality, coastal aquifers, DWQI, IWQI, geo-statistics*

TRENDS IN GROUNDWATER QUALITY AND HEAVY METAL POLLUTION IN HARIDWAR DISTRICT, UTTARAKHAND, INDIA: A CALL FOR SUSTAINABLE MANAGEMENT

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This study investigates the quality of groundwater and its suitability for drinking in the Haridwar district of Uttarakhand, India, utilizing the Water Quality Index (WQI) and assessments of heavy metal pollution. Haridwar district encompasses an area of 2,360 km², characterized by diverse geological formations, including the Siwalik Range and the alluvial plains of the Bhabar region situated in the southwestern part of Uttarakhand. These unique geographical features contribute to the hydrological dynamics of the area, making it essential to evaluate groundwater quality, especially given the rapid urbanization and industrialization that have intensified in recent years. As urban development and industrial activities expand, concerns regarding groundwater contamination have increased significantly. The discharge of untreated and treated wastewater into the environment has raised alarms about the accumulation of heavy metals in groundwater, posing serious health risks to local populations. This study aims to provide a comprehensive assessment of groundwater quality in Haridwar, focusing particularly on the presence of heavy metals and the potential health risks associated with their consumption.

Groundwater samples were systematically collected from various locations across the district over three years (2021 to 2023). The samples were analyzed for a range of physicochemical parameters, including pH, electrical conductivity, carbonate, bicarbonate, chloride, fluoride, sulfate, and nitrate. Additionally, major cations such as calcium, magnesium, sodium, and potassium were measured. The analysis also included heavy metals such as iron (Fe), manganese (Mn), zinc (Zn), Copper (Cu), Arsenic (As) lead (Pb) and Uranium (U). These analyses were conducted at the Central Ground Water Board (CGWB), NR, Lucknow Laboratory, utilizing standard procedures to ensure reliability and accuracy. Chemical analysis of groundwater constituents in Haridwar involves various standardized methods. pH and electrical conductivity are measured using pH and EC meters, respectively. Carbonate and bicarbonate are quantified through titrimetric methods, while chloride is assessed using Mohr's method. Other ions, such as fluoride, nitrate, and sulfate, are analyzed via spectrophotometry, sodium and potassium levels are determined using flame emission photometry.

The results indicated a predominance of magnesium bicarbonate-dominated water, as represented in the Piper diagram, with alkaline earths exceeding alkalis and weak acids surpassing strong acids. The Durov diagram revealed that reverse ion exchange processes dominate the area, suggesting significant rock weathering influences along with some evaporation and crystallization effects. These geochemical processes underscore the freshwater recharge nature of the groundwater in Haridwar. The WQI was employed to categorize water quality into several classifications: excellent, good, poor, and very poor. This index serves as a valuable tool for stakeholders and policymakers, facilitating a clearer understanding of the groundwater conditions. The results revealed significant variations in groundwater quality over the three-year period. In 2021, the WQI values ranged from 35 to

111. Notably, 26.2% of the samples were classified as good quality, while 45.23% and 26.19% were categorized as poor and very poor, respectively. Alarmingly, 2.38% of the samples were deemed unfit for drinking. These findings highlight the concerning state of groundwater quality in Haridwar at the outset of the study. By 2022, the WQI values exhibited a range from 32 to 240. This year saw a marked improvement, with 40.53% of the samples classified as good quality. However, despite the positive trend, 19% of the samples remained unfit for consumption. This suggests that while some areas experienced improvements, significant pockets of contamination persisted, necessitating ongoing monitoring and intervention. The year 2023 showed a further decline in groundwater quality, with WQI values ranging from 38 to 404. In this year, only 31.72% of samples were classified as good quality, while 43.9% and 12.19% fell into the poor and very poor categories, respectively. A notable concern is that 12.19% of the samples were entirely unfit for drinking, particularly in certain regions of the district. This downward trend in water quality raises alarms about the sustainability of groundwater resources and the health implications for local communities.

In addition to assessing overall water quality, the study evaluated heavy metal contamination using the Heavy Metal Pollution Index (HPI). This index provides a quantitative measure of the impact of heavy metals on groundwater quality. The analysis revealed that most samples in both 2022 and 2023 fell under the low pollution category. In 2023, only one sample exceeded acceptable pollution levels, indicating localized issues that necessitate further scrutiny. In 2022, the pollution levels were similarly low, with just one sample classified as medium pollution. In 2021, all samples remained well below risk thresholds, suggesting that heavy metal contamination was less pronounced at that time. Moreover, the Heavy Metal Evaluation Index (HEI) was utilized to assess the overall quality of groundwater concerning heavy metals. In 2023, the analysis indicated that 65.85% of samples fell under the low HEI category, while 14.63% and 19.52% were categorized as medium and high risk, respectively. In 2022, 59.52% of samples were classified as low HEI, with 21.42% and 19.06% falling into medium and high categories. In 2021, 53.48% of samples were classified as low HEI, while 11.63% and 34.89% were medium and high, respectively. High risk zones are mostly restricted in the Bahadrabad, Khanpur, Laksar and parts of Bhagwanpur blocks of the Haridwar district. These results highlight a troubling trend of increasing heavy metal risk over the study period.

The study highlights the overall poor groundwater quality in the Haridwar district over the past three years, as indicated by WQI assessments. The analysis demonstrates that while some improvements have been made, the overall trend points to a concerning decline in water quality, particularly in 2023. Although the HPI indicates a predominance of low pollution levels, the troubling trends in both WQI and HEI underscore the urgent need for continuous monitoring and comprehensive management strategies to ensure safe drinking water availability in the region. The findings of this research underscore the critical importance of implementing sustainable water management practices to mitigate the adverse effects of urbanization and industrial growth on groundwater resources. Policymakers and local authorities must prioritize efforts to enhance wastewater management, reduce pollution sources, and invest in community awareness programs to safeguard public health. Continued research and monitoring will be essential to track groundwater quality trends and address emerging contamination challenges effectively.

Keywords: *Durov Diagram, groundwater, heavy metal, risk assessment, water quality*

EVALUATION OF HYDRO CHEMICAL CHARACTERISTICS AND HEAVY METAL CONCENTRATION OF GROUNDWATER AT KALPAKKAM COASTAL SITE, TAMILNADU, INDIA

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The chemical composition of groundwater is essential for evaluating water quality. In unpolluted systems, major ions in groundwater originate from the weathering of rocks. The water quality of a region is influenced by various factors such as geology, weathering regime, the quality and quantity of recharge water and water-rock interaction. Rapid industrialization and activities like agriculture can elevate the concentration of various ions and trace elements in groundwater, leading to a decline in water quality. Over exploitation of groundwater can result in diminished water quality, as increased salinity levels may arise near the terminus of groundwater flow lines. The intrusion of seawater into inland aquifers due to the over-exploitation of groundwater in coastal areas represents a major environmental issue. Investigating the sources of saline water and their mobility mechanisms is crucial for the sustainable development of coastal groundwater resources. Environmental hazards cannot be entirely prevented or controlled; however, they can be mitigated through appropriate measures such as effective land use planning, development, and management. Therefore, this study aims to identify the sources of salinity and the mechanisms by which they migrate into groundwater, with the goal of developing effective management strategies to address salinity issues in the studied region. The study area is located between Chennai and Pondicherry on the southeast coast of India. The site is bounded by Bay of Bengal on the eastern side, the Buckingham Canal on the north western side and agricultural fields on the western side. The physicochemical characteristics and heavy metal concentrations in the groundwater of the coastal region of Kalpakkam, Tamil Nadu were examined during the pre-monsoon and post monsoon seasons. Cations and anions were determined using ion chromatography. The concentration levels of six heavy metals (Zn, Cd, Pb, Cu, U and Fe) in the groundwater were analyzed through the analytical procedures of Voltammetry (Zn, Cd, Pb, Cu and U) and UV Spectrometry (Fe). The cations were present in the descending order of sodium > calcium > magnesium > potassium and anions as chloride > bicarbonate > sulfate > nitrate. pH and alkalinity were observed to be higher in post-monsoon season. Electrical conductivity and total dissolved solids of ground water samples was observed to be less during post monsoon as compared to pre monsoon. Total dissolved solids, total alkalinity and total hardness exceeded the guideline values in majority of wells in both the seasons. The concentration of fluoride in the studied region was observed to be less than the optimal range prescribed by WHO. In the study area's groundwater, chloride is the most abundant ion. A strong correlation of Cl^- with Ca^{2+}, Mg^{2+} and Na^+ indicates that these ions have same origin. Sodium and chloride are substantially positively correlated in correlation matrices, indicating an increased mixing influence of seawater. When compared to the Piper and Chadhas diagrams, it is clear that the bulk of groundwater samples are in the sodium and chloride zones particularly during pre-monsoon period. The Na–Cl and Ca-Mg-Cl water type were the most dominant water types observed in the study region followed by the Ca-Mg–HCO3 water type. Simpson's ratio and chloroalkaline indices also demonstrates that the interaction between seawater and groundwater in the study area is a major factor in the aquifer's contamination by seawater intrusion. The study also tries to explore the applicability of chloride to bromide ratio in understanding freshwater saline interface in coastal region. The concentration of bromide in seawater is around 65 ppm while that of the water samples collected in our study area ranged from 0.68 to 6.86 ppm. The chloride to bromide ratio of ground water samples in the study area ranged from 55 to 305 whereas the same for seawater was 288. The concentration of studied heavy metals was found to be well within the stipulated guideline values. The concentration of zinc was found to be in the range of 80-200 ppb which is much below the permissible limit of 5 ppm. Cadmium was below detection limit of 0.02 ppb in most of the samples analysed. The Uranium levels in most of the samples were below detection limits (1 ppb) except for the samples collected from sources close to agricultural fields where the concentration was found to be in the range of 1 to 5 ppb. This could be attributed to the usage of fertilisers. The concentration of heavy metals was found to be high in pre monsoon period as compared to post monsoon period. In order to prevent seawater intrusion in the study region, appropriate preventive measures are required. It is recommended that adequate recharge structures be built, the current pumping rate be reduced, pumping wells be relocated, and intrusion barriers be built to restore groundwater quality.

Keywords: *Ground water, trace elements, ionic ratio, seasonal changes, water quality*

ROLE OF GEOLOGY AND GEOMORPHOLOGY IN ARSENIC DISTRIBUTION IN GROUNDWATER OF THE CACHAR FOLD BELT, BARAK VALLEY ASSAM, INDIA

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Geological, hydrogeological, and human activities can interact in complex ways to influence the levels of arsenic in groundwater. In Northeastern States of India, understanding the prevalence of arsenic contamination is essential for effective water resource management. The study was conducted to explore the influence of various geological-geomorphological features scattered throughout the Barak Valley region in the Cachar Fold Belt (CFB) in Assam on the occurrence and distribution of arsenic in groundwater. Geologically, CFB is situated in between two orogenic belts i.e., the Himalayan to the north and the Indo-Myanmar range to the southeast. The CFB is characterized by a thick pile (10–11 km) of sedimentary deposit (upper Cretaceous to Cenozoic) folded into a series of NNE–SSW trending, sub-parallel and highly faulted anticlines and synclines. Hydrgeologically, the valley has unconfined and semi-confined to confined type of aquifer. The major aquifers are Quaternary alluvium and Tertiary sandstone. Geomorphologically, the region represents a ridge and valley province with meridional to sub-meridional anticlines and synclines. The main valleys of the region are the Silchar-Dhalai, Hailakandi-Lala and Anipur Valleys. The geological-geomorphological units are classified as Younger Alluvium (YA), Older Alluvium (OA) and Tertiary Formation based on remote sensing, hydrogeology and field observations.

Geographic Information System (GIS) platform was used to study the lateral and vertical extensions of the aquifer and to delineate aquifers. Three aquifer disposition sections are prepared using Rockworks software for the three valleys in the region. Critical analyses of data obtained from the groundwater exploration programme by Central Ground Water Board helped in identifying two distinct aquifer groups in the area: Aquifer Group I (AG-I, depth 0 to 30 mbgl) and Aquifer Group II (AG-II, from 30-50mbgl upto 300 m bgl). Groundwater samples were collected from different aquifers to study the difference in chemical quality. Each sample was analyzed for a range of physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, Na^+, K^+, Ca^{2+}, Mg^{2+}, total hardness, bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), total alkalinity, sulfate (SO_4^{2-}), chloride (Cl^-), nitrate (NO_3^-) and heavy metals such as iron(Fe) and arsenic(As) using standard methodology. The principal component analysis (PCA) technique was used to interpret the relationships with specific processes influencing water quality.

There is a striking difference between the hydrochemistry of groundwater from Tertiary Formation and the Alluvium. The groundwater of YA and OA are classified as magnesium-bi-carbonate type facies, while the groundwater of Tertiary Formation is classified to be of mixed type facies. The groundwater from the YA exhibits a higher concentration of iron than the OA and Tertiary formations. Chemically, the groundwater in YA and OA has HCO_3^- of 143.49 mg/L and 123.28mg/L respectively. The groundwater of YA is characterized by high HCO_3^-. The iron concentration in the groundwater of YA, OA and Tertiary Formation is 7.68 mg/L,

5.05mg/L and 3.7mg/L respectively. High Arsenic concentrations (12-97 μg/L) have been detected in the groundwater of the region. Approximately 24% of the groundwater samples from YA show arsenic concentrations above the permissible limit of 10 μg/L set by BIS. In contrast, the average arsenic concentrations in groundwater from the OA and Tertiary formations are 6.58 μg/L and 9.03 μg/L, respectively. The OA sediments have a relatively lower arsenic load compared to the YA and Tertiary formations, indicating that groundwater in the YA area is more susceptible to arsenic contamination (>10 μg/L) than that in the OA and Tertiary formations. PCA was applied using ten components, viz., HCO_3^-, Cl^-, NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, *Fe* and *As*. The analysis rendered four significant PCs (PC1, PC2, PC3 and PC4), explaining 72.99% of the total variance of the data set. PC1 explains the contribution of rainfall infiltration and seepage from surface water bodies. High loadings of *As* and *Fe* in PC2 indicate a similar geochemical origin. PC3 is indicative of the dissolution of silicate minerals. The cross plot of Arsenic versus depth suggests that the tube wells tapping AG-II have comparatively less As load, possibly indicating that the contamination is confined in the upper part under the influence of the local-scale groundwater flow regime. As and Fe show a strong positive correlation in the samples of YA. The region beneath YA is characterized by numerous swamps, cutoff channels, oxbow lakes, and other waterlogged areas, which act as locations for biomass accumulation. Infiltration from these water bodies carrying organic carbon contributes to vertical groundwater percolation. The shallow aquifer in this region is prone to elevated arsenic levels when organic matter is introduced, likely promoting microbial respiration and the reductive dissolution of iron oxyhydroxides. This process releases arsenic adsorbed in oxyhydroxides and Fe^{2+}, resulting in a positive correlation between *As* and *Fe* in groundwater. Additionally, HCO_3^- ions are released into the groundwater during this process, establishing a relationship between arsenic and HCO_3^- in the shallow aquifers of YA. The present study indicates that the geomorphology, hydrogeology, hydrochemistry, organic matter and the depth of the aquifer play a significant role in the mobilization of arsenic in groundwater.

Keywords: *Geology, geomorphology, arsenic contamination, Cachar fold belt, Barak valley, groundwater quality, younger alluvium*

HYDRO-CHEMICAL CHARACTERIZATION OF GROUNDWATER AND ASSESSMENT OF WATER QUALITY FOR DRINKING AND AGRICULTURAL USE IN AND AROUND URANIUM-CONTAMINATED AREAS OF GWALIOR, CENTRAL INDIA

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This study investigates elevated uranium levels in groundwater in specific areas of the Gwalior district, Madhya Pradesh, within the context of broader occurrences across India, particularly in the Indo-Gangetic Basin and central and southern regions. It offers a comprehensive analysis of groundwater quality for drinking and agricultural use, comparing findings with established safety standards. The study examines potential sources of uranium contamination, linking its presence to factors such as fertilizer application, nitrate pollution, climate, and local geology. Additionally, it explores uranium's correlation with bicarbonate levels. Addressing immediate water quality concerns, the study suggests that natural geological and petrological processes may be primary sources of uranium, emphasizing the need for sustainable groundwater management strategies in the affected areas.

The study region is located within Gwalior district, Madhya Pradesh, and is covered by Survey of India topographical sheets 54-J/3, 54-J/4, 54-J/7, and 54-J/8. Physiographically, it falls under the Central Highland division, specifically the Central India Plateau subdivision. Groundwater quality, including key parameters and trace metals like uranium, was evaluated in both pre-monsoon and post-monsoon seasons across 99 locations, with a grid size of 5 x 5 sq. km. Basic parameter analysis was conducted at CGWB's Regional Chemical Laboratory in Bhopal, and trace metal analysis at the Chandigarh lab using ICP-MS. Data accuracy for ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, NO_3^{-}, SO_4^{2-}, and F^{-}) was within a 5% margin, verified by the charge balance error. Hydrochemical characteristics, water chemistry mechanisms, hydrochemical facies, and ion sources were analyzed using various graphical and statistical tools, including ionic ratios, Piper, and Gibbs diagrams. Hydrochemical facies were used to classify water types and dominant ions. Water suitability for drinking was assessed through the NSF-WQI, focusing on 12 primary parameters (e.g., pH, TDS, TH, Ca^{2+}, and Mg^{2+}), grading water from excellent to poor quality. For agricultural suitability, indices like SAR, RSC, SSP, MH, and KI were applied.

To examine spatial and temporal variations, ion concentration datasets (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, NO_3^{-}, SO_4^{2-}, F^{-}, Mn, Ni, Pb, Fe, and U) for both pre-monsoon and post-monsoon seasons were analyzed using systematic techniques and to assess drinking water quality, the study applied BIS standards to groundwater parameters across the study area. Basic analysis indicated that no location exceeded the BIS pH limit of 8.5. Electrical conductivity (EC) ranged from 751 to 1500 µS/cm in most samples, with some areas showing EC < 3000 µS/cm. Exceeding nitrate levels (>45 mg/l) were observed at 19.19% of locations in the pre-monsoon season and 45.45% in the post-monsoon season. Fluoride concentrations surpassed the BIS limit (1.5 mg/l) at 16.16% of locations in pre-monsoon and 8.8% in post-monsoon, while one site recorded phosphate beyond the WHO limit (1.0 mg/l) in the pre-monsoon only. Additionally, total hardness (TH) exceeded 600 mg/l at 4.44% of locations in the post-monsoon season. Results showed elevated post-monsoon concentrations for nitrate, silica, TH, calcium, and potassium, with minimal seasonal variations in pH, EC, alkalinity, chloride, sulfate, fluoride, phosphate, and sodium.

Trace metal analysis found no chromium, copper, selenium, or arsenic pollution but identified partial contamination from manganese, nickel, lead, and iron. Uranium concentrations exceeded the BIS limit (30 µg/l) at 29.29% of locations in pre-monsoon (max 944.9 µg/l) and 27.27% in post-monsoon (max 207.8 µg/l), with 11 sites above the AREB limit (60 µg/l). Factors for uranium mobilization included hydrogeological, geological, climatic, nitrate pollution, and fertilizer use, showing a positive correlation with bicarbonate.

The Piper trilinear diagram categorized the region's water as Ca-Mg-HCO_3 type, with Na^+ and HCO_3^- dominating at most sites. Temporary hardness was found in about 50% of samples, with mixed-type waters in the remainder. Gibbs' model indicated that groundwater chemistry is influenced by rock-weathering, increasing salinity and reducing quality. The assessment of agricultural indices for groundwater in the study area showed that nearly all samples fall under the S_1 category for SAR, indicating an excellent sodicity index. Over half of the samples had Residual Sodium Carbonate (RSC) values below 1.25, making them safe for irrigation. Most samples also had a Soluble Sodium Percentage (SSP) under 60%, supporting their suitability for irrigation. Additionally, the majority of samples fell into the 'Permissible' range based on % Na and had a Permeability Index between 25-75%, which is favorable for irrigation. However, samples were unsuitable according to the Magnesium Hazard (MH) and Kelly Index (KI). The USSL Staff diagram placed most samples in the C_3-S_1 class, denoting high salinity but low sodium. Water Quality Index (WQI) analysis classified 60% of the locations as good for drinking and 32.32% as fair.

In summary, the magnesium levels were found to be higher in the pre-monsoon season, while nitrate, silica, total hardness, calcium, and potassium concentrations increased post-monsoon. Parameters like pH, EC, alkalinity, chloride, sulfate, fluoride, phosphate, and sodium showed minimal seasonal variation. Concentrations of chromium, copper, arsenic, and selenium remained within safe limits, indicating minimal pollution impact. However, uranium concentrations exceeded BIS limits in some samples, with no significant seasonal difference, and were correlated with nitrate and bicarbonate levels. The Piper trilinear diagram identified the water type as Alkaline Earth-Bicarbonate (Ca-Mg-HCO_3) in both seasons, with sodium (Na^+) and bicarbonate (HCO_3^-) as the dominant ions in most locations. About 50% of samples showed temporary hardness, while others had mixed water types. According to Gibb's model, rock-weathering processes influence groundwater chemistry year-round, increasing salinity and lowering water quality.

Keywords -*Uranium, Gwalior, NSF-WQI, agricultural quality indices, Gibb's model*

APPLICATION OF RICE HUSK MODIFIED BIOCHAR FOR GROUNDWATER REMEDIATION

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The utilization of surface-modified biochar composites in hydrological applications represents a growing area of scientific inquiry. Preliminary investigations indicate that rice husk-derived biochar exhibits effective bio-sorbent efficiency for heavy metals and micro-pollutants, while also contributing to carbon sequestration in both soil strata as well as groundwater sources. Furthermore, the integration of acid-modified biochar composites shows remediation potentials for environmental contaminants, along with low cost, high carbon content, and enhancement of overall density of treated biochar. The price of modified biochar is also known to be almost half of activated carbon, and its adsorption capacity is much higher compared with other cheap adsorbents such as Zeolites and modified clay composites. This makes the chemical-modified biochar suitable as a promising material for large-scale environmental remediation projects. Despite existing studies on biochar's application in groundwater remediation, there remains a significant gap in understanding the long-term stability and regeneration potential of modified biochar composites. Moreover, the interaction mechanisms between these composites and diverse groundwater contaminants under varying environmental conditions have been inadequately explored. Addressing these gaps is crucial to optimize the application of modified biochar in real-world remediation scenarios. Further, the success of field trials to evaluate the performance of modified biochar under real-world conditions should consider the influence of varying environmental factors, such as temperature, pH, presence of multiple contaminants, adsorption capacity, and stability of biochar. Understanding these interactions will provide valuable insights for optimizing biochar-based remediation technologies. An additional factor of environmental viability and regeneration, the modified biochar stands out using desorption models and usage of certain chemicals which introduces effective cationic concentration displacing the sorbed metal ions proving as a reusable adsorbent option inside a filtration setup for groundwater remediation. The acid modification of pristine biochar results in a significant increase in specific surface area, expansion of pore size, polarity, charge characteristics, O/C ratio, and total acidity, particularly due to the introduction of various oxygen-containing functional groups, including C=C, C=O, C–O, and phenol-alcoholic –OH bonds. These functional group introduce more binding sites on the biochar surface which is effective for adsorbate attachment through chemisorption interactions, confirmed through functional groups on the surfaces of the biochar determined qualitatively and quantitatively following different sorption isotherm models. Moreover, functional groups are also crucial for the immobilization of heavy metals and other contaminants through mechanisms such as electrostatic attraction, ion exchange, and surface complexation. To address the reduced carbon ratio, the usage of a dual acid mixture is an effective solution resulting in a balanced biochar composition. Additionally, the capability of heavy metal immobilization or sorption efficiency are explainable by the unique characteristics of surface-modified biochar and the experimental conditions followed for the regeneration of surface properties. The chemical modification conditions of using optimized pyrolysis temperature and pyrolytic cycle duration depends on the biochar's characteristics and the acid's ionic strength used in the treatment. Further theories of metal availability or the dissolved state of the metal also govern the sorption kinetics and isotherm, redefining the adsorption equilibrium in groundwater or natural conditions for modified biochar samples. The morphology and surface chemical composition of biochar were analyzed using methods such as XRD (X-ray diffractometry), SEM (Scanning Electron Microscope), BET (Brunauer-Emmett-Teller method), and FTIR (Fourier-Transform Infrared Spectroscopy). The chemical modification using HCl, NaOH, and HNO_3 : H_2SO_4 acid admixture improved the physical and chemical properties of biochar, enhancing the adsorption of Cd(II) as an effective adsorbent in comparison to pristine biochar. Primarily, the lignin structure inside the biochar expands while hindering the stabilization of soluble metal salts, and the chemical modification majorly liberates the metal ions in the feedstock before pyrolysis and other impurities adhering to the surface of biochar, thereby increasing the overall hydrophilic or hydrophobic nature. The hydrophilic nature introduction on surface increases the aromatic nature on the surface due to the upsurge of nitrogen and oxygen containing groups leading to crosslinking reaction in presence of alkaline modifying agents. The results for different surface modifications, from single-factor experiments demonstrated the effectiveness of pH variation for studying the adsorption of Cd(II) ions onto the pristine and modified biochar surfaces, initial concentration of Cd(II), and biochar dosage using different modified biochar samples for significant adsorption of Cadmium nitrate ($CdNO_3$). Out of all the biochar modifications the dual acid-modified biochar provided maximum surface area, and pore volume, with an increasing number of oxygen-containing groups on the surface, thus more adsorption sites were enhanced for cadmium ions, resulting in coordinated adsorption with cadmium (II) ions, due to interaction of negative-positive charge interaction on the surface. At 25°C and pH = 8, the acid-modified biochar exhibited a maximum adsorption capacity of 143.69 mg/liters for Cd(II) after 24 hours, representing a significant enhancement in adsorption. Additionally, a conclusion was drawn with increase of pH promoted the dissociation of carboxyl functional groups and simultaneously increased the negative charge on the surfaces, leading with enhanced electrostatic attraction and hydrolysis of Cd(II) by the biochar, which was conducive to the adsorption reaction.

Keywords: *Biochar, water remediation, cadmium removal, surface modification, adsorption efficiency*

CONSTRUCTED WETLANDS FOR REMOVING PESTICIDES AND ANTIBIOTICS FROM CONTAMINATED WATER

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Around the world, groundwater is an essential resource for industrial operations, agriculture, and drinking water. It sustains over 2 billion people worldwide and contributes to about 30% of freshwater resources. However, a number of pollutants have seriously compromised its quality, with pesticides and antibiotics emerging as the most significant contaminants. Pesticides are widely employed in agriculture, are poisonous to humans and aquatic life, and pose major health concerns to the public when they leak into groundwater through surface runoff, leaching, and inappropriate disposal. Similarly, antibiotics are extensively used for treating microbial infections, and 30-90% of the antibiotics that are consumed are excreted which ends up in the wastewater discharge. The release of antibiotics into the environment fuels the worrying increase in antimicrobial resistance (AMR), a developing global public health emergency. These pollutants are persistent in the environment and are not removed by traditional wastewater treatment systems. Therefore, the development of innovative and long-lasting remediation techniques for contaminated water is urgently needed. Among the promising methods, constructed wetlands (CWs) have drawn interest as a practical, economical, and sustainable way to remove antibiotics and pesticides from water.

This review presents the mechanisms underlying CWs and their efficacy in cleaning up pesticide and antibiotic contamination in water. To remove contaminants from wastewater, CWs—artificial wetland systems—use physical, chemical, and biological processes. A thorough assessment of the many CW designs, including hybrid CW systems is part of the review. To remove contaminants from contaminated water, each CW design makes use of special properties such as plant uptake, adsorption, microbial degradation, and photolytic processes. Data was collected from a wide range of peer-reviewed publications, based on field trials and laboratory experiments, published over the last decade, offering a thorough understanding of CWs' performance in the removal of pesticides and antibiotics. This review also examines a number of design factors that have a huge impact on the efficiency of CWs in removing pollutants, including substrate type, water depth, hydraulic retention time (HRT), and plant species selection. To improve CWs' capacity to eliminate a variety of pollutants from water, the significance of combining them with other treatment technologies is being examined. With an emphasis on water as the treatment medium, the data in this study is based on multiple studies that assessed CWs' capacity to treat a range of pesticides (including atrazine, chlorpyrifos, and glyphosate) and antibiotics (including tetracycline, ciprofloxacin, and ampicillin).

Although the effectiveness of CWs varies depending on the kind of pollutant and the design of the CW system, the review finds that CWs can dramatically lower the quantities of pesticides and antibiotics in contaminated water. The vertical flow systems, which encourage aerobic conditions and microbial breakdown in the root zone, demonstrates high removal efficiencies for hydrophobic pesticides. On the other hand, anaerobic microbes that can degrade more persistent pollutants thrive in horizontal flow CWs. Hybrid CW systems have been shown to offer the best performance, combining both vertical and horizontal flow to take advantage of the benefits of both systems, improving the removal of a wide range of contaminants, including pesticides and antibiotics. Enhanced removal rates is mostly dependent on the plant species utilized in CWs. It has been observed that aquatic plants like *Typha*, *Phragmites australis*, and *Canna indica* are efficient at both removing pollutants from the water and creating an atmosphere that encourages microbial breakdown in the rhizosphere. The researchers also emphasize how different substrate types, such as sand, gravel, and organic matter, have an impact on the filtering and adsorption procedures that help in removing pollutants. Furthermore, the biodegradation of antibiotics and pesticides depends on the microbial communities in CWs, especially those in the rhizosphere. In CWs, microorganisms including bacteria, fungi, and actinomycetes have the ability to break down harmful compounds into less harmful biodegradable compounds, increasing the removal efficiency overall. The efficiency of CWs in eliminating pesticides and antibiotics from water varies across investigations, despite the encouraging findings. There are still several issues, such as shifting removal efficiencies in response to changes in temperature, flow rate, and nutrient availability. Furthermore, whereas CWs have proven effective at eliminating single pollutants, little is known about how well they work in situations involving multiple pollutants.

The removal of pesticides and antibiotics from contaminated water can be accomplished effectively and sustainably with constructed wetlands. Because CWs combine physical, chemical, and biological processes, they are a flexible and environmentally responsible substitute for mechanized wastewater treatment techniques. CWs can be made more efficient by incorporating hybrid CW systems, choosing the right plant species, and structuring the system to guarantee the ideal hydraulic retention time. However, there are still a number of unanswered questions, especially about the long-term efficacy of CWs in practical settings and their capacity to eliminate numerous pollutants at once. Additionally, further studies are required to understand the fate and transformation of contaminants within CWs and to develop strategies for improving their performance under varying environmental conditions. The use of CWs for water remediation, particularly for treating complex mixtures of pesticides and antibiotics, is not well documented in the literature. There is little study on the field-scale application of CWs; the majority of the investigations are laboratory size scale. Future studies should fill this knowledge vacuum by concentrating on long-term monitoring and field testing to confirm lab results and enhance the scalability of CWs for groundwater remediation. Additionally, CWs may be more effective at treating contaminated water when combined with other cutting-edge treatment methods like membrane filtration or advanced oxidation processes. Overall, CWs represent a promising and sustainable technology for water remediation, but continued research is essential to fully understand their potential and limitations in diverse environmental conditions.

***Keywords**: Constructed wetlands, groundwater contamination, pesticide removal, antibiotic degradation, sustainable remediation*

IMPACT OF LAND-USE AND LAND -COVER CHANGE ON GROUNDWATER QUALITY IN NORTHERN PART OF ODISHA, INDIA: A HYDROGEOCHEMICAL AND GIS APPROACH

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Water is one of the most valuable resources that is widely distributed all over the world and is available to mankind for sustenance and survival. Groundwater is the most important resource for almost all sectors globally: residential, agricultural, and industrial applications. About 40% and 70% of global water resources are used for household and irrigation purposes, respectively. The proposed study carried out in the Urban and its surrounding area of Keonjhar District, which is one of the popular tourist destinations in Northern part of Odisha. Since it is one of the regions of large-scale mining activities, leading to pollution of water resources and the degradation of groundwater. Further, rapid urbanization and increasing number of tourists has increased dependency on water resources, resulting in over-extraction of groundwater and increasing the risk of contamination. Even though there are several reports on variation in groundwater quality and suitability of groundwater for various purposes, but still there is not much significant work has been attempted to link change in LULC patterns to groundwater quality fluctuation yet. Thus, in this study a hydrogeochemical and GIS based approach has been attempted to evaluate the groundwater quality and linking it to change in LULC patterns. The study area experiences tropical to sub-tropical climate with hot summer, high and well-distributed rainfall during the monsoon and a cold winter. The district is mainly drained by the river Baitarani and its tributaries barring a very small patch in the extreme south-western part, falling in Brahmani, the Singhbhum Granites cover 50% of the district's land, while the Iron Ore Group covers the western and south western limit. The study area's groundwater is divided into fractured, fissured, and consolidated basement rock formations, with shallow levels during pre and post monsoon periods. A total of 56 groundwater samples were collected from different locations during PRM period (April 2024), maintaining its spatial distribution and based upon lithological and LULC variance. The physical parameters like pH, EC and TDS were measured in-situ and samples were brought to Laboratory for further analysis. The major cation and anion analysis were done following standard procedure and each parameter were measured thrice to maintain the accuracy with an error percentage of 5 to 10%. Landsat 8 satellite imagery was processed using Arc GIS tools to create an LULC map of the study area 2014 & 2024, using supervised classification. Study categorized land cover types into five classes urban areas, agricultural land, barren land, forests, and water bodies. Using GIS software, the samples with higher nitrate concentration on the LULC map 2024, enabling spatial analysis of contamination patterns in relation to land use categories. Cations shows dominance of Na>Ca>Mg>K and Anion dominance in order of HCO_3^->Cl^->NO^{3-}>SO^{4}_{2-} All ions are under permissible limit except nitrate, about 19 samples show higher concentrations prescribed both by WHO (2011) and BIS (2012). This could be attributed to an increase in agricultural activity to meet the crop demand of the rising population. The groundwater samples are plotted in the Piper (1944) Trilinear Diagram. The plot shows four fields where groundwater samples are reported. Most of samples are falling in Field F which is Mixed Ca-Mg-Cl type while one sample is falling in A field which is Ca-HCO^3type and three samples are falling in B field which indicates Na-Cl type.

Two sets of LULC Maps for year 2014 and 2024 were compared to evaluate the changes in land use over the decade and an assessment was made of their impact on groundwater quality for the year 2024. It is inferred from the study that there is increase of urbanization from 32.09sq km to 40.04sq km (24.77%) and agricultural land from 66.1 sq km to 70.82sq km (7.14%) from 2014 to 2024. It may be predicted through LULC maps that increased urbanization has led to anthropogenic activities, intensive farming, and improper disposal of residential wastewater, all of which may have been linked to elevated nitrate contamination. Thus the study infers that the groundwater quality of the area is safe for various purposed except the locations having high nitrate concentration. The high nitrate concentrations in these locations are mainly due to the change in LULC patters i.e. increasing urbanization and agricultural activity. This initial phase of contamination requires immediate attention, with the implementation of rigorous management policies and strategies essential to ensure the sustainable use and protection of resources. Thus, it is imperative for better land use planning and the adoption of sustainable farming practices in the study area to address groundwater contamination and protect the resources.

Keywords**:** *LULC, groundwater quality, hydrogeochemistry, urbanization, agriculture*

EVALUATION OF GROUNDWATER SUITABILITY FOR DRINKING AND IRRIGATION PURPOSES IN PULLAMAPATTI WATERSHED USING CCME-WQI WITH SPECIAL EMPHASIS ON HEALTH RISK IN FLUORIDE AND NITRATE CONTAMINATION

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Assessing groundwater quality is essential for ecosystem health and human well-being. Quality is impacted by lithology, geochemistry, and human activities, with contaminants like fluoride and nitrate posing health risks, particularly in regions like Dharmapuri. Fluoride contamination is a major concern in many parts of India, including the various hamlets of Dharmapuri district. The objective of the present study aims to: (1) assess groundwater quality for drinking and irrigation, (2) investigate fluoride contamination origins and geogenic sources in Pullamapatti watershed, Dharmapuri District, and (3) calculate the CCME- Water Quality Index and assess health risks for various age groups due to fluoride-nitrate exposure. The findings will support effective drinking water management strategies in Pullamapatti, Northern Tamil Nadu, India.

The Pullampatti watershed in Dharmapuri district, Northern Tamil Nadu, has an area of 1701.69 km^2, located between 78°00' to 78°35'E longitude and 12°00' to 12°31'N latitude. The terrain consists of Charnockites and gneissic rocks from the Archaean crystalline formations, with undulating plains and upland plateaus in a semi-arid, hot, dry climate. Groundwater is found in phreatic to semi-confined conditions within crystalline rocks and alluvial formations. There were 51 dug well samples and 18 bore well samples of each season (pre and post monsoon period 2022), representing the entire watershed collected. Water samples were analyzed for pH, EC, TDS, hardness, alkalinity, and major cations and anions, following BIS and WHO standards. In situ measurements of pH, EC, and TDS were conducted using a Horibba LAQUA multi-parameter analyzer. Titrimetric methods were used for Ca^{2+}, Mg^{2+}, Cl^-, and HCO_3^-; flame photometry (Model 1385) for Na^+ and K^+; colorimetry for SO_4^{2-}; and a Continuous Flow Analyzer for F^- and NO_3^-. Spatial distribution of physicochemical parameters was mapped in ArcGIS 10.3 using IDW interpolation. Analytical values for parameters like EC, pH, total hardness, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, Na^+, K^+, CO_3^{2-}, HCO_3^-, NO_3^-, and F^- determined groundwater quality from dug wells. Indicators such as SAR, RSC, Na%, Kelly’s ratio, and magnesium hazard ratio were evaluated for irrigation suitability. Drinking water quality was assessed using the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (WQI). Health risk assessment (HRA) followed USEPA guidelines to evaluate potential health risks from contaminants like fluoride and nitrate.

In the pre-monsoon period, groundwater in the Pullamapatti watershed showed EC levels from 758 to 6780 µS/cm, indicating high dissolved ions. Sodium, potassium, sulfate, and nitrate ions were found in the ranges of 37–730 mg/l, 1.2–43 mg/l26–270 mg/l, and 3.16–106 mg/l, respectively. Groundwater samples showed hardness ranging from 65 to 1865 ppm, averaging 654 ppm. Calcium levels varied between 10 and 365 ppm, while magnesium ranged from 13.37 to 266.3 ppm. Bicarbonate (HCO_3^-) was the dominant anion, with

concentrations between 119 and 585 ppm, though some samples had chloride (Cl^-) as the primary anion. Carbonate (CO_3^{2-}) levels were lower, ranging from 0 to 50 ppm, indicating varied chemical composition in the groundwater. In the post-monsoon period, groundwater samples have TDS between 288 and 3391mg/l reflecting a slight mineral increase from pre-monsoon. Electrical conductivity (EC) ranged from 576 to 6760 µS/cm, indicating high ion presence. Cl^- concentrations varied from 56.8 to 900.9 mg/l, averaging 322.93 mg/l. Sodium and potassium levels ranged between 11–368mg/l and 1–20mg/l, respectively. Sulfate concentrations were between 3.6 and 617.98 mg/l, while nitrate ranged from 0.01 to 216.84mg/l. Hardness spanned from 100 to 1590 mg/l, with an average of 528.85 ppm, reflecting higher calcium (16–310 mg/l) and magnesium (19.44–360.13 ppm) levels. Bicarbonate was the dominant anion (70–390mg/l), with carbonate between 0 and 150mg/l. pH values remained within the permissible range (6.94–8.29). Fluoride ranged from 0.13 to 2.84mg/l, with an average of 1.11mg/l, sometimes exceeding the WHO limit of 1.5mg/l. Phosphate levels were minimal, between 0 and 0.2496 ppm. For irrigation, sodium percentage (Na%), SAR, Kelly's ratio, RSC, PI, MHR, and potential salinity indicated that most samples were suitable. Agriculture indices are as follows: Na% was found between ranges (10.32 - 91.62) & (2.85 - 82.3), sodium absorption ratio varies from (0.66 – 19.45) & (0.15 – 10.6), Kelly's ratio (KR) varies from (0.11 - 10.87) & (0.02 to 4.64), residual sodium carbonate varies from(-27.43 – 7.84) & (−28.12 to 6.14), permeability index (PI) varies from (17 – 107.02) & (2.60 to 86.65), magnesium hazard varies from (18.46 – 80.02) & (16.90 to 90.99), potential salinity varies from (10.16 – 91.58) & (2.49 – 82.29) during pre and post monsoon respectively; results shown that the majority of the groundwater samples were suitable for irrigation uses. The CCME-WQI for drinking showed values from 34.9 to 77.15 (average 55.59), indicating marginal to poor quality. Health risk assessment (HRA) showed that over 34% of samples exceeded safe limits for fluoride and nitrate, with higher risks for infants and children compared to adults.

The hydrochemical parameters of the dug well water samples of the study area are compared with the standards of BIS & WHO, which shows that the values are within the permissible limit. Higher values of EC indicate the presence of inland salinity along the watershed. Analysis showed that dug wells are mostly affected by fluoride contamination, 34.61% and 25% of samples during pre- and post-monsoon respectively have fluoride concentration >1.5mg/l, particularly in areas including Dharmapuri, Karimangalam, Manicknoor, Mittanahalli, Timmanapuram, Nallampalli, Bandarahalli, and Kongarapatti. The CCME-WQI for drinking purpose showed that 26.92% of samples are fair, 61.53% samples are marginal and 11.53% are poor. The present study indicates that the groundwater chemistry is mostly controlled by geogenic processes (weathering, dissolution and ion exchange) as the dominant factor affecting groundwater chemistry to some extent of anthropogenic activities. The health risk assessment revealed that 37% of the samples exceeded safe fluoride levels for infants, children, and adults. Oral ingestion of nitrates poses significant health risks, particularly for children, who are the most vulnerable across all age groups. The Total Hazard Index indicates that nitrate levels in several groundwater samples exceed safe limits (HI > 1), especially for children. Although 80% of the groundwater remains appropriate for agriculture, the study stresses the need for targeted groundwater management to tackle contamination issues and mitigate health risks from elevated fluoride and nitrate ingestion, particularly for vulnerable populations of infants and children.

Keywords: *Health risk assessment, WQI, hazard quotient, hazard index, groundwater*

REMOVAL OF INORGANIC CONTAMINANTS FROM GROUNDWATER USING LATERITE SOIL IN MIDDLE WESTERN GHATS, INDIA

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Groundwater contamination by inorganic pollutants, particularly fluoride and arsenic, is a major environmental and public health issue in many parts of India. These contaminants lead to severe health problems, including skeletal and dental fluorosis, various cancers, and neurological disorders. The demand for clean groundwater is especially high in rural regions, where 85% of drinking water is supplied by groundwater. Addressing these contaminants is crucial for ensuring safe water access in India. Given the high treatment costs associated with traditional methods, there is a growing interest in finding affordable, sustainable, and regionally appropriate treatment alternatives. This study explores the potential of using typical laterite soil of Middle-Western Ghats, a naturally occurring material rich in many minerals especially iron and aluminum oxides and abundant in the region, as a low-cost adsorbent for removing fluoride and arsenic from groundwater. Laterite soil's specific adsorption properties, natural abundance, and low environmental impact make it a promising material for sustainable water purification. The choice of laterite soil for this study is based on its composition and widespread availability in the Middle Western Ghats. Iron and aluminum oxide minerals create a porous structure with a large surface area, enabling the soil to adsorb contaminants through multiple mechanisms, including electrostatic attraction, ion exchange, and ligand exchange. These mechanisms make laterite soil particularly effective in removing anionic contaminants like fluoride and arsenic, which tend to bond with the positively charged sites on iron and aluminum oxides. This adsorption potential, combined with the soil's natural abundance, suggests that laterite soil could serve as a sustainable and locally viable solution for groundwater purification in remote areas.

The methodology involved sample collection, soil preparation, and batch adsorption experiments. Laterite soil samples were collected from NITK campus. The collected soil samples were then cleaned, air-dried, and sieved to create a uniform particle size, which improves adsorption efficiency. The XRD results revealed significant peaks for iron oxides (hematite and goethite) and aluminum oxides (gibbsite), confirming the soil's composition and supporting its high potential for adsorbing fluoride and arsenic. In the laboratory, synthetic fluoride and arsenic solutions will be prepared in simple ultra-pure water, allowing for controlled testing of the soil's adsorption capabilities. The adsorption experiments will involve immersing the laterite soil in these solutions under varying conditions of contact time, pH, and contaminant concentration. Arsenic and fluoride concentration will be measured using spectrophotometric analysis and ion selective electrode meter, respectively. Parameters such as pH and contact time will be adjusted to identify the optimal conditions for contaminant removal. The efficiency of arsenic and fluoride removal under acidic and alkaline conditions will be checked. The time taken to reach the adsorption equilibrium will also be checked which will tell the rate of arsenic and fluoride adsorption. Further, pH at point-of-zero-charge and arsenic and fluoride adsorption isotherm of the soil will be determined.

The use of laterite soil as a low-cost adsorbent presents several advantages for sustainable water treatment, particularly in rural and semi-urban areas. Laterite's widespread availability in the Middle Western Ghats and minimal processing requirements make it a cost-effective alternative to synthetic adsorbents, which are often expensive and difficult to implement on a large scale. Additionally, laterite soil is biodegradable and poses little environmental risk, making it a safe option for rural communities that lack advanced waste disposal facilities. Utilizing laterite soil aligns with principles of sustainability by reducing the need for synthetic chemicals, lowering costs, and supporting a local supply chain that benefits regional economic development. Moreover, the use of a locally available resource minimizes environmental impact, reduces transportation costs, and enhances the feasibility of community-level groundwater treatment projects.

This study evaluates laterite soil as an effective, sustainable, and locally available adsorbent for removing fluoride and arsenic from groundwater. Its natural composition, particularly its high iron and aluminum oxide content, may enables strong adsorption, making it a feasible alternative to conventional treatment methods. The Middle Western Ghats' abundant laterite deposits offer a readily accessible solution for communities facing challenges with groundwater quality. By providing an affordable and environmentally responsible solution, this approach has the potential to become a cornerstone of decentralized water purification efforts, improving groundwater safety and public health while fostering sustainability and regional resource utilization across India. Further research will focus on optimizing the adsorption process, investigating potential for soil regeneration and reuse, and conducting field trials to validate laboratory results in real-world conditions.

***Keywords*:** *Adsorption, sustainability, laterite soil, inorganic contaminants, arsenic, fluoride, adsorption-isotherm*

EFFECT OF MICROPLASTICS ON THE DYNAMICS OF EMERGING CONTAMINANTS IN GROUNDWATER

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Microplastics (MPs) are defined as plastic particles having sizes less than 5 mm and have emerged as a serious threat to public health. MPs are found in all the environmental matrices: surface water, groundwater, sediments and WWTPs. One more important problem with MPs is that they are now found in almost all the food items as well as in the blood samples of newborn babies and found in copious quantities of them. In previous literature MPs have been linked to pharmaceutical and personal care products (PPCPs) and heavy metals. Some studies have also explored the potential of MPs in the transportation of antibiotic-resistant genes (ARGs) in surface waters. The level up to which the MPs are acting as a reservoir for ARGs, and other co-selectors is little understood, especially in groundwater. The current study focuses on the impact of MPs found in groundwater on its antibiotic resistance potential, to minimize the susceptible microbes from becoming resistant. The study sheds light on the type of MPs found in the area and its abundance in the studied samples.

Groundwater samples were collected from 6 locations in Roorkee and nearby villages. These samples were pre-processed for different analysis. For antibiotic analysis, one litre of groundwater sample was collected in amber glass bottle. After the SPE procedure the samples were loaded on the LC-MS/MS (Shimadzu, Japan) and analysed for the target compounds: ciprofloxacin and triclosan. 100 mL groundwater sample was collected in PVC bottles for heavy metal analysis. The samples for heavy metal (copper, chromium and zinc) analysis were filtered using 0.45μm cellulose nitrate filter papers (Axiva, India). Samples were digested using aqua regia (3:1 ratio for HCL:HNO_3) at 103°C following APHA protocol for heavy metal analysis. The heavy metals were analysed using inductively coupled plasma mass spectrometry (Agilent 8900; ICP-MS: triple quad, Agilent Technologies, Inc., USA). 100 litres of groundwater filtered from 63μ sieve was reconstituted using one litre Milli Q water and was utilized for MP analysis. Micro–Raman spectroscopy was utilised for characterization of the microplastics. A 20x, 50x and 100x objective lens (NA 0.55) and 532 and 785nm laser source (5 mW; grating 1800 lines/mm) were used as the method conditions for the Raman Spectroscopy. The spectra generated from the Raman` Spectroscopy was identified manually using origin software. Four litres of groundwater sample was collected in sterilized PVC bottles and was filtered using 0.22μ cellulose acetate filter paper. For analysis of resistant genes (16 S rRNA, *ycc*T, *tet*A, *sul*1, *mcr*5) DNA was extracted using MO BIO kit for sediments (MOBIO) following manufactures protocol. Each qPCR was performed in thermal cycler of Applied Biosystems with assay that included 2μl DNA insert (normalized to 5ng/μl), 1ul each forward primer and reverse primer (5mM), 5μL SYBR green master mix, 1μl DNA free molecular biology water. The cycle conditions for qPCR included initial denaturation at 95°C for 3 min, followed by 40 cycles of: denaturation 95°C for 10 secs; annealing at 60°C for 30 secs and extension at 72°C for 30 secs. The melt curve analysis was performed using temperature 60°C – 95°C with 5°C increment, each step for 30 secs. The absolute abundance of the ARGs was calculated in gene copies per liter (GCL) in MS excel after incorporating all the dilutions; and for further analysis the relative abundance

was calculated by dividing absolute abundance by 16S rRNA gene copies per liter (the resulting number was unitless). Shapiro Wilk test was used to test the normality of the dataset and non-parametric tests were used. The Wilcoxon rank sum test was utilized to ascertain the relation of the target ARGs with the co-selectors. Principal component analysis (PCA) was utilized to understand the behavior of ARGs in the co-selector stress. Statistical tests were performed using R (version 4.3.2) and R-Studio (version 3.2.1).

All the samples showed ARGs and the co-selectors. The relative abundance of *sul*1 gene was highest in all the samples while the levels of *mcr*5 were minimum. There was a correlation between the levels of *ycc*T and zinc in L1 and L4 (L: location). Also, there was correlation between the levels of *tet*A and ciprofloxacin in L1, L2 and L6. MPs found were in blue, black, red and transparent colour. MP fibres and films were the shapes of the MPs studied. L3 sample had the highest concentration of MP fibres while L4 had high MP films concentration. The study concludes that MPs may be acting as carriers for ARGs and heavy metals into the groundwater. The study also concludes that there is a cross resistance is occurring in groundwater, and this might cause various pathogens to become resistant. The authors suggest that various measures should be taken by the local people and the government to stop the dissemination of the pollution in the studied areas.

Keywords: *Emerging contaminants, ARGs, antibiotics, heavy metals, microplastics, groundwater*

EMERGING POLLUTANTS IN WATER, SOURCES, HEALTH IMPACTS AND MANAGEMENT

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Water is very important resource for surviving of human beings on the Earth, used for drinking as well as irrigation and industrial works provided by the surface and groundwater sources. Water resources played important role in the developments and established socio-economic balance in a country also but nowadays anthropogenic and natural activities introduced the Emerging Pollutants (EPs) and toxic contaminants into the water resources globally. These newly introduced chemicals are not in the regulatory guidelines & standards and have the potential of toxicity to humans and ecosystems. Recently, the chemicals, personal care products and fragrances, micro plastic, pharmaceuticals waste, medicines, Bisphenole A (BPA), house hold cleaning product, fertilizers, disinfectants-bi-products (DBPs), pesticides, plasticizers, hormones and endocrine–disrupting compounds, persistent, organic pollutants and industrial by-products, rare & trace elements and pathogens were observed in the water. The concentration of the emerging pollutants increases day by day as a result of increasing urbanization, industrialization, and agriculture activities. The concentration of the EPs in water depends on the its properties like solubility, degree of persistent, volatility, polarity, adsorption and degradations. These EPs analysed in water by use of advanced instruments such as the HPLC (High-Performance Liquid Chromatography), GC-MS (Gas Chromatography-Mass Spectroscopy), ICP-MS (Inductively Coupled Plasma-Mass Spectrometry), therefore, increases the cost of analysing, monitoring and characterization of EPs in the water. The sources of the emerging pollutants in groundwater as well as surface water include disposal of domestic, industrial, hospital, agriculture waste and landfill leachate and runoff. These pollutants are an emerging concern due to the negative impact on the health of the human beings and ecosystems, accumulated in the food chain, and then the body organs of the human beings and aquatic animals. The adverse impact to human health of EPs includes genotoxic and mutagenic, endocrine disruption, acute and chronic toxicity, resistance of micro-organisms to antibiotics, bladder tumours, carcinogenic effects, fetal loss anomalies, long gestational duration etc. Studies revealed that the EPs lead to liver and central nerves system disorders, skin allergy, otitis, and neuro-psychological disorders. EPs are toxic for the ecosystem directly and indirectly, affecting the plant's growth and health of aquatic animal. Therefore, there is a need to control the EPs in water. However, there are some challenges to control the EPs such as identification, lack of guidelines and standards limits and protocol, accurate techniques for analysis and measurement, and its removal. Generally, management and removal of the EPs from the water is done by use of physico-chemical and biological processes such as filtration by sand and media filtration, advanced oxidation processes, chlorination, use of zeolite, adsorption using granular activated carbon, constructed wetland (CW), hydrolysis processes, bio-sorption, bio-char, adsorption by carbon nanotube and clay minerals, decomposition by micro-organism, membranes, bio-reactors and phytoremediation. The integrated treatments or combination of treatment systems such as constructed wetlands and activated carbon with oxidation process are very effective and low energy consumption treatments for removal of EPs from water.

Some of the important aspects in control and management of EPs in water are effluent quality monitoring and characterization for the identification, stabilization of waste disposal system, and setting the limits by the pollution control agencies. A proper environmental management plan is required to be implemented including the green technology with emphasis on organic farming. Use of natural and non-toxic personal care products, bio-degradable products can help in minimizing the EPs in effluents, thereby helping to reduce he adverse impacts on health of humans and ecosystems.

Keyword: *Emerging pollutants, water, health impacts, sources, management*

REVOLUTIONIZING SMART WATER SAFETY: A FAST, LOW-COST PAPER STRIP DIP TEST FOR ON-SITE BACTERIAL CONTAMINATION DETECTION

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Safe water drinking is an important criterion to maintain public health, requiring effective monitoring to prevent bacterial contamination. In this study, we developed a novel colorimetric paper strip dip (PSD) test for quantification of bacterial contamination. This test utilizes dye-coated paper strips that undergo Fenton reaction when immersed in a mixed solution of DI water and hydrogen peroxide (H_2O_2). The bacterial catalase in contaminated water competes with the Fenton catalyst for H_2O_2, resulting in a visually observable color change in both the strip and solution. The intensity of the decolorization on the strip/solution determines the bacterial contamination level in the water sample. The method offers a lower detection limit of 50 CFU/ml for catalase positive bacteria (*Escherichia coli)* within 5 min at room temperature (25 ºC). Moreover, the test exhibited minimum interference for bacterial detection in the presence of potential contaminants present in natural water sources. The test is integrated with a mobile app for effortless and reliable quantification of bacterial contamination. In addition, the app recommends the chlorination requirement for disinfection of contaminated water sample. Thus, the PSD test is rapid, precise, specific, economical (~0.060 USD per test), and user-friendly for on-site bacterial monitoring of drinking water sources.

Water-borne diseases are primarily caused by bacterial presence in water that infect millions of people in developing countries. Diseases caused by water contamination result in 3.4 million deaths yearly. Therefore, it is imperative to devise efficient tools for water quality monitoring. Among the pivotal parameters for gauging water quality, coliforms and other catalase-positive bacteria are paramount, serving as vital indicators of water contamination. According to the World Health Organization (WHO), the concentration of viable bacteria and coliforms in drinking water should not be more than 10 CFU/100 ml and 1 CFU/100 ml, respectively. Therefore, reliable bacteria monitoring methods for precise, convenient, and rapid on-site detection are essential for alleviating waterborne diseases.

The PSD test developed for monitoring bacterial contamination in water is based on the classic Fenton reaction, where the dye on the paper strip gets decolorized via the action of $OH\cdot$ radicals when the water sample is contamination-free. In the presence of bacteria, the reagent responsible for $OH^{\cdot}$ radical production, i.e., H_2O_2 is broken down into water and oxygen by the action of the catalase enzyme, and the dye on paper stays intact. Thus, the color intensity on the strips in a PSD test decreases with reducing bacterial concentrations in water. The dip test paper strips were prepared using Whatman filter paper immersed in a solution containing optimized concentrations of $FeSO_4$ and MB dye. The paper was soaked in the solution for 30 min, followed by air drying at room temperature. The dried dye-coated paper was cut into 2 cm × 0.7 cm strips. The working of strips was validated by immersing the coated paper strips into a solution containing H_2O_2 (optimized concentration) and an equal volume of catalase/catalase-positive bacterial sample (known concentration). After incubation, the strips were removed from the solution and dried at room temperature.

The test was conducted with controls, including distilled water and a water sample. The bacteria-spiked test solutions and the control solutions were incubated for 30 s. Subsequently, the dye-coated paper strips were immersed in the solution for 5 min at room temperature to quantify the catalase/microbial activity of the sample. After that, an optimized concentration of $NaNO_2$ was added and mixed with the test solution for 30 s to quench the Fenton reaction, stabilizing the color. The strips were then removed from the mixture and air-dried. The strip and solution color were analyzed visually. The results were further corroborated by measuring the absorbance of MB remaining in the solution after the PSD test at 665 nm. The color of the dye on the strips recedes from blue to grey and further to darker grey as the bacterial concentration decreases, which was quantified by a mobile app, "Color Grab". The ΔE^* values are inversely correlated with the color gradient on the paper strip. The ΔE^* values of the colorimetric PSD test showed higher LOD values of *E. coli* was 50.06 CFU/ml. The PSD test shows high sensitivity for *E. coli*, 0.477, ΔE^*/dec. For b^* measurement, the sensitivity for *E. coli*, *C* 0.800, b*/dec. In the case of solution absorbance measurement (OD_{665}), the sensitivity for *E. coli*, was 0.034 per dec. The disinfection of the bacterial solutions was further verified by conducting a PSD test before and after chlorination. For all the bacterial solutions, the dye color on the strip faded from their respective blue (prior chlorination) to grey (after chlorination) indicating a decrease in bacterial concentration after disinfection.

Rapid contamination of water bodies necessitates the development of quick, reliable, and low-cost monitoring systems, which can indicate bacterial contamination to ensure the consumption of clean drinking water. In this study, a rapid, accurate, and user-friendly PSD test has been developed for on-site bacterial detection in water, which is a function of Fenton chemistry and catalase action on dye-coated strips. The degree of decolorization of the paper strip indicates the level of bacterial contamination in the water. Integration with mobile apps further enhances the applicability of tests for smart water management. Moreover, initiatives can be taken to collaborate with water management authorities and regulatory bodies to integrate the developed test into existing water quality monitoring frameworks.

Keywords: *Colorimetric paper strip, coliform, Fenton reaction, catalase-positive bacteria, chlorination*

MICROPLASTIC DETECTION IN UNCONFINED GROUNDWATER AQUIFER SPOTS OF HARIDWAR, INDIA

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The water sample collection and microplastics study in Uttarakhand's Haridwar sector involved an organised evaluation of groundwater from six different locations: Dhanori, Karanpur Mafi, Bhagwanpur, Kawad Marg, Sitapur, and Piran Kaliyar. The selected locations were chosen based on their use of handpump groundwater stations in the district, situated in the southwestern section of the state. The groundwater extraction focused on unconfined aquifers, with samples collected every 10 days over a three-month period This extensive sampling technique was developed to provide a full understanding of microplastic (MP) pollution in groundwater sources, which remains relatively unexplored compared to marine environments. The aquifers in this area form a three-tier system typical of Indo-Gangetic belt. This system is characterized by three distinct zones, each separated by thick restricting clay layers of varying thicknesses. The complex character of these alluvial sediments, with frequent alternations between fine and coarse textures, has a considerable impact on the behaviour of water and possible contaminants like microplastics in the subsurface environment.

Microplastics, tiny plastic particles that may survive in the environment for long periods of time, are common in a variety of habitats, including marine ecosystems, where their abundance is well documented. However, their presence and behaviour in groundwater systems remain poorly understood. Identifying this knowledge gap, the study aimed to identify and quantify microplastic pollution in groundwater in Haridwar district, with a focus on eight of the most regularly found microplastics in the environment. These included polyethylene (PE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polycarbonate (PC), polymethylmethacrylate (PMMA), and polyamide. To guarantee rigorous examination, groundwater samples were taken in triplicate from six capped monitoring bores in the Roorkee district.

The sampling and analysis process for microplastics was meticulously conducted to minimize contamination and ensure reliable results. Groundwater was taken from the handpump stations with a 10-liter steel bucket. For each sample session, 100 liters of groundwater were acquired by passing the water through the process ten times, with each iteration resulting in the collection of ten liters. The collected volume was then treated to a pre-filtration procedure to remove debris and bigger particles. For this aim, a 63-micron sieve was used, which successfully captures microplastics while allowing smaller particulates to pass through. To ensure that microplastics stuck to the sieve mesh were not missed, the sieve was jet-sprayed with deionized water.

The microplastics released during this stage were transferred to a 1000-liter glass bottle for further investigation. The next step in the technique was to transport the collected water to IIT Roorkee's laboratory facilities. The water samples were vacuum filtered using an assembly equipped with 0.2-micron filter paper. This method guaranteed the retention of even the smallest microplastic particles. The filtrate, which contained microplastic particles trapped on the filter paper, was then subjected to characterization. These investigations used micro-Raman spectroscopy for polymer identification, which is particularly useful for determining the chemical composition of individual microplastic particles. Furthermore, SEM provided detailed imaging that revealed the size, shape, and surface morphology of the collected particles, providing useful information about their likely sources and environmental behaviour.

Given that the groundwater samples in this investigation were collected from capped bores, microplastics most likely entered these unconfined aquifers via porous media or soil layers. The alternation of fine and coarse sediments in the research area's alluvial deposits lends credence to this concept, as these heterogeneous substrates can facilitate the movement and accumulation of microplastics. This work emphasizes the need to broaden the scope of microplastic research to encompass groundwater systems on a larger geographical scale. The samples tested via the Micro-Raman facility at IIT campus indicated the presence of PET, PTFE, PP and PE in the groundwater samples.

While the findings from the Haridwar area give useful baseline data, more research is needed in other parts of India and around the world to acquire a more complete knowledge of microplastic pollution in groundwater. Such research would help to discover the variation in microplastic occurrence across different hydrogeological settings, as well as the factors that influence their transport and persistence. Finally, the detection of microplastics in Haridwar's Indo-Gangetic aquifers emphasizes the significance of monitoring and managing this increasing pollutant. The systematic collection and analysis of samples using advanced characterization techniques such as micro-Raman spectroscopy and SEM are crucial for better understanding microplastic dynamics in subsurface water systems. Further research into varied aquifer systems around the world is required to provide a global perspective on microplastic contamination and its implications for human health and the ecosystem.

Keywords: *Microplastics, groundwater, unconfined aquifer, soil, porous media*

DESIGN OF Ag-MODIFIED 3D-GRAPHENE-BASED ELECTROCHEMICAL SENSOR FOR DETECTION OF MERCURY IONS IN WATER AND SOIL SAMPLES

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The mercury ion (Hg^{2+}) is considered one of the most dangerous heavy metal pollutants, posing a high risk to human health and to various organisms. Therefore, detecting Hg^{2+} ions is essential in water and other environmental samples. Various methods have been developed to identify Hg^{2+} ions, including atomic absorption spectrometry (AAS), microwave-induced plasma atomic emission spectroscopy (MIP-AES), inductively coupled plasma mass spectrometry (ICP-MS), and atomic fluorescence spectrometry (AFS). Voltammetry has always been an important alternative to several spectroscopic instruments-based techniques that can measure Hg^{2+} ions at ultra-trace levels in complex matrices. Graphene is a sp^2-hybridized carbon allotrope with a 2D honeycomb lattice with remarkable electron mobility, a large theoretical surface area, and good electric conductivity. However, the conventionally synthesized graphene is generally in 2D, which is prone to clumping and aggregating, thus losing the surface area and the electron transport property. It's exciting to report that new research has shown 3D graphene can offer larger surface area, conductivity, and mass transfer efficiency than 2D graphene because of their porous architectures and it's generally anticipated that this technology will be employed to create high-performance electrochemical sensors. In the present investigation, a low-cost freeze-casting approach has been adopted for the preparation of AgNPs/3D-graphene nanocomposite. The obtained detection limit of 0.39nM is significantly lower than in prior publications when compared to the methods using nanocomposite materials. This AgNPs/3D-graphene/GCE sensor has been used successfully to monitor Hg^{2+} in actual samples, such as soil and borewell samples. Overall, this work demonstrated the great potential of using AgNPs/3D-graphene nanocomposite to create a new class of electrochemical sensors that will enable accurate and dependable measurement in real systems. Ag nanoparticles modified with 3-D graphene (AgNPs/3D-graphene) nanocomposite have been synthesized through a simple, cost-efficient, one-step freeze-casting route. XRD was used to explain the phases and structural properties of the as-synthesized graphene oxide (GO), bare 3D-graphene and AgNPs/3D-graphene nanocomposite. AgNPs/3D-graphene nanocomposite. The strong peaks at $2\theta = 37.9°$, 44.1°, 64.1°, 77.2°, and 81.1° can be indexed to the (111), (200), (220), (311), and (222) planes of face-centered cubic (fcc) Ag crystals. Scanning electron microscopy (SEM) and high-resolution transmission electron microscopy (HRTEM) were used to examine the surface morphology of the as-prepared AgNPs/3D-graphene nanocomposite and bare 3D-graphene. A 3D porous cellular structure, composed of interconnected graphene sheets with pore sizes ranging from sub-micrometers to micrometers, is observed in both the AgNPs/3D-graphene nanocomposite and bare 3D-graphene. In the HRTEM study, the Ag nanoparticles, which have an average size of 30 nm, are evenly distributed across the graphene sheet surfaces and do not exhibit any evidence of aggregation. Also, the loading content of Ag in the AgNPs/3D-graphene nanocomposite was evaluated by ICP-AES analysis, and the findings verify that 12% of the Ag is loaded in the nanocomposite.

The cyclic voltammetry (CV) experiment was performed using the AgNPs/3D-graphene/GCE at a scan rate of 30 mV/s in a 0.1 M KCl solution containing 10 mM $K_4[Fe(CN)_6]$ as a redox probe to explore the electron transfer mechanism at the catalyst-modified surface.The AgNPs/3D-graphene/GCE was shown to have a greater current responsiveness when compared to the bare GCE and the bare 3D graphene-modified GCE. The fast increase in the redox probe's current over the modified electrode suggests that the AgNPs/3D-graphene nanocomposite modified electrode has an enhanced charge transfer property. To further verify the specific roles of 3D-graphene and AgNPs, the interfacial charge transfers properties of the bare GCE, 3D-graphene-modified GCE, and AgNPs/3D-graphene/GCE at the electrode-electrolyte interface were investigated using electrochemical impedance spectroscopy. Compared to the bare GCE and 3D-graphene-modified GCE electrodes, the AgNPs/3D-graphene/GCE showed lower charge transfer resistance due to the decreasing radius of the semicircles. In electrochemical experiments, the sensitivity is mainly determined by the pH, accumulation potential, and accumulation duration. The optimal electrochemical parameters used in the current investigation include a deposition potential of -0.5 V, a deposition time of 50 s, a potential scan range from 0.2 to 0.6 V, a step potential of 0.05 V, and a modulation amplitude of 0.025 V. Differential pulse anodic stripping voltammetry (DPASV) measurements were employed to assess the Hg^{2+} in solutions. The experiments were conducted in 0.1M KCl and 0.1M KNO_3 supporting electrolyte medium (pH 5) at the applied voltage of -0.5V for the 50s, and the potential scan was carried out in a range of 0 V to + 0.6 V. The DPASV responses of Hg^{2+} using a modified AgNPs/3D-graphene/GCE electrode was recorded in the concentration range of 0.1 to 40 μg/L. The responses showed a linear increase in the stripping peak current. A detection limit of 0.08 μg/L (0.39 nM) was achieved based on a signal-to-noise ratio (S/N) of 3. With an accumulation time of 50 seconds and an R^2 = 0.999 in Fig. 6(e), the manufactured sensor demonstrated good sensitivity of $1.9x10^{-8}$ A per μg L^{-1} of Hg^{2+}. There was no significant variation of the stripping current of Hg^{2+} was observed using five different modified electrodes. Among the five examined electrodes, the current response variation from these electrodes varies by only 5.58%. Sensor's stability was observed for 28 days, and the relative standard deviation was 1.57%. It has been used to measure Hg^{2+} in soil and underground water samples to evaluate the practicability of fabricated sensors further. Three soil samples were taken from a synthetic bed received by the Analytical Chemistry Division, BARC, for analysis, and two borewell water samples were collected from the 24 Pargana area of West Bengal. The cold vapor atomic absorption spectroscopy (CVAAS) technique was used to validate the values. The results of the analysis agree well with the two methods of determination. AgNPs/3D-graphene/GCE utilized as the working electrode for detecting Hg with high sensitivity and selectivity. The AgNPs/3D-graphene/GCE exhibited a wide linear range for Hg^{2+} detection, spanning from 0.2 to 50 μg/L, with a low detection limit of 0.08 μg/L, indicating high sensitivity. The analytical method was validated using the certified reference material (CRM), and the Z score was reported to be 0.64. After being stored in the ambient environment for 28 days, the AgNPs/3D-graphene/GCE exhibited electrocatalytic current towards Hg (II) at 95.8%, demonstrating good long-term stability. Very good results were obtained when the AgNPs/3D-graphene/GCE sensor was applied to detect Hg^{2+} in soil and borewell real samples. The method would provide new insight into the sensible design and use of AgNPs/3D-graphene/GCE for precise and reliable Hg (II) sensing in real samples.

Keywords: *Electrochemical sensor, Hg^{2+}, 3D-graphene, Ag nanoparticles, Stripping voltammetry*

EXPLORING ELECTROCHEMICAL OXIDATION FOR THE REMOVAL OF BISPHENOL-A FROM CONTAMINATED GROUNDWATER

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Groundwater is essential for maintaining the long-term viability of ecosystems, since it serves as a crucial supply of potable water for people, sustains agricultural activities, and plays a significant role in maintaining a global water cycle balance. In recent decades, concerns regarding the presence of various organic pollutants in water bodies have intensified, with Bisphenol A (BPA) emerging as a prominent target of environmental scrutiny. As an endocrine-disrupting compound commonly found in plastics, BPA has been linked to adverse health effects, making its removal from water sources a severe environmental challenge. The release of BPA into the environment is a critical issue with diverse sources, encompassing both industrial and consumer-related activities. The pathways through which BPA is released include not only the direct release from production facilities but also indirect routes, such as the discharge of wastewater and wash water from BPA production facilities or consumer product manufacturing facilities utilizing BPA. Moreover, the effluent from wastewater treatment plants contributes to the environmental release of BPA, and leaching from discarded consumer products at hazardous waste landfill sites adds to the complexity.

To address this issue, innovative technologies have been explored, and one such promising way is the application of electrooxidation (EO) technology with graphite electrodes. Recently, there has been a growing emphasis on advanced oxidation processes (AOPs), particularly the electro-oxidation process and photocatalytic processes. Consequently, there is a vital need to develop and popularize new methods that enhance emerging contaminant degradation while minimizing their environmental impact. In EO process, contaminants undergo oxidation either by the oxidizing radical species generated on the anode surface or through direct electron transfer from organics to the electrode surface. RSM is a statistical approach which can be used to model experiments, evaluate the effects of multivariable on response values and optimise the process parameters. The degradation of BPA was designed and optimised by central composite design of RSM. In this regard, the removal efficiency of BPA was chosen as the response value. Based on the results of some preliminary studies, acceptable input variables were investigated to get the optimum response using CCD.

To investigate the effect of current density, a series of experiments were conducted at 1, 3, 5.5, 10 mA cm^{-2} using graphite electrodes. In the presence of ROS, the degradation efficiency of BPA was determined by scavenging experiments using different conventional quenchers: KI, Ethyl alcohol, and TBA. The scavenger-induced inhibitory effect on BPA degradation followed the order of Synthetic water>groundwater>KI>Ethanol>TBA. The degradation efficiency reached 98.59 ± 0.81% under 120 min of electrolysis when no radical scavengers were present. After the addition of 10 mM KI in the reactor, the degradation efficiency declined to 31.67 ± 1.3%. However, after the addition of 10 mM EtOH and TBA in the reactor, the degradation efficiency declined to 61.68 ± 1.3% and 63.77 ± 0.4%, respectively.

This study confirmed that anodic oxidation, facilitated by the generation of hydroxyl radicals, is an effective method for BPA mineralization in aqueous environments. The research shows the critical role of applied current density in the BPA degradation efficiency and highlighted the need for nuanced strategies in water treatment. The use of MALDI-TOF mass spectrometry enabled detailed analysis of the byproducts resulting from BPA degradation, revealing a complex degradation pathway involving aromatic ring cleavage and subsequent oxidation reactions. Scavenger studies demonstrated that the addition of radical quenchers significantly reduced BPA degradation efficiency. The EPR studies, using DMPO further confirmed the primary role of hydroxyl radicals (surface and free) and singlet oxygen in BPA degradation.The study also revealed a significant reduction in bacterial colony formation with increasing BPA concentrations, indicating potential disruption to biological wastewater treatment processes in the presence of BPA. These findings not only highlight the importance of addressing BPA contamination for human health but also underscore the need for maintaining the integrity of drinking water treatment systems.

Keywords: *Emerging contaminants, Groundwater treatment, Electrooxidation, By-products, Solar energy*

OCCURRENCE AND EXTENT OF ELEVATED URANIUM CONTAMINATION IN THE GROUND WATER SOURCES, KRISHNAGIRI DISTRICT, TAMIL NADU, INDIA

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India is the largest ground water user in the Earth and ground water is the backbone of India's agriculture and drinking water security. Groundwater contributes nearly 62% in irrigation, 85% in rural water supply and more than 50% in urban water supply. The occurrence and availability of the ground water in the crystalline basement complex of the Southern India, including Tamil Nadu is highly complex due to its heterogeneity nature. Further, the minerals present in the rock formation get dissolved in the ground water and make enriched with minerals. In certain places, the mineral enriched ground water become harmful to the human consumption. Uranium (U) as a potential drinking water health hazard is brought to the notice after the provisional guideline given by World Health Organization (WHO). One such contamination was investigated in the parts of Krishnagiri District of Tamil Nadu. Groundwater being crucial source of water in the region, this study was carried out with an objective to identify the distribution and spatial extent of Uranium in ground water source. This study provides a strong database for better understanding the source of uranium in the aquifer system of Krishnagiri region and the results would be useful for further studies in semi-arid regions

Based on the recommendations of the parliamentary standing committee in 2019, CGWB was entrusted to carry out baseline survey for Uranium in groundwater throughout the country for the first time. Accordingly, 1208 samples were collected from all districts in Tamil Nadu during NHS Monitoring in May 2019. Uranium analysis has been performed using ICPMS. Perusal of the results showed that nineteen samples had Uranium concentrations above the BIS permissible limit of 30ppb**.** Of which, 5 samples (26%) were from locations in Krishnagiri District with the highest value being 302 ppb at a bore well in Megalachinnapalli.Based on the baseline study, CGWB, SECR had taken up a special study to identify the occurrence of Uranium in ground water of Krishnagiri and Palepalli firkas of Krishnagiri District. A total of 40 ground water samples including dug wells, bore wells, hand pumps have been collected during pre-monsoon season (September 2022) and it has been found that the Uranium concentration varied from 0.34 to 485 ppb with average value of 79 ppb and standard deviation of 105 ppb (68% data falls within plus or minus 1 standard deviation). Out of 40 samples, 22 (55%) of samples have Uranium concentration more that the BIS permissible limit. During postmonsoon, the Uranium value ranged between 1.7 and 351 ppb with an average of 72 ppb and standard deviation of 82 ppb. Out of 48 samples, 29 (60%) of samples have Uranium more than the BIS permissible limit.

A total of 998 km^2 area has been identified in Krishnagiri district comprising six firkas namely Krishnagiri, Barugur, Alapatty, Pallepalli, Guruparapalli and Periyamutur of Bargur, Veppenapalli, Kaveripattinam, and Krishnagiri Blocks for the present study area based on the precious studies by the CGWB. A total of 110 nos. of ground water samples have been collected during May 2024, out which 41 samples from phreatic aquifer and rest are from the confined aquifer of the study area. All the samples were analysed for basic parameters using standard methodology and Uranium using Fluorometric analysis.

Out of 110 nos. of ground water samples collected from 110 gram panchayats, 18 (16.4%) samples showed Uranium concentration more than the BIS permissible limit for Drinking Purposes (0.03 mg/l). Groundwater from shallow aquifer unit and deep aquifer have high concentration of Uranium. 3 gram panchayats viz. Narlapalli, Chennasandiram and Achchamangalam showed Uranium concentration in shallow aquifer. 15 samples showed Uranium concertation beyond permissible limit for deep aquifer (Bore Wells), gram Panchayats viz. Pedatalapalli, M.C.Palli, Kammampalli, Agaram, Kurubarapalli, Beemandapalli, Kuppachiparai, Chennasandiram, Marasandiram, Madhepalli (Gurubarapalli) Kodiapalli, Palepalli, Guruvinayanapalli, Madhepalli (Palepalli). In dug wells, the electrical conductivity ranges between 649- 4610 µS/cm at 25^{o} C with mean value of 1974 µS/cm. The concentration of nitrate ranges from 3 to 74 mg/l with a mean value of 30 mg/l. The concentration of Uranium ranges from 1 to 68 µg/l with an average of 12 µg/l. Whereas in Bore Wells, the electrical conductivity ranges between 860 - 5140 µS/cm at 25^{o} C with mean value of 1883 µS/cm. The concentration of nitrate ranges from 2 to 78 mg/l with a mean value of 32 mg/l. The concentration of Uranium ranges from 1 to 156 µg/l with an average of 23 µg/l.

The present study reveals that the Uranium concentration in ground water in 18 Gram Panchayats from the part of the Krishnagiri district of Tamil Nadu is more than the BIS for drinking water. The village people of 18 GPs are vulnerable to Uranium contamination. Further, it is observed that the higher concentration of the Uranium in ground water is from Northern, North East and North Western part of the study area which is basically Grantic Gnesis complex. The Uranium concentration in ground water collected from the Migmatic Complex is within BIS for drinking water. Study shows that uranium distribution is not homogenous throughout the region, however, spatial distribution graphs reveal that concentration increases towards Northern, North East and North Western direction.

Keywords: *Groundwater, uranium, Krishnagiri district, water chemistry*

DRIP IRRIGATION PROMOTED MIGRATION OF MICROPLASTIC PARTICLES ACROSS VERTICAL SOIL COLUMNS

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The widespread use of plastics has undeniably brought numerous advantages to society**,** facilitating countless advancements in technology, industry, and daily life. However, the proliferation of plastic debris in various environmental systems has become an escalating concern. Among the most insidious forms of plastic pollution are microplastics, which have garnered significant attention due to their ubiquity and potential to harm ecosystems and human health. While research on microplastic contamination has been extensively conducted in aquatic environments, there remains a notable gap in studies focused on terrestrial ecosystems, particularly soils. This disparity is concerning, as microplastic pollution is an increasingly severe issue with far-reaching implications, including its presence in the human body, where it has been linked to adverse health effects such as immune response dysregulation and neurotoxicity.

Recognizing this pressing issue, our research has undertaken an experimental investigation to study the transport behavior of microplastics within soil matrices. Specifically, we focus on Nile red-stained microplastic particles, sized between 35 to 40 microns, as tracers to understand their migration patterns. This study employs vertical soil columns as experimental setups, designed to mimic natural subsurface conditions. Each soil column has a depth of 30.5 cm and is packed with carefully prepared soil types to replicate varying real-world scenarios. By using artificial drip irrigation systems to simulate rainfall or water infiltration, we aim to elucidate the mechanisms by which microplastics are transported through soil systems, potentially leaching into underlying groundwater reservoirs.The primary objective of the study is to systematically investigate the factors influencing the downward movement of microplastics in different soil types. The influence of several variables on microplastic transport was examined, including variations in soil pH, organic matter content, fulvic acid concentration, and drip irrigation intensity. These parameters were chosen because of their potential to alter the physicochemical properties of the soil environment, thereby affecting the mobility of microplastics.

To begin the experiments, vertical soil columns were packed with either fluvial sand or gravel soil. The soil was pre-conditioned to achieve specific pH levels and organic matter contents, ensuring controlled and reproducible conditions across trials. Microplastic particles stained with Nile red dye were introduced at the top of the soil column along with water droplets, mimicking natural infiltration processes under varying drip irrigation intensities. The simulated irrigation allowed for precise control over water volume and flow rate, enabling us to observe how the changes in hydrodynamic conditions affect the transport and retention of microplastics within the soil matrix.The effluent from the outlet at the bottom of the soil column was collected at regular intervals to quantify the number of microplastic particles that had traversed the column. These collected samples were then subjected to analysis under a fluorescent microscope, which enabled accurate detection and quantification of the microplastic particles. By examining the concentration and distribution of particles in the effluent, we developed correlations to determine how factors such as soil composition, chemical properties, and water flow influence the movement of these contaminants through porous media.

Our findings suggest that the transport behavior of microplastics is strongly influenced by the interplay between soil properties and hydrological conditions. For instance, soils with higher organic matter content exhibited increased retention of microplastics, likely due to enhanced adsorption facilitated by the interaction between the microplastics and organic molecules. Similarly, variations in pH were observed to affect the surface charge of both the soil particles and the microplastics, thereby influencing their mobility. Fulvic acid, a naturally occurring component of soil organic matter, played a critical role in altering the transport dynamics by potentially modifying the soil's porosity and particle aggregation characteristics. The study also highlighted the impact of drip irrigation intensity on microplastic migration. Higher flow rates were found to promote greater transport of microplastics, as the increased water velocity reduced the residence time of particles within the soil and minimized opportunities for retention or adsorption. Conversely, lower flow rates allowed for more pronounced interactions between the microplastics and the soil matrix, leading to increased retention. These insights provide a clearer understanding of the factors that govern the movement of microplastics in terrestrial environments. Importantly, they underscore the potential risks associated with microplastic contamination in soil, as these particles could migrate downward and contaminate groundwater resources—a critical concern for both environmental and human health. The results of this research also have broader implications for the development of mitigation strategies aimed at minimizing microplastic pollution in soils. By identifying the key parameters that influence microplastic mobility, it may be possible to design interventions or soil amendments that enhance the retention of these particles, preventing their further spread into the subsurface environment.

In conclusion, our experimental study represents a significant step forward in understanding the transport phenomena of microplastics in soil systems. By using Nile red-stained microplastics as tracers and employing meticulously designed soil column experiments, we have been able to systematically investigate the effects of various soil properties and hydrological conditions on the movement of these particles. The findings provide valuable insights into the complex interactions between microplastics and soil environments, paving the way for future research and practical applications aimed at addressing the growing challenge of microplastic pollution in terrestrial ecosystems. As the threat of microplastic contamination continues to rise, studies like ours are critical to advancing scientific knowledge and informing policies that promote sustainable environmental management.

Keywords: *Microplastics, soil column transport, drip irrigation, contaminant transport, porous media*

FLUORESCENCE-BASED DETECTION OF MICROPLASTICS: ADVANCING RAPID AND RELIABLE WATER QUALITY MONITORING

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Microplastics are small plastic particles less than 5 mm in size, that have caused significant environmental concern, due to their widespread presence and persistence in different ecosystems. This study aims to optimize methodologies for the detection and quantification of microplastics using Nile Red as a fluorescent dye. Nile Red is a lipophilic stain that is widely used in the detection of microplastics. The principle behind this detection technique is to fix the stain onto the microplastics, followed by extraction and destaining to analyze the fluorescence intensity using a fluorescence spectrophotometer. The rapid detection of contaminants, including microplastics, in aquatic environments is crucial for effective water quality monitoring and public health and hygiene. Conventional analytical methods are often tedious and demand complex sample extraction and isolation. Such conditions limit their feasibility for large-scale and real-time applications. Rapid detection methods like fluorescence spectroscopy, provide significant precedence over conventional methods, by allowing quick response times. This enables faster decision-making and implementation of mitigation strategies. Contaminant hotspots can be identified and water quality trends can be actively monitored with the aid of such rapid detection. Thus, ensuring that interventions can be carried out before contaminants impose greater risk to the environment and human health. This study compares the effectiveness of detection methods for microplastics like Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, Scanning Electron Microscopy (SEM), Pyrolytic gas chromatography/ mass spectroscopy (Py GC/MS), with fluorescence spectroscopy. While each technique has its advantages, fluorescence microscopy stands out for its rapid and cost-effective screening capabilities. However, challenges such as potential staining of organic particles and required sample preparation were noted as limitations.

Our research detected several types of microplastics namely, polyethylene terephthalate (PET), polystyrene (PS), polypropylene (PP), and polyvinyl chloride (PVC). Stain fixation tests were conducted to assess the binding efficacy of Nile red over different durations (1, 5, and 10 days). The results indicated that the dye adhered effectively to the microplastic surface for extended periods. This enabled robust visualization and analysis of the microplastic particles. Images with the fluorescence microscope reproduced distinct images which confirmed the stability dye-plastic interaction. The control set included staining without microplastics. The dissipation of the fluorescence was also analysed by exposing the samples to UV light under various conditions.

Fluorescence spectroscopic analysis was conducted after de-staining, at excitation wavelength 560 nm, while the emission intensity was recorded. The quantum yield of the setup was also assayed to understand the photophysical properties. Principal Component Analysis (PCA) was used to analyse the correlation between microplastic type and concentration. Inference from the biplot suggests that PE and PET were closely associated, as were PP and PVC. Thus, similarities in fluorescence intensity and concentration profiles were established. Concentration was positively correlated with the type of plastic, affirming the reproducibility of fluorescence spectrophotometry for quantitative analysis.Visual images were acquired with a Scanning Electron Microscope, for gaining additional insights into the surface characteristics of different microplastics. PP displayed a smooth surface with sharp edges and a hard texture, while PE exhibited a rough surface with uneven edges and a softer texture. These observations align with the fluorescence intensity data, where variations in surface morphology possibly influenced the dye absorption and emission pattern.This study highlights the effectiveness of Nile Red as a multifaceted fluorescent dye for the rapid detection of microplastics. This feature hence enables enhanced water quality monitoring. The strong correlation between concentration and fluorescence intensity strengthens the reliability of the method. The PCA analysis corroborated with the consistency of fluorescence data across different microplastic types, confirming the reproducibility for rapid screening and detection.

The future scope involves exploring different factors, like the influence of various environmental matrices and microplastic shapes on dye fixation and detection. Method standardization for different size ranges and optimizing conditions like time, temperature, and concentration will be crucial for wider application. Currently, this method supports the detection of particle sizes greater than 75 microns. Further research can enhance this method for the detection of smaller microplastics and reduce sample preparation efforts. This study contributes to the development of efficient, scalable methodologies for the detection and analysis of microplastics using fluorescence spectrophotometry. It paves the way for more extensive environmental monitoring and a deeper understanding of microplastic distribution and behaviour in various ecosystems.

Keywords: *Nile Red, polyvinyl chloride, polyethylene, polypropylene, polystyrene, principal component analysis*

GEOCHEMICAL AND HYDROCHEMICAL EVALUATION OF GROUNDWATER IN SEMI-ARID PHALTAN AREA, SATARA DISTRICT, MAHARASHTRA, INDIA: IMPLICATIONS FOR POTABLE WATER AND AGRICULTURAL USE

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This study examines the hydrochemical characteristics of groundwater in the Phaltan area of Satara district, Maharashtra, and evaluates its suitability for drinking and irrigation. The region, situated on basaltic lava flows, experiences a semi-arid climate with limited water resources. Groundwater, as the primary source of potable water, is heavily reliant on irregular and sparse rainfall. Factors such as recharge, atmospheric precipitation, surface water, and subsurface geochemical processes significantly influence groundwater quality. Ninety-one groundwater samples from dug and bore wells were collected and analyzed to assess geochemical variations and overall water quality.

Hydrochemical analysis was combined with GIS-based Inverse Distance Weighting (IDW) to study spatial variations in groundwater quality. The chemical analysis followed standard procedures outlined by the American Public Health Association (2002) and Trivedi and Goel (1984). Key chemical parameters analyzed include pH, electrical conductivity (EC), total dissolved solids (TDS), total alkalinity (TA) as $CaCO_3$, total hardness (TH) as $CaCO_3$, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), and fluoride (F^-). On-site measurements for pH, EC, and TDS were conducted using handheld analysis kits. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) concentrations were determined through acid titration, while total hardness, calcium, and magnesium were analyzed using standard EDTA titration methods. Chloride (Cl^-) was measured by $AgNO_3$ titration, and sodium and potassium were determined using a flame photometer. Sulfate was analyzed using the $BaCl_3$ method with a spectrophotometer, while nitrate levels were assessed using the cadmium column reduction method. All chemical parameters, except for pH and EC, are expressed in milligrams per liter (mg/L), milliequivalents per liter (meq/L), and millimoles per liter (mol/L). The pH is expressed in units, and EC is in micromhos per centimeter (µS/cm) at 25°C. Ion balance errors were within the acceptable range of ±5%, as recommended by Domenico and Schwartz (1990).

Geochemical data were presented using graphical charts such as the US Salinity diagram and Wilcox salinity diagram to assess groundwater suitability for irrigation. Groundwater samples were classified based on sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and sodium percentage. Graphical representations including the US Salinity, Durov, Piper trilinear, Wilcox, and Gibbs plots were utilized to understand factors influencing groundwater chemistry. The study revealed that some groundwater samples exceeded the desirable limits for total dissolved solids (40%), total hardness (80%), calcium (15%), magnesium (31%), Fluoride (14%), and Iron (7%). However, all samples remained within permissible limits except for EC. Chloride, sodium, calcium, and bicarbonate were identified as the dominant ions in the groundwater. From the Piper trilinear diagram, it is apparent that majority of the samples (60%) belong to Ca2+-Mg2+-Cl--SO42- demonstrating the dominance of alkaline earths over alkali (viz., Ca+Mg > Na+K) and weak acidic anions over strong acidic anions (i.e., HCO3 > Cl+SO4). The hydrochemical facies were primarily of mixed Ca-HCO_3, Na-HCO_3 and Mg-HCO_3 types, with some samples representing Ca-Cl and Na-Cl types, indicating fresh recharged water. Hydrochemical facies predominantly belonged to mixed Ca-Mg-Cl and Na-Cl types, with some samples showing fresh recharged Ca-HCO_3 type groundwater. The US Salinity Laboratory and Wilcox diagrams also suggested that some samples fell into irrigation zones (C4S2) that may not be ideal for crop growth. In terms of drinking water suitability, 31.9 % of samples were found to be excellent while 6.6% of samples were found to be unsuitable according to the Water Quality Index (WQI), with some exceeding the permissible limits set by WHO and ISI standards. The Gibbs diagram indicated that rock-water interactions were the dominant factor affecting water quality in the region. The chemistry of groundwater is largely rock dominated. The suitability of groundwater for irrigation was assessed using agricultural indices, including Sodium Adsorption Ratio (SAR), Sodium Percent (Na%), Kelly's Ratio (KR), Residual Sodium Carbonate (RSC), Residual Sodium Bicarbonate (RSBC), Magnesium Hazard (MH), Corrosivity Ratio (CR), and Permeability Index (PI). The results indicated that most samples were suitable for irrigation, although 37% were classified as potentially harmful due to high magnesium content, and 35% were deemed unsuitable based on Kelly's ratio due to excess sodium. Overall, the study suggests that groundwater quality in study area is generally good, suitable for both drinking and irrigation, with a few exceptions. To ensure sustainable water quality, it is critical to manage groundwater use, reduce over-exploitation, enhance rainwater harvesting, and monitor the impact of urbanization. Further research in other basaltic regions of Maharashtra is recommended to provide a comprehensive assessment of groundwater quality across the southeast Deccan Volcanic Province. This study offers valuable insights into groundwater quality management and supports the development of strategies for sustainable water use in the region.

Keywords: *Hydrochemical characterization, hydrochemical facies, groundwater suitability, rock-water interactions, Kelly's ratio*

POLYCYCLIC AROMATIC HYDROCARBONS IN SURFACE AND GROUNDWATER: DISTRIBUTION, HEALTH RISK AND MANAGEMENT

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Polycyclic Aromatic Hydrocarbons (PAHs) are persistent organic pollutants characterized by multiple fused aromatic rings, known for their persistence, toxicity, and hydrophobic nature. Their occurrence in surface and groundwater systems has raised global concerns due to their toxic, mutagenic, and carcinogenic properties. Rapid industrialization, urbanization, and an increase in vehicular emissions have intensified PAH contamination, posing significant risks to environmental and public health. PAHs enter water bodies primarily through atmospheric deposition, wildfires, industrial discharges, urban runoff, and improper waste management. Their distribution in surface and groundwater is influenced by factors such as the source of contamination, hydrological conditions, seasonal variations, and the physicochemical properties of the water body. The hydrophobic nature of PAHs leads to their strong affinity for sediments, resulting in long-term contamination of aquatic systems, particularly in regions with inadequate wastewater treatment infrastructure, leading to widespread ecological and public health concerns. This review paper presents a comprehensive analysis of PAH distribution, estimation, health effects, and management. Furthermore, the paper aligns with the United Nations Sustainable Development Goals (SDGs), particularly Goal 6: Clean Water and Sanitation and Goal 3: Good Health and Well-being.

The levels of PAH contamination, with urban and industrial zones exhibiting significantly higher concentrations than rural or remote areas. Major river systems, including the Ganges and Yamuna, have been identified as hotspots for PAH pollution due to extensive anthropogenic activities. Groundwater contamination is a growing concern in regions where PAHs leach into aquifers from contaminated soils and surface sources. Seasonal variations, particularly during monsoons, exacerbate the problem by increasing runoff and sediment transport, leading to elevated PAH levels in water bodies. Advanced analytical techniques such as Gas Chromatography-Mass Spectrometry (GC-MS) and High-Performance Liquid Chromatography (HPLC) are widely employed for PAH detection due to their high sensitivity and selectivity. These methods are often complemented by sample preparation techniques like solid-phase extraction (SPE) and liquid-liquid extraction to enhance accuracy. Recent developments in sensor technology and nanomaterials have improved the real-time detection of PAHs at ultra-low concentrations, making them promising tools for environmental monitoring.

The toxic effects of PAHs on human health are well-documented, with chronic exposure linked to cancer, respiratory ailments, immune dysfunction, cardiovascular diseases, endocrine disruption, and developmental disorders. PAHs such as benzo[a]pyrene, is a potent carcinogen. Human exposure occurs through direct consumption of contaminated water, dermal contact, and bioaccumulation in the food chain. Aquatic organisms exposed to PAHs accumulate these compounds in their tissues, leading to biomagnification across the food chain. This not only disrupts aquatic ecosystems but also increases human exposure through the consumption of contaminated water and seafood. Epidemiological studies in India have highlighted the prevalence of waterborne diseases and health disorders in communities exposed to polluted water sources, emphasizing the urgent need for effective PAH management and mitigation measures.

Effective management of PAHs in aquatic environments requires integrated strategies combining prevention, remediation, and policy interventions. Preventive measures include adopting cleaner combustion technologies, implementing stricter regulations for industrial discharges, and promoting sustainable agricultural practices to reduce runoff contamination. Remediation techniques have advanced significantly in recent years, ranging from physical removal methods to chemical treatments such as advanced oxidation processes (AOPs) and biological approaches like bioremediation. The use of PAH-degrading microorganisms offers a cost-effective and environmentally friendly solution, particularly for large-scale contamination in resource-limited settings. Monitoring programs play a crucial role in tracking PAH distribution and assessing risks, with geographic information systems (GIS) and remote sensing technologies enabling real-time data analysis. Effective collaboration among government, academia, and industry is crucial for developing sustainable water management practices that will protect water resources, and public health, ensuring a cleaner, healthier, and sustainable environment for present and future generations.

Keywords: *PAHs, groundwater, health risks, environmental pollution, water quality, sustainable water management*

COMPARATIVE HYDRO-GEOCHEMICAL ASSESSMENT OF SHALLOW TUBEWELL IN PARTS OF NORTH AND SOUTH BANK PLAIN OF BRAHMAPUTRA

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This study evaluates the suitability of groundwater for drinking as well as irrigation in two regions of Assam: Dalgaon-Sialmari block in Darrang district and the Mayong block in Morigaon district. In these areas, groundwater is the primary source for drinking and irrigation, especially in regions where vegetable cultivation relies heavily on agrochemicals, In Dalgaon-Sialmari, 40 groundwater samples were randomly collected from 10 Gaon Panchayats, while in Mayong, 48 samples were collected during the pre-monsoon season in 2024.For drinking water, parameters such as pH, total dissolved solids (TDS), and heavy metal concentrations were assessed against BIS 10500:2012 and WHO. For irrigation, considerations included Sodium Absorption Ratio (SAR), Sodium Ratio (Na%), Residual Sodium Carbonate (RSC), Kelly's Index (KI) and Permeability Index (PI) to determine the water's potential impact on soil structure and crop health. These were assessed against standards such as Food and Agriculture Organization (FAO) standards. The hydrogeochemical characterization of groundwater was conducted using multiple graphical representations such as Piper, Schoeller, Durov, Radial plots, Wilcox and Gibb's diagram. These tools facilitated the identification of dominant hydrogeochemical facies and inter- ionic relationships, offering insights into the underlying geochemical processes influencing water quality variability. Spatial distribution maps were developed using Geographic Information System (GIS) technology, provide a visual representation of groundwater quality variations across the study area. These maps help in illustrating the variation in groundwater quality across the study area. The findings reveal localized contamination in certain areas of the study region, where specific parameters exceed permissible limits set for safe human consumption and agricultural use. This underscores the necessity for continuous monitoring to effectively manage and enhance groundwater quality in these identified zones. There was no significant nitrate contaminations observed in both the study areas, despite increased use of nitrogenous fertilizers which may be due to high dilution effect of rainwater, surface runoff, soil compaction, etc. This study concluded by evaluating groundwater quality against standards, highlighting its suitability for intended uses and identifying potential concerns.

Keywords: *Groundwater contamination, water qualiy index, physiochemical parameters, hydrogeochemical processes*

HYDRO-GEOCHEMICAL APPRAISAL OF GROUNDWATER IN BOLOGARH BLOCK OF KHURDA DISTRICT, ODISHA, INDIA

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Bologarh Block of Khurda District located in the central-eastern region of Odisha comprising of 234 sq.km of area. The major part of the block occupied by hard rock formation with moderate to very low yield. This block is categorized as semi-critical from ground water extraction point of view, with an extraction rate exceeding 70% and characterized by water scarcity, which significantly impacts the quality of life of local population. Additionally, there are areas within these blocks that suffer from fluoride contamination in groundwater. The blocks are geologically underlain by hard rock formations of the Eastern Ghats, including Khondalite, Charnockite, and Granites/Granite gneiss with limited ground water potential. The problem of groundwater in this block has a substantial impact on the inhabitants of the area. This work is, therefore, designed to recognize various hydrogeochemical processes responsible for the modification of water chemistry and to assess the drinking and irrigational water quality with a view to establishing its safety in the Bologarh Block of Khurda district, Odisha.

The ground water samples collected from 59 nos. of dug wells and 30 nos. of tubewells from different locations throughout entire Bologarh Block in two seasons i.e. premonsoon and postmonsoon. To understand the various geochemical processes and suitability for various purposes, the groundwater quality is examined by the physico chemical parameters during the both seasons (pre & post monsoon). The major cation and anion content, changes in the cation and anion composition of groundwater, as well as their shifts, are used to identify variations in hydro chemical characteristics. The analyzed results are plotted in the Piper Diagram which illustrates the variations in hydro chemical characteristics during the pre and post monsoon seasons. The variation in the ground water chemistry is affected by the different natural processes like rock–water interaction, evaporation, and precipitation. Also, the plot of the analyzed data on Gibbs diagram is used to explaining the natural mechanism affecting the groundwater chemistry in the study area, identifying rock weathering (rock–water interaction) as the predominant process responsible for changes in groundwater chemistry. The impact of the weathering processes on groundwater chemistry and identification of possible sources of major ions in groundwater depend on the correlation between cation and anions. Scatter plots of different cation and anion like Na+ and Cl−, Ca^{2+} and SO_4^{2-}, and Ca^{2+} + Mg^{2+} and HCO^{3-} can indicate whether carbonate or silicate weathering is the primary factor affecting groundwater quality. The scatter plot of Ca^{2+} + Mg^{2+} and SO_4^{2-} + HCO^{3-} can indicate whether ion exchange or mineral dissolution is the primary factor affecting groundwater quality.

The results of the physicochemical parameters during in the both seasons suggest changes in hydrochemical characteristics, with major cations being sodium and calcium, and bicarbonate as the dominant anion. These changes are influenced by rock–water interactions, including carbonate and silicate weathering processes, along with cation exchange processes. The groundwater quality for drinking purpose compare with drinking water standards IS 10200:2012. The primary parameters affecting drinking water quality in this study area are

fluoride contamination, followed by hardness. To further asses the drinking groundwater quality suitability, the water quality index (WQI) is calculated. The WQI classification for drinking water quality for the both seasons assigned with to the excellent to poor water classes. This study was performed to understand the impact of groundwater quality on the crop yields and its suitability for the irrigation. The values of, SSP, PI, RSC, KR and TDS show that most of the samples fall under good to suitable category. Wilcox Plot shows groundwater to be within excellent to a good class.

The study reveals that groundwater quality in Bologarh Block is significantly affected by geochemical processes, particularly weathering of minerals in the hard rock formations. Fluoride contamination and hardness are the key challenges for drinking water, while groundwater quality for irrigation is largely within acceptable limits. The seasonal variations in water chemistry emphasize the importance of monitoring both pre- and post-monsoon conditions to manage water resources effectively. The dilution in fluoride contamination is observed in some of the groundwater samples from few locations during post monsoon. These findings are crucial for developing strategies to address water scarcity and contamination issues, ensuring sustainable water use in the region for both domestic and agricultural needs. Thus, a sustainable management plan is prepared to mitigate the vulnerability zone of ground water. Alternate source for drinking water supply has also been suggested. The different measures of intervention such as nala-bandh on the ephemeral stream, percolation tank and check dam have also been suggested for sustainability of Ground water resources of the Block.

Keyword: Groundwater, contamination, cation exchange, rock weathering, sustainability

COMPREHENSIVE GROUNDWATER QUALITY ANALYSIS IN PUNJAB STATE, INDIA

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The analysis draws upon data from 242 groundwater monitoring stations (GWMS) across Punjab, consisting of 85 bore wells and 157 dug wells, collected during the pre-monsoon period of May 2022. These monitoring stations are strategically distributed across the state, which is known for its extensive dependence on groundwater for agricultural irrigation, industrial activities, and drinking water. The groundwater samples were collected with careful consideration of local hydrogeological conditions, and the samples underwent comprehensive chemical analysis using standard methods. The parameters analyzed included pH, temperature, electrical conductivity (EC), TDS, hardness, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, chloride, sulphate, and other elements that are critical for understanding groundwater chemistry. Sodium Adsorption Ratio (SAR) was also calculated to assess the suitability of water for irrigation purposes.

The results indicate significant spatial variability in groundwater quality across the state, highlighting both areas of concern and regions with acceptable water quality. The pH values of groundwater in most regions are found to be slightly to moderately alkaline, which is suitable for most uses. However, salinity levels, measured by electrical conductivity (EC), show considerable variation, with some areas exhibiting high salinity, rendering the water unsuitable for drinking and irrigation. Groundwater in the northern parts of Punjab is generally of desirable quality, whereas the central parts of the state exhibit mostly permissible quality water. The southern and southwestern regions, however, are characterized by predominantly saline groundwater, making it unfit for consumption and agricultural use. Calcium levels across the state are typically low, while magnesium concentrations are elevated in certain areas, affecting the water's hardness and quality. Sodium concentrations, in particular, are high in several districts, impacting both water and soil health. Potassium concentrations tend to be low in most regions, although they may be elevated in specific areas. The chloride and sulphate levels also exhibit considerable variation, with certain regions showing values above the permissible limits, which compromises the water quality. Additionally, arsenic contamination, although localized, exceeds the permissible limits in parts of Ferozepur, posing significant health risks to local populations. Nitrate contamination is particularly problematic in the southern and southwestern districts, with nitrate levels often surpassing acceptable limits, primarily due to the overuse of fertilizers and agricultural runoff. Fluoride levels, while mostly within acceptable limits, show localized exceedances, which require attention in specific regions.

The primary sources of groundwater contamination in Punjab can be attributed to both anthropogenic activities and natural factors. The over-extraction of groundwater for agricultural irrigation and industrial use has led to significant depletion of aquifers, exacerbating the challenges of maintaining water quality. The intensive use of fertilizers and pesticides in agriculture has contributed to the increase in nitrate levels, making the groundwater unsuitable for drinking and irrigation. In addition, untreated or inadequately treated industrial discharges are a significant source of contamination, contributing to the presence of harmful chemicals in groundwater. Poor waste management practices, including improper disposal of solid and liquid wastes, further exacerbate the contamination of groundwater resources. Over-extraction has also caused saline water intrusion in certain regions, especially in the southern parts of the state, where the aquifers are more prone to salinization. Natural factors, such as geological conditions, contribute to elevated levels of arsenic and fluoride in certain pockets of Punjab. Inefficient irrigation practices, including flood irrigation, lead to excessive runoff and waterlogging, which further exacerbates salinity issues. Moreover, inadequate drainage systems result in waterlogging, which increases the risks of contamination and further deteriorates water quality. Climate change, with its potential to alter rainfall patterns and affect groundwater recharge, adds an additional layer of complexity to groundwater quality management. Reduced rainfall and erratic monsoon patterns may impact groundwater recharge, leading to lower water levels and a greater concentration of contaminants. This highlights the urgent need for proactive and sustainable water management practices to safeguard the quality of groundwater resources in the region.

The findings of this study underscore the importance of implementing targeted measures to address groundwater quality issues in Punjab. Based on the analysis, several key recommendations are proposed. First, there is an urgent need to enhance groundwater monitoring systems by establishing a continuous and robust framework for monitoring key water quality parameters. This would allow for early detection of contamination trends and enable timely interventions. Second, improving waste management practices, especially in industrial and agricultural sectors, is essential to minimize the impact of agricultural runoff and industrial discharges on groundwater. Regulating the use of fertilizers and pesticides will help control the levels of nitrates and salinity in groundwater, thus reducing the adverse effects on water quality. Upgrading irrigation methods, such as adopting drip irrigation and sprinkler systems, can minimize water wastage and help prevent salinity buildup. Public awareness campaigns aimed at educating local communities on the importance of groundwater conservation and sustainable water practices are essential for promoting long-term water quality improvements.

To mitigate the adverse effects of contamination, the development of groundwater recharge strategies, including rainwater harvesting and artificial recharge, should be prioritized to replenish aquifers and enhance water quality. Addressing specific contaminants such as arsenic and fluoride will require the establishment of treatment facilities in affected regions. Additionally, research on advanced water treatment technologies and sustainable water management practices should be promoted to address emerging challenges. Finally, comprehensive policies and regulations should be developed and enforced to ensure the sustainable use and management of groundwater resources for future generations.

Keywords: *Groundwater quality, chemical parameters, pH, TDS, nitrates, heavy metals, salinity, contamination, sustainable management*

HYDRO-FRACTURING THE UNCONVENTIONAL HYDROCARBON RESERVOIR ROCKS LIKE SHALE AND ITS IMPACT ON GROUND WATER

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The demand of conventional hydrocarbon (HC) is steadily decreasing in recent years as the oil-gas production rate, due to overall worldwide depletion of reserves, falling reservoir pressure and hydrocarbon recovery factor, has become less in most of the existing reservoirs. Hence, the industry slowly but steadily started leaning towards unconventional energy sources such as shale and similar tight rocks. Exploitation of shale gas & oil started in USA in 1821 and the development began in 1914. However, the ventures were not economically viable till Mitchell Energy introduced dual technology of horizontal drilling (HD) of wells followed by hydro-fracturing (HF) in order to enhance production considerably and economically in 2007-'08. HF became the key factor in this Shale Revolution which made US, world's highest producer of oil & gas wherein shale oil contributed 65% and shale gas 78% of the total production. HF is water intensive, as every well requires an average 6-7 million (MM) of freshwater. The post HF flowback and produced water (FPW), is highly toxic (may be carcinogenic too) and should not be allowed to contaminate groundwater and environment. Another issue is water should be efficiently used for HF so that the neighourhood aquifers need to be safeguarded from overuse.

Although during oil-gas exploration earlier, many wells were drilled in Shale, they were never economically viable because shale being a poorly permeable to impermeable rock, always had very poor production rate. It was only 2007-08 onwards when Mitchell energy came out with a unique dual technology which was proved to become successful of enhancing production with economic viability. This combined methodology included HD followed by HF and instantly became a game changer with a cheaper lifting cost. With the advent of dual technology, drilling of shale oil-gas wells started increasing in USA and in many other countries, including Canada, India, China, Russia. Every well started enhancing their production by applying HF technology. USA has become the highest producer of oil and gas in the whole world, six years in a row, because of substantial contribution from shale oil (about 2/3rd of total oil production) and gas (about 3/4th of overall gas production). However, HD and HF applications involve two challenges, one is requirement of huge quantity of freshwater of about 2-16 million gallons of water with an average being 6 million gallons for a HF well. The average for India is also 6 MM gallons. Use of so much freshwater causes a depletion of groundwater resource in the area around the oil-gas field which becomes very challenging in arid or semi-arid area. Research and field applications are on as to how to prevent this colossal wastage or overuse of so much freshwater and whether a true replacement of freshwater can be found.

It can easily be imagined that if so, much freshwater is required to HF a well, the postfrac return, which is nearly 75-80% of water used in making the fracturing fluid or slickwater, contributes a huge volume of Flowback and Produced water (FPW), that needs to be taken care of. Remaining volume of 15-20% is consumed by the bedrock or formation. The other challenge is how to safely deal or dispose of the postfrac FPW which includes toxic chemicals. The chemicals are of undisclosed composition as well-operators or HF-companies do not mention most of them under an agreement between companies and the government.

In the last 15-16 years, the success stories of shale gas/oil have been reported and published in many documents, including books, scientific papers from journals, government reports, monographs, policy documents. They originated from USA, Canada, India and many other countries. All such documents are downloaded and critically studied. Moreover, the 1st author has worked for nearly 20 years in many unconventional oil/gas fields out of his 43 years of experience in overall oil/gas upstream industry. Also, he has been dealing with unconventional energy sector on behalf of the Government of India as Senior Advisor and as Geological Coordinator in a principal National Oil Company of India in between 2005-2006 and 2015-2016. Literature survey and discussion amongst all the authors and interactions were done with the industry people to prepare this paper. During literature survey the following highlighting points have come forward: a) In HD, initially the well is drilled vertically/directionally, and then horizontally (for 1-2 km), followed by HF from the furthest end of the hole and progressed inwards towards the well bore, after getting separated by a number or set of packers. HF is done with slick water or frac-gel, consisting of water, sand and chemicals and hit the formation mostly radially around the bedding plane under very high pressure ranging in between 350-700kg/cm^2, so that the effect becomes maximum; b) LPG (Liquefied Petroleum Gas) fracturing is waterless fracturing, but the method is found to be very costly and unsafe, as there is chance of fire and explosion and so, LPG has to be handled very cautiously; A good number of researches have contributed significantly in the direction of the various methodologies of recycling post HF FPW and reusing them in various sectors including HC industry; d) Recycling process needs to be techno-economically viable as the treatment process and costs vary.

Various applications by the industries and research could not indicate any techno-economically viable substitution of hydro-fracturing the shale without water to safeguard the freshwater overuse and wastage. Also, the effluents including the post frac FPW are to be disposed of in effluent disposal wells which are generally going upto a depth of 1000-1200 m. In USA, through research it has been found that the effluents, injected into deep wells create cracks and fractures due to low scale seismicity induced by the effluents under high pressure and contaminate groundwater by leaking and leaching into formation or bedrocks. So, no deep disposal as per current US regulations for the effluent water including FPW in deep wells. These effluents need to be handed over to a government approved third party who will do recycling of the effluents at designated plants after collection from the operators and return the treated water after Recycling for Reuse as a replacement of freshwater in drilling, water injection or HF job in the nearby wells and fields. The surplus water is made available for irrigation, transportation and general cleaning in many sectors. Based upon the present status of knowledge and practice, it is recommended that similar steps are to be taken in India and other countries as practiced in USA. Sufficient Research & Field application are required, so that the FPW/effluents with bad chemicals needs to be de-toxified, neutralized and softened. This way, the FPW/effluent water after recycling if used in the oil/gas upstream industry can minimize or completely replace the huge volume of freshwater requirement and the need of effluent disposal will also not arise.

Keywords: *Shale-oil/gas, hydro-fracturing, horizontal drilling, FPW-Effluents, recycle-reuse*

FRESHWATER RESOURCES UNDER MICROPLASTICS SIEGE: A GLANCE AT ASIA

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Global plastic production has experienced a dramatic increase since the beginning of the 21st century, reaching approximately 413.8 million tons (MT) in 2023. Despite the staggering production volume, only 36 MT was derived from post-consumer recycling, highlighting significant inefficiencies in global waste management and recycling practices. Asia, with a population of 4.8 billion, is responsible for nearly 60% of the world's plastic production, underscoring the region's critical role in plastic consumption and waste generation. More than half of ocean plastic dumps are contributed by 5 Asian countries: China, Indonesia, Philippines, Thailand, and Vietnam. Plastics have become integral to modern life due to their durability, flexibility, and weight. They have largely replaced traditional materials such as metals and wood across various applications, driven by their functionality, versatility, and cost-effectiveness. However, the rapid urbanization and population growth in many regions have increased plastic usage. Most of the used plastic ends up in the environment as waste due to improper and decentralized waste management practices and human behavior. This accumulation poses significant environmental concerns, contributing to various social and ecological issues.

Plastics undergo further disintegration and degradation due to various physical, chemical, and biological processes in the environment and small-size (<5mm) particles are formed, which are popularly known as micro-plastics. These particles are called secondary microplastics, while primary microplastics are manufactured for various applications. As per the literature survey, it is being reported that microplastics (MPs) are being detected in the environment, but their versatility and omnipresence make source identification very challenging. MPs are present in the air, water and soil. Microplastics are particularly problematic in aquatic environments. According to a study of 2017, globally rivers transport around 1.15 to 2.41 million tons of plastic waste to oceans every year. MPs are frequently found in oceans and landfills where larger plastic debris disintegrates into smaller particles. The landfills and wastewater contain both primary and secondary MPs. The use of plastic equipment and materials, fertilizers, and pesticides in agriculture contributes to the MPs in the agricultural soil, which are subsequently mobilized by surface runoff during rainy season and irrigation period while some particles find their way to deeper soil layers due to infiltration. MPs in surface water bodies are well known and are being reported by various workers in surface water, including lakes, ponds and flowing rivers and sea water. The highest concentration of MPs in river water is about 5,00,000 particles/m^3, reported in the Saigon River of Vietnam. This river passes through Ho Chi Minh City, which is the most populous city in Vietnam. In addition to surface water, MPs are now being reported and identified in the groundwater at various water levels in different geological environs.

It is found that MPs concentration is more in and around highly populated city centers where high numbers of anthropogenic activities are reported. The comparison and analysis of data from different studies pose a challenge due to variations in the methods and protocols of sampling, sample volume, their pretreatment, handling, the observed size range of MPs, and tools used for quantitative and qualitative analysis. Quality control practices during the procedure also affect their concentration, which is missing in some studies. Microplastics variation in size, shape, composition, density, attachment and detachment tendency, interaction with other organic and inorganic pollutants, and heterogeneous subsurface properties make them a complex entity to model their transport. This leads to a challenge for scientists and academicians involved in developing suitable transport models for microplastics in the groundwater in different geological environs.

Among Asian countries, China is at the forefront of research into microplastics in groundwater systems, followed by India and South Korea. However, comprehensive data on microplastics concentrations from countries like Thailand and Indonesia remain less reported despite their significant contributions to global plastic pollution. China reported an alarming concentration of MPs in groundwater, 6832 particles/L. It is reported around Rizhao City of Shandong Province, located in the northeast coastal area of North China. The concentration of MPs in groundwater India reported 0-80 particles/L, Indonesia about 236 particles/L from groundwater wells of Jakarta Megacity While, South Korea, Thailand, and Iran reported relatively lesser concentrations. Despite growing awareness of microplastic pollution's implications for environmental health and human safety, significant research gaps open the opportunity to carry out study on MPs in GW. The migration of MPs in groundwater from surface water and soil/rock interactions needs to be studied. The escalating issue of microplastics pollution necessitates urgent action from governments and researchers. Enhanced waste management strategies are crucial to mitigate plastic pollution's impact on ecosystems and human health. Furthermore, establishing standardized research protocols will facilitate a better understanding and comparison of microplastics contamination across different geological environs. As the global community grapples with the consequences of rampant plastic production and waste mismanagement, addressing the challenges posed by microplastics must be prioritized to safeguard environmental integrity and public health moving forward.

Keywords: *Waste management, pollution, microplastics, freshwater, groundwater, transport modelling*

Cr(VI) TRANSPORT MODELING IN MODIFIED TOTHIAN BASIN IN A TWO-LAYERED AQUIFER SYSTEM

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Groundwater is an extremely vital resource of drinking water in developing countries like India. Therefore, a proper understanding of the relationship between regional groundwater flow and natural subsurface phenomena is extremely vital to analyze several geological processes like contaminant transport, groundwater aging, and groundwater interaction in the hyporheic zone. This research focuses on the impact of hydraulic head distribution developed by analytical and numerical models on the transport characteristics of hexavalent Chromium [Cr(VI)] in the Tothian basin comprising a two-layered aquifer system. Toth (1962) represented the Tothian basin which is basically located in central Alberta of Canada. The tributary of the Red Deer River creates a series of parallel and equally spaced valleys, and water divides over most of the area (Toth 1962).

For estimating hydraulic head distribution, the two-dimensional rectangular flow domain is considered with a steady water table at the top. The water table is assumed to be topography-controlled. Therefore, the water table is a subdued replica of the topography. The water table is considered the regional as well as the local undulation of the topography. The groundwater flow basin is modified with two-layered, anisotropic aquifer systems. The right boundary of the flow domain is the midpoint of the highest water divide of the region, and theoretically, no horizontal flow is involved through this boundary. Therefore, the right boundary of the flow domain is considered as the no flow boundary. The left boundary of the domain is the midpoint of the lowest valley of the basin. Therefore, it is also considered as no flow boundary for the same reason as the right-hand side boundary. The bottom boundary of the domain is impervious rock and therefore, it is also considered as the no flow boundary. At the interface of the two strata in the computational domain, the hydraulic head and the water flux are identical for both layers. The separation of variables method and Fourier series have been used to develop the analytical groundwater model. The proposed analytical solution has been validated with a previously proposed analytical solution for a simplified flow system. Analytical solutions provide a deeper understanding of groundwater flow behavior in comparison to numerical models. Moreover, they conventionally aid in the mathematical representation of water movement in the hydrological system.

This study represents the effect of estimated hydraulic head distribution (analytical and numerical) on the transport characteristics of contaminants. The numerical model is simulated utilizing the COMSOL software, incorporating identical boundary conditions that have been considered in the analytical model. Cr(VI) has been used as a contaminant in this regional transport modeling as Chromium (Cr) has been used extensively in numerous industrial processes, mining, plumbing, gasoline, and tannery industries. Excessive concentration of carcinogenic Cr(VI) poses significant concern in the quality degradation of subsurface groundwater resources in the regional scale. In addition, consumption of groundwater contaminated by excessive concentration of Cr(VI) leads to skin irritation, DNA damage, and the development of cancer, depending on exposure dose, exposure level, and duration. Several mechanisms, including molecular diffusion, advection, and hydrodynamic dispersion, are incorporated into the regional contaminant transport model to investigate the mobilization and retention characteristics of Cr(VI) in the fully saturated aquifer system. The two-dimensional advective dispersive equation incorporating adsorption is utilized in the research work to interpret the transport characteristics of Cr(VI) in the two-layered aquifer system. The contaminant transport model evaluates the impact of anisotropic hydraulic conductivity in the two-layered soil system. The result of the transient Cr(VI) transport model reveals that the contaminant plume reaches the interface of the two layers for the case of the isotropic medium. In addition, the contaminant transport model is simulated for both conditions when the hydraulic conductivity is higher in the top layer and that is higher in the bottom layer. The simulated spatial distribution of Cr(VI) interprets that the advection mechanism plays a crucial role in the migration of Cr(VI) in the zone of low hydraulic conductivity. The retention of carcinogenic Cr(VI) significantly enhances at the interface of two layers where the hydraulic conductivity alters notably.

The simulation result revealed that the chance of quality degradation of groundwater is higher if the source of contaminants exists near the valley bottom of the domain. This study helps to understand the plume migration characteristics of Cr(VI) in the Tothian basin. The simulation result can offer vital information regarding the amount of eluted contaminant mass and the average residence time of the contaminant in the computational domain. Furthermore, a probabilistic human health risk assessment utilizing Monte-Carlo simulation can be performed to provide a realistic scenario of risk assessment for adults and children through the ingestion and dermal exposure of groundwater resources contaminated by Cr(VI). Both carcinogenic and non-carcinogenic risk quotients can be estimated from the breakthrough curves of Cr(VI) using statistical measures. This information is crucial to establish remediation strategies for contaminated groundwater resources in the regional scale to oppose the harmful effects of carcinogenic Cr(VI) on human health.

Keywords: *Regional groundwater flow, Tothian basin, analytical model, carcinogenic Cr(VI)*

HEALTH RISK ASSESSMENT OF FLUORIDE CONTAMINATION IN GROUNDWATER: A CASE STUDY OF ALWAR DISTRICT, RAJASTHAN, INDIA

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Globally, groundwater is a crucial resource for sustaining human life, agricultural production, and industrial requirements. However, the current trends in its utilization are causing a significant decline in both its quality and quantity, posing a serious threat to long-term water security. Furthermore, over-extraction of groundwater due to increasing demand lowers water tables, concentrating geogenic elements and worsening water quality. Additionally, anthropogenic activities like mining and industrial activities worsen the problem by releasing effluents into the environment. These challenges highlight the urgent need for regular monitoring and effective management to protect this vital resource. In view of this, the present study is to assess the groundwater quality and associated health risks in the Alwar District of Rajasthan, focusing on the fluoride contamination that poses significant health challenges. The study aims to evaluate fluoride levels in groundwater across different villages and analyze their impact on various age groups of the local population, who heavily rely on groundwater resources for domestic and agricultural needs. Groundwater quality data from CGWB wells, collected between 2016 and 2021, were analyzed to determine the extent of contamination and identify villages where fluoride concentrations exceed the Health Quotient threshold for safe consumption.

Alwar District, situated in Eastern Rajasthan, is geographically characterized by the presence of the Pre-Cambrian Aravalli hills, which is the dominating topography of the region. The plains in the district are primarily composed of Quaternary alluvium, forming the main aquifer system that supports groundwater availability. The hydrology of the study area is significantly influenced by seasonal rivers i.e., Sabi, Ruparail, Chuhar Sidh, and Landoha originating from Aravalli hills flow in the north-east direction. Since 2019, 9285 habitations across India have been identified as affected by fluoride, out of them 4,349 are in Rajasthan. The National Fluorosis Prevention and Control Programme (NPPCF, 2014) has been implemented in 30 districts of Rajasthan, including Alwar, to tackle this widespread issue (Directorate of Economics and Statistics, 2023-2024). These factors highlight the critical significance of Alwar District as a priority region for addressing the pressing issue of fluoride contamination in groundwater.

The study analyzed groundwater quality data from CGWB borewells across villages in Alwar District, Rajasthan, for the period 2016 to 2021. The number of wells sampled varied each year for the study area. In 2016, data from 42 wells were collected, followed by 32 wells in 2017, 24 in 2018, 19 in 2019, 10 in 2020, and 26 in 2021. These data were analyzed to assess groundwater quality trends. The key health parameter, Health Quotient (HQ) with considering standard Reference Dose (RfD = 0.06 mg/kg/day), was calculated based on the United States Environmental Protection Agency (USEPA, 1993) recommendations. Daily

Water Intake (DWI), Average Lifespan (AL), Exposure Frequency (EF), Mean Body Weight (MBW), and Mean Age Exposure Duration (MEAD) were factored into the risk calculations for each demographic group. The study used standard values for health risk assessment parameters. Daily Water Intake (DWI) was set at 1, 3, and 4 liters per day for children, women, and men, respectively. Average Lifespan (AL) was considered as 12 years for children, 67 years for women, and 64 years for men. Exposure Frequency (EF) was uniformly set at 365 days per year for all groups. Mean Body Weight (MBW) was taken as 15 kg for children, 55 kg for women, and 65 kg for men, while Mean Age Exposure Duration (MEAD) was 4380 days for children, 24455 days for women, and 23360 days for men. A Health Quotient greater than 1 indicates a significant risk of severe health effects, such as dental and skeletal fluorosis. Conversely, an less than 1 is considered within the acceptable limit for non-carcinogenic risk from fluoride in groundwater, as per USEPA (1993) guidelines.

The study revealed significant variations in fluoride concentrations across well locations over the study period. In 2016, out of 42 wells, 37 wells had fluoride concentrations within the desirable limit (≤1 ppm), while 5 wells exceeded the permissible limit (≥1.5 ppm). For 2017, among 32 wells, 27 were within the desirable limit, 2 wells had fluoride levels between 1–1.5 ppm (safe limit), and 3 exceeded 1.5 ppm. In 2018, 22 out of 24 wells fell within the desirable limit, with 2 wells in the 1–1.5 ppm range. For 2019, 16 out of 19 wells were within the desirable limit, 1 well had fluoride levels between 1–1.5 ppm, and 2 exceeded 1.5 ppm. In 2020, 7 out of 10 wells had fluoride concentrations ≤1 ppm, 2 were in the 1–1.5 ppm range, and 1 exceeded 1.5 ppm. For 2021, among 26 wells, 21 had fluoride concentrations ≤1 ppm, 3 were in the 1–1.5 ppm range, and 2 exceeded 1.5 ppm.

The Health Quotient values for children indicated severe health risks (HQ ≥ 1) at 6, 7, 3, 4, 3, and 8 places for the years 2016, 2017, 2018, 2019, 2020, and 2021, respectively. For males, values ≥1 was observed at 5, 4, 2, 2, 3, and 3 places for the respective years, while for females, such values were found at 5, 6, 2, 3, 3, and 7 places for the respective years. The maximum HQ value for children was 3 at Ramgarh in 2021. For women, the highest value was 3.3 in Govindgarh in 2017, and for men, it was 3.7 at the same location and year. The study also indicated that fluoride concentrations tended to increase toward the plain areas, likely due to transport via runoff. Groundwater in the study area was found to be alkaline in nature, dominated by Ca^{2+} and Mg^{2+} ions over SO_4^{2-} and Cl^-. The analysis of the Piper diagram revealed that the groundwater is predominantly of the Ca-Mg-Cl-SO_4 type, typically associated with mineral dissolution from carbonate rocks or agricultural activities that contribute to increased sulfate and chloride levels in soil and groundwater. These findings underscore the need for targeted interventions to mitigate fluoride contamination and protect public health.

Keywords: *Alwar, fluoride, groundwater, health risk assessment, health quotient*

INFLUENCE OF MINERAL WEATHERING SEQUENCE AND ORGANO-MINERAL COMPLEXES ON FATE AND TRANSPORT OF NANOPLASTICS IN RIVERINE AND GROUNDWATER SYSTEMS

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Globally growing plastic production and its mismanagement are significant concerns due to its high durability, versatility, and robustness, leading to massive plastic accumulation in the riverine and subsurface environments. The majority of discarded plastic products in the environment undergo degradation into smaller fragments, i.e., microplastics (MPs, size < 5 mm) and nanoplastics (NPs, size < 1 µm) due to various environmental factors, and find their way across multiple water bodies. NPs, owing to their smaller size, exert a more significant adverse effect on human health and the environment. Surface water carrying NPs can percolate into the subsurface and ultimately reach the aquifer, which might cause groundwater contamination with NPs. Further, NPs can dominantly facilitate the co-transport of other contaminants due to their greater adsorption capacity, posing greater threats to subsurface ecosystems and endangering groundwater resources.

NPs fate and transport in the environment is significantly influenced by existing particulate matter and aqueous chemistry. Detailed investigation of NPs interaction with environmental colloids is of extreme scientific and societal significance. Colloidal mineral particles are omnipresent and often associated with organic matter and form organo-mineral complexes (OMCs) exhibiting different reactivity than their pure mineral phase. Mimicking the natural scenario, we investigated NPs interaction with abundantly occurring ferrihydrite its weathered product i.e., goethite and their corresponding OMCs i.e., organo ferrihydrite (O-Fh) and organo goethite (O-Goe). Our study provides insight into environmentally relevant mineral phases and OMCs impact on the fate and transport of NPs in aqueous and terrestrial environments.

Ferrihydrite, goethite, O-Fh, and O-Goe were synthesized and characterized. Polystyrene latex beads (100 nm, fluorescently labeled) were procured for this study, as a proxy of naturally occurring NPs in the environment. All experiments were performed at pH = 6 and 25°C. Stability studies of NPs (10 mg/L) have been carried out in order to investigate the potential role of minerals/OMCs on aggregation and sedimentation of NPs in suspension using the dynamic light scattering (DLS) technique and UV-Visible spectroscopy. Batch sorption experiments were performed to delineate the kinetics and adsorption capacity of respective minerals/OMCs for NPs. The unidentified concentration of remaining NPs in the supernatant was quantified using a fluorimeter. Further, systematic experiments involving column transport were conducted to understand the transport of NPs in subsurface porous media. Quartz sand was used to mimic the subsurface media, however, in real scenario, granular particles are usually coated with minerals and OMC, which can significantly impact NPs transport in the saturated porous media. Therefore, we performed the comparative transport experiments with bare, mineral, and OMC coated quartz sand and also estimated the role of pore water chemistry on the NPs retention in the column. XRD data revealed that ferrihydrite and O-Fh particles were amorphous and matches with the XRD pattern of two-line ferrihydrite exhibiting two characteristic broad peaks at 2θ of ~ 34° and ~ 63°. While, typical peaks at 2θ = 18°, 21°, 33.2°, 36.7°, 53.2°, and 59.1° corresponds to goethite, with similar peaks observed in O-Goe, suggesting that association of organic matter with minerals couldn't change the overall crystal structure of OMCs. The achievement of the point of zero charge in the presence of goethite at 35 mg/L, however in the presence of Fh, O-Fh, and O-Goe results suggested that overall zeta potential of respective NPs-mineral bimodal system remains negative, suggesting enhanced stability of NPs. Sedimentation kinetics results correlated well with the obtained zeta potential results, suggesting larger hetero-aggregation of goethite+NPs followed by their sedimentation.

Ionic strength (IS) and pH are significant factors influencing NPs interaction with minerals/OMCs in the aqueous system. We found that in all varying IS conditions goethite has shown almost similar maximum NPs adsorption, however, with increasing IS concentrations, O-Goe shown increased NPs adsorption. Similarly, we have seen insignificant change in obtained q_e values for ferrihydrite-NPs at different IS concentrations, however, O-Fh shows increasing NPs adsorption with increasing IS concentrations. In case of OMCs, at lower IS, there was a competition between ions and NPs to bind on the OMCs surface, which could result in partial attachment of NPs. Whereas, at higher IS, self-aggregation of NPs leads to enhanced adsorption on OMCs. Further, results revealed that increasing pH (5-9) of the solution has drastically decreased ferrihydrite sorption capacity with NPs. Whereas, goethite has shown moderate decreased in NPs adsorption with increasing pH of the solution, suggesting goethite-NPs interactions are less susceptible to pH variation of the aqueous systems. Further, OMCs have also exhibited similar trend of decreased NPs adsorption with increasing pH. Hence, acidic and alkaline conditions of aqueous systems can highly impact NPs interactions with minerals/OMCs, and ultimately dictate NPs fate. To represent the real scenario, we conducted sorption experiments in river water. Results revealed that in river water also goethite has shown significantly higher NPs sorption. However, ferrihydrite and OMCs have shown similar limited interaction with NPs in river water, attributing to combined effect of interfering ions and dissolved organic matter. Our experiments in controlled conditions shows good alignment with result in natural water matrices, suggesting this study could be useful to predict fate of NPs in aqueous systems.

Ferrihydrite, goethite and OMCs are abundantly present in subsurface media, they often occur as patches over sand grains which can significantly impact the fate and transport of NPs. Results in RW revealed that, NPs retention in ferrihydrite and goethite-coated quartz sand was higher than their respective OMCs-coated sand, suggesting that pure mineral phase is efficient than OMCs to restrict NPs mobility in subsurface media, and acting as natural filter to protect groundwater aquifer from plastic contamination. This study provides insightful details on the role of pure mineral phase and their respective organo-mineral complexes on NPs fate and transport in aqueous and subsurface environments, emphasizing the mobility of NPs in riverine and groundwater systems.

Keywords: *Nanoplastics, mineral-organic complex, sorption, transport, groundwater*

EVALUATION OF IMPACT OF MINING ON GROUNDWATER QUALITY IN AND AROUND SINGRAULI COALFIELD, INDIA

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The study area, Singrauli coal field region is located in the Singrauli district of Madhya Pradesh and in the Sonbhadra district of Uttar Pradesh state in central India. Singrauli (NCL) is one of the largest coal fields and power complexes (Mini Ratna, Category I) in the world, presently contributing about 16% of India's coal production by large mechanized opencast mines. At present, Indian coal is the most abundant fuel resource, the principal source of energy, and most significant contributor to the country's industrial success. Geologically study area is composed of Gneissic complex, metamorphic rocks and sandstone with clay, ferruginous sandstone, sandstone shale with clay of Lower Gondwana group. Barakar is the only coal bearing formation in which all the coal mines are operating. The Major River draining the area is Rihand, which is a tributary of river Son. Open-cast coal mining processes generate a substantial quantity of solid wastes, such as waste rock debris, heap leach materials caused by overburden disposal, tailings, and liquid wastes from the washing facilities. Coal mining have impacted the natural water quality, quantity, its flow direction and produce environmental, ecological, and geological imbalance.

Acid mine drainage is a serious issue in coal mining area where sulfide-enriched coal is present. Among the various contaminants affecting groundwater quality in which fluoride and nitrate have emerged as two of the most concerning. High levels of fluoride in groundwater can lead to dental and skeletal fluorosis, and Nitrate contamination in groundwater can cause methemoglobinemia in infants (a condition known as "blue baby syndrome") and other health problems in humans. The contamination of groundwater by these substances is a growing public health concern, especially in rural areas where people heavily rely on untreated well water. This study focuses on assessing the groundwater quality in and around the Singrauli coalfield, with a specific emphasis on fluoride and nitrate contamination. By analyzing groundwater samples from various sources across the region, this research aims to understand the extent of contamination and its potential implications for public health.

During Pre-monsoon season 2022, a total 54 grid-wise water samples were collected from Northern coalfield of Singrauli district, M.P. and adjoining district of Sonbhadra, Uttar Pradesh and analyzed by the National Institute of Hydrology (NIH), Roorkee Uttarakhand. At every sampling site, wells were perched for a few minutes before collecting the representative water sample. Our study focused exclusively on 31 groundwater (GW) samples collected from boreholes, hand pumps, and dug wells. All the water samples were collected in the pre-washed HDPE bottles APHA (2005) and filter through Micro Separation Filter Paper Nylon Springe (0.45-µm) filters for major ion chemistry. In-situ parameters such as pH, EC, ORP and temperature were measured using portable waterproof Hanna Instrument. Alkalinity such as concentration of HCO_3^-, CO_3^{2-} of the water samples were identified by Titrimetric method, using suitable reagent such as methyl alcohol, phenolphthalein and Measure ions were determined by Ions Chromatograph method using Standard Cations, Anions mobile phase and silica is analyzed by UV Spectrophotometer respectively. Before analysis of the sample, the instrument was calibrated as per standard norms. The minimum detection limit (MDL) of various ions is about 1 mg/L, except fluoride which is 0.2 mg/L.

The measured physicochemical parameters of the groundwater samples are compared with the drinking water standards established by Bureau of Indian Standards (BIS, 2012) World Health Organization standards (WHO, 2011). The pH of the groundwater in the study area varies from 5.5 to 7.3 with an average of 6.4, which is indicating acidic to alkaline nature of the water samples. Out of total sample, 32% of groundwater samples pH values are lesser than the desirable limit of 6.5 for drinking water. The TDS value for groundwater varied from 160 mg/L to 947 mg/L (avg: 493 mg/L). TDS value in AMD water is exceeding the permissible limit. Sulphate concertation in groundwater samples are varies between 3.28 to 212.48 mg/l with an average of 65.29 mg/l, and $NH4^{+}$ in the groundwater are varies between 0 to 1.21 mg/l with an average of 0.36. The $NH4^{+}$ concentration in 29% groundwater samples is exceeding the permissible limit. The cation and anion abundance in the groundwater samples are in order of Ca^{+2}>Na^{+}>Mg^{+2}>K^{+} and $HCO3^{-}$> $SO4^{+2}$>Cl^{-}>$NO3^{-}$>F^{-}. Majority of the groundwater samples are having water facies of Ca^{+2}- Mg^{+2}-$HCO3^{-}$, Ca^{+2}-Mg^{+2}-$SO4^{-2}$-Cl^{-} and mixed type. The result of WAWQI given in suggests that 31% and 22% of groundwater samples respectively are excellent to good type for drinking, irrigation purposes, while 22% and 3% of samples are poor to very poor water type and 9% of the samples are unfit for any purpose. The concentration Nitrate range from 0.06 to 153.87 mg/l with an average of 26.81 mg/l. The Nitrate concentration exceeds permissible limit in 16% in the groundwater. The fluoride values in the groundwater vary between 0.06 to 4.27 mg/l with an average of 0.86 mg/l. The fluoride concentration exceeds prescribed limit in 13% of the groundwater. The K^{+} in the groundwater 2.40 to 28.64 mg/l with an average of 8.30 mg/l and K^{+} values are exceeding 29% in the groundwater sample. The Ca^{2+} in the groundwater vary between 5.65 to 119.76 mg/l with an average of 63.68 mg/l, respectively.

The present study reveals that the Fluoride and Nitrate concentration in ground water is more than the BIS for drinking water. Nitrate contamination in groundwater due to human induced and contamination from industrial effluents while fluoride contamination in groundwater due to both geogenic and anthropogenic activities. Anthropogenically, high fluoride concentration in groundwater near fly ash ponds (rich in fluoride) may result due to leaching & percolating water near the mine area. Geogenic fluoride mobilization may occurs due to presence of apatite, biotite and hornblende bearing rocks such as Granitic Gneissic Complex present in the study area. The weighted average water quality index (WAWQI) indicates 34% of the groundwater samples were unfit for drinking purpose in the coal mine area. The major water facies of the water system were found to shift from fresh water type Ca-HCO3 to (Na+K)-SO4, Ca-SO4 and mixed type shows dominance of alkaline earth metals over alkalis and dominance of weak acid ($HCO3^{-}$ + $CO3^{-2}$) over strong acid suggestive of $HCO3^{-}$ driven silicate weathering in the area. Silicate weathering, and ion exchange are major Hydrogeochemical processes operating in study area.

***Keywords**: Groundwater, water quality, impact of coal mining, fluoride contamination, groundwater depletion, WAWQI*

HYDRO-GEOCHEMISTRY AND ISOTOPIC CHARACTERIZATION OF PHREATIC GROUNDWATER IN PART OF CENTRAL GANGA PLAIN, INDIA

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Groundwater constitutes 97% of the planet's freshwater resources and is indispensable for drinking water, agriculture, and industrial activities. It serves as the primary source of drinking water for approximately half of the world's population, with 2.5 billion people relying solely on it to meet their daily needs. The quality and availability of this resource, however, are increasingly compromised by industrialization and modern agricultural practices. This degradation is driven by the excessive withdrawal of groundwater and uncontrolled use of fertilizers, pesticides and insecticides, a challenge further exacerbated by population growth and the escalating impacts of climate change. Aquifer water chemistry is the result of both geological factors and anthropogenic processes. The alluvial aquifer of the Central Ganga Plain (CGP) is crucial for the livelihoods of residents providing water for irrigation, drinking and household use. The increasing overexploitation of groundwater driven by high demand and intensive agricultural activities resulting in deteriorating water quality and declining water level in the area.

Present study was carried out in the part of CGP, comprising of two districts (Azamgarh, and Jaunpur) of state Uttar Pradesh which covers an area of 7,932 km^2. The study area is characterized by alluvial sediments, which are classified into two distinct units: younger alluvium, limited to the active floodplain, and older alluvium, occupying higher elevations. The unconsolidated nature of these sediments, exhibiting both porosity and permeability, which results in a potential groundwater aquifer. Gomti, Sai, and Tamsa are the major rivers flowing in the area. Groundwater samples (n=48) were collected from handpumps, and tubewells in March 2021. In situ measurement of spatial data, pH, EC, ORP, and temperature were carried out in the field. Groundwater samples were analyzed for major ions and stable isotopes (^{18}O and ^{2}H) at the National Institute of Hydrology, Roorkee. The groundwater samples are near neutral to slightly basic in nature and EC values vary from 510-2890 µS/cm indicate groundwater mineralization. Na^+ is the dominating cation followed by Ca^{2+} and HCO_3^- is the most abundant anion followed by Cl^-. NO_3^- (n=3) and SO_4^{2-} (n=3) ions exceed the permissible limit of BIS. The Mg-Ca-HCO_3 (32%) is the major water facies followed by Na-HCO_3 (14%). The Gibbs plot for cations and anions suggest the rock water interaction is the key process for the mineralization, which is in agreement with the result of Na/Cl vs EC plot. Hydrogeochemical analysis, using different bivariate plots suggest silicate weathering is the major process operating in the area followed by ion exchange.

The $\delta^{18}O$ values vary from -8.95‰ to -3.92‰ and δ^2H values vary from -61.24‰ to -29.7‰. The groundwater line (GWL) has been developed using 41 samples which is given as: $\delta^2H = 5.6\times\delta^{18}O - 10.5$. The lesser slope of 5.6 and intercept of GWL in comparison to Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL) suggest the effect of evaporative enrichment. The d-excess value varies from -1.8‰ to 14.3‰. The d-excess of the majority of the samples confirm the evaporative enrichment of groundwater. Two samples with $\delta^{18}O$ values of -8.95‰ and -8.57‰, are close to the canal isotopic values (mean -9.96‰) which suggest to recharge of phreatic aquifer through canal. The hydrochemical and isotopic study indicate that local rain is main source of recharge to phreatic aquifer and geogenic processes are the main controlling factor of the hydrochemical characteristic of the groundwater.

Keywords: *Silicate weathering, stable isotope, middle ganga plain, geogenic contamination*

PRINCIPAL COMPONENT ANALYSIS AND MODIFIED GROUND WATER QUALITY INDEX AS POWERFUL ACTIONABLE TOOLS FOR GROUND WATER QUALITY ASSESSMENT AND POLICY INTERVENTION: A CASE STUDY IN PART OF THE GANGETIC RIVER BASIN OF GORAKHPUR DISTRICT, INDIA

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Groundwater serves as a crucial source of drinking water in India. Regions like Gorakhpur District, Uttar Pradesh, India, having population >4.4 million (2011) with decadal growth rate of 17.81%. The district has nearly 100% groundwater-based drinking water supply. Indian Government's vision to achieve piped water supply to each household in sufficient, safe and affordable manner is largely dependent upon the groundwater resources. Hence, determination of groundwater quality for stakeholders becomes paramount considering public health concerns. The present study uses the Principal Component Analysis (PCA) to reveal the factors controlling ground water quality and proposes a modified version of the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) to provide actionable index assessment. This modification incorporates the BIS guidelines for drinking water quality, ensuring alignment with national regulatory standards and public health needs.

The study area is Gorakhpur Administrative District having 3484 km^2 geographical area. The study area, lies in the Gangetic Plains and is drained by structurally controlled Rapti River. The plains consist of Quaternary alluvial deposits. Sandy and Silty-sandy layers form the unconfined aquifers which are underlined by the clayey layer acting as confining layer. Ground water samples were collected from 32 locations from the study area during pre-monsoon of year 2023 in such a manner that whole area is covered evenly. Samples were collected from the ground water sources tapping phreatic aquifer. Standard procedures and guidelines of sampling, storing, and transferring were followed as prescribed by APHA. 14 basic physio-chemical parameters (pH, TDS, Chloride, Carbonate, Bi-carbonate, Sodium, Potassium, Magnesium, Total Hardness, Calcium, Fluoride, Sulphate, Silica, Nitrate) and 6 Heavy Metals (Manganese, Iron, Arsenic, Lead, Zinc and Uranium) were analysed for this study. PCA is a powerful tool for multivariate statistical analysis. PCA can provide information about hidden relationships among original variables. For present dataset, Principal Components (PCs) were calculated and loading factors for top contributing PCs were also determined. The analysis was performed using Python 3.9 on Google Colab using the scikit-learn library.

GWQI is calculated using CCME-WQI. This method gives the values in range of 0 to 100 and scale divides water in 5 categories (95-100 Excellent, 80-94 Good, 65-79 Fair, 45-64 Marginal, 0-44 Poor). The issue with this index is that when the fewer number of variables are above the recommended values it may fail to appropriately incorporate their effect on drinking water quality. There might be cases when a heavy metal or carcinogenic variable is present above prescribed maximum limit but CCME-WQI might classify the water sample in higher categories. Since, drinking water supply is directly linked to the public health aspects, decision makers and stakeholders need to have a tool which can clearly point out the contaminated water source for timely and effective policy interventions and remedial measures. To address these challenges a simplified method has been proposed which takes into account the CCME-WQI and the standards set by the regulatory agencies. The Indian Standard for Drinking Water prescribed by BIS provides a range of concentration for various physio-chemical parameters. It defines as Acceptable limit and Permissible limit. The standard recommends the Acceptable limit to be adopted for the drinking water purposes. Values above this limit renders water unsuitable for human consumption and may cause health risk. But in case of absence of alternate water source, up to permissible limit of water can be used. The prescribed classification is Permissible (CCME-WQI>90 and no failed parameters), Acceptable (CCME-WQI>65 and One or More Parameters Beyond Acceptable but under Permissible Limit) and Unacceptable (CCME-WQI<65 or One or More Parameters beyond Permissible Limit). The basic statistical analysis was performed for all the 20 physio-chemical constituents of 32 sampling locations. Mean, Median, Mode and Standard deviation for each parameter were calculated. The maximum values in case of TDS, Total Hardness, Bi-carbonate, Calcium, Magnesium, Manganese, Iron, Arsenic are above acceptable limits recommended by Indian Drinking Water Quality Standards.

The PCA reveals that the first four principal components explain 71.27% of dataset variation as shown in Table 2. PC1 contributes 35.28% of total variation in the data set. Loading factor analysis reveals that the TDS (0.3778, Cl (0.3425), TH (0.3408), Mg (0.3184), Na (0.3190), and HCO3 (0.2944) are the important constituents of PC1. Whereas, PC2 contributes to the 17.34% variation with Zn (0.3589), As (0.3578), Mn (0.3405), Fe (0.3324), and Ca (0.3641) as the main contributors for PC2. As per original CCME-WQI, 08 sampling locations have ‘Excellent’ category of groundwater for drinking and domestic purpose, while 15 locations have ‘Good’ and 9 have ‘Fair’ category. Our proposed Modified CCME-WQI shows that only 05 locations have ‘Permissible’ quality of water, whereas 09 locations have ‘Acceptable’ quality and 18 locations have ‘Unacceptable’ quality of ground water. PCA analysis suggests that PC1 component likely represents the overall mineralization of groundwater, driven by natural geological processes or anthropogenic factors while PC2 is primarily associated with heavy metals (Zn, As, Mn, Fe). This component might indicate geochemical processes and reactions such as dissolution of minerals. PC3 highlights lead (Pb) and fluoride (F), which are significant contaminants in groundwater. PC4 captures the trends associated with arsenic contamination, a critical concern in groundwater, particularly in regions with natural arsenic mobilization from sediments. The modified CCME-WQI, incorporating Indian drinking water standards, provides a clear and actionable assessment of groundwater quality. Out of 32 locations analysed, 18 were classified as "Unacceptable," indicating significant challenges in water quality management, and urgent mitigation measures to be adapted. 9 locations have “Acceptable” type of quality, where remedial steps should be adopted to minimize the long-term health risks. Only 5 locations met "Permissible" standards. Hence modified CCME-WQI provides targeted locations for positive interventions by decision makers and stakeholders. This study underscores the utility of modified CCME-WQI type indices in guiding informed policymaking for sustainable, safe drinking water management.

Keywords: *Water quality index, principal component analysis, ground water contamination, public health risks, drinking water, Gangetic Plains*

HYDRO-GEOCHEMICAL INVESTIGATION OF GROUNDWATER AND SURFACE WATER QUALITY IN THE MINING-IMPACTED REGIONS OF NORTHERN COAL FIELD SINGRAULI, CENTRAL INDIA

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Coal mining is an important global operation, which drive to energy production and economic development of a nation. However, it also has a negative impact on environmental, especially on water resources. Both open-pit and underground coal mining operations have been linked to surface water contamination, groundwater depletion, and disruption of natural hydrological systems worldwide. Acid Mine Drainage (AMD), causes the leaching of heavy metals and sulphates, causing severe pollution in water bodies and affecting ecosystems and human health. In India, coal mining plays a pivotal role in meeting the nation's energy demands, with coal contributing over 70% of the total energy generation. The country's coal-rich regions, especially in states like Jharkhand, Chhattisgarh, Odisha, and Madhya Pradesh, are hotspots for extensive mining activities. The Northern Coal Field (NCL), Singrauli region in central India is experiencing significant water contamination challenges due to extensive mining operations, thermal power plants (TPPs), ash ponds, and industrial activities. This factor contributes to environmental degradation adversely impacting ecosystem and human health while raising concerns about the portability of water resources in the region. The study focuses on mines of NCL Singrauli and its surrounding areas aiming to establish a comprehensive baseline dataset on water quality. By analyzing hydro-geochemical attributes of collected water samples, the research seeks to identify key factor influencing water quality and contamination in the area. Understanding groundwater hydro-chemistry in coal mining regions is crucial for assessing water-rock interactions and identifying water sources. In this study, the effects of coal mining, TPPs, and industrial activities on the quality of groundwater and surface water in and around NCL Singrauli have been systematically evaluated. The findings provide critical insights into the hydrogeochemical processes and contamination pathways shaping the region's water resources.

To obtain a hydro-geochemical characterization of groundwater and surface water in the study area, water sampling surveys were carried out during pre-monsoon 2022, Grid-based sampling for 1525 sq. km area has been done (10km×10km grid) during summer 32 water samples (21 groundwater samples, 7 mines water samples, 4 surface water) samples were collected from check dams, flowing water, industrial/mine effluents and from shallow and deeper sources (i.e., dug wells, hand pumps, and bore wells), in mines of NCL Singrauli and the surrounding areas as per the standard procedures of APHA (2012). Separate samples have been collected for major ions, trace metals, stable isotopes, and radiogenic isotopes. The physical and chemical parameters that were measured during the sampling survey are listed, including the pH, ORP, electrical conductivity (EC), sample location, and water temperature (T). The water samples were filtered using 0.45-μm filter paper and preserved by adding concentrated nitric acid (HNO_3) (2 ml) to maintain the pH of 2. Alkalinity was also measured by titrating with H_2SO_4 (0.1 N) and methyl orange as an indicator in the Hydrology Laboratory of the Department of Geology at Banaras Hindu University. Major anions Ca^{2+},

Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, F-, HCO_3^- , NO_3^- and Cl^- were analyzed by using an ion chromatograph at NIH Roorkee. The ion balance error is found below 10% for the analyzed samples. After being acidified with HNO_3 (pH<2), samples were kept cold until they were transported to the lab to be analyzed for trace metals like Cu^{2+}, Ni, Fe^{2+}, Co^{2+}, Mn^{2+}, Zn^{2+}, Cr, Pb, Cd, Al^{3+}, B, Se and As by using ICPMS at NIH Roorkee.

The pH of water samples varies from 2.5 to 8.2 (average value of 6.3) i.e. acidic to alkaline in nature. From the total samples, 44% of the groundwater and 31% of surface water samples had lower pH values than the permissible limit of pH and showed an acidic nature. TDS values ranging from 154 to 1570 (average of 560) mg/L in water samples were mainly within the freshwater category, except 4 samples from acid mine drainage which had TDS values> 1000 mg/L. The Piper diagram (Piper, 1944) plotted for hydrochemical facies in the study area shows that the dominating facies are Ca^{2+}-Mg^{2+}-SO_4^{2-}-Cl^- (41%), followed by Ca^{2+}-Mg^{2+}-HCO_3^- (37%), Mixed (Ca^{2+}-Mg^{2+}-SO_4^{2-}-Cl^-) (16%), (Na^++K^+)-SO_4^{2-}-Cl^- type (6%). All the MW and AMD samples fall in Ca^{2+}-Mg^{2+}-SO_4^{2-}-Cl^- water facies and the majority of GW samples fall in Ca^{2+}-Mg^{2+}-HCO_3^- water facies. In Gibb's diagram sub-surface water chemistry was controlled by rock-weathering along with the influence of evaporation dominance. Out of the total groundwater samples analyzed, 13% exceeded the permissible limit for nitrate, 19% for fluoride, and 38% for ammonium. In surface water samples, 6% exceeded the permissible limit for fluoride, 6% for calcium, 25% for electrical conductivity (EC), and 44% for ammonium. The Gibbs plot indicates that the groundwater samples are influenced by rock-water interactions. However, all Acid Mine Drainage (AMD) and one Mine Water (MW) sample show a trend towards evaporation. Among the groundwater samples, the low Mg^{2+}/Na^+ and Ca^{2+}/Na^+ ratios observed in two samples suggest an additional source of Na^+. Furthermore, silicate weathering and its associated minerals have left a distinct signature on the groundwater chemistry. For the groundwater samples, 19% exceeded the permissible limit for aluminium (Al), while 6% exceeded the limits for boron (B) and manganese (Mn). In surface water, 38% exceeded the limit for aluminium, 19% for manganese, 25% for nickel (Ni), and 6% for selenium (Se).

The pH of (44%) groundwater samples and (31%) surface water samples are acidic in nature and have pH below the permissible limit of BIS (2012), i.e. (6.5 – 8.5). Major hydrochemical facies in AMD and mine water samples are characterized by Ca^{2+}-Mg^{2+}-SO_4^{2-}-Cl^-, and groundwater samples are characterized by Ca^{2+}-Mg^{2+}-HCO_3^-. The major ions like F^-, NO_3^-, and NH_4^+ in the groundwater and Ca^{+2}, F^-, NH_4^+, NO_3^-, and SO_4^{2-} in surface water samples exceeded the permissible limit of BIS (2012). The source of fluoride contamination in the study area is due to coal burning in a thermal power plant and pink granite formation of the area; both anthropogenic and geogenic sources are implied. High nitrate and ammonium concentrations are observed in mine water sump samples and the samples that are near rural areas. Trace metals like Al, B, and Mn in the groundwater Al, Mn, Ni, and Se in surface water samples exceeded the prescribed limit of BIS (2012). Silicate weathering and ion exchange are the major hydrogeochemical processes observed to control the groundwater chemistry in the study area. The reason for this unusually high concentration of some of the major ions and trace metals in the groundwater of Singrauli may be due to both geogenic and anthropogenic activities like coal mining and leaching from the waste generated from the various power plants, ash ponds, industries, etc.

Keywords: *NCL, AMD, hydrochemistry, water chemistry, hydrogeochemical*

SYNTHESIS OF BAMBOO-DERIVED ACTIVATED CARBON FOR GROUNDWATER TREATMENT: TURBIDITY AND HARDNESS REDUCTION

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Activated carbon has emerged as a promising adsorbent for water purification due to its high surface area and porosity. Bamboo charcoal, characterized by its high porosity and exceptional adsorption capacity, presents an economical and non-toxic alternative to conventional adsorbents. Furthermore, bamboo-derived carbon materials exhibit unique properties such as electromagnetic shielding and infrared radiation absorption. Therefore, we concentrated our efforts on the appropriate engineering and development of materials based on bamboo-derived activated carbon discovering practical and efficient ways to utilize this abundant supply of adsorbents material for groundwater treatment, with a focus on turbidity and hardness reduction. In this work we synthesis, characterization, and application of bamboo carbon (BC) and activated bamboo carbon (ABC) for water treatment. This study evaluates the efficacy of bamboo-derived activated carbon for groundwater treatment as well with a focus on turbidity and hardness reduction.

The research methodology encompassed the synthesis, characterization, and application of BC and ABC for water treatment. Waste bamboo chunks were carbonized to produce BC, which was subsequently activated using HNO_3 to enhance its adsorption properties and facilitate reuse. The structural, morphological, and functional properties of BC and ABC were comprehensively characterized using various analytical techniques. XRD analysis was employed to determine the crystalline structure and sizes of BC and ABC. X-ray photoelectron spectroscopy (XPS) provided insights into the surface chemical composition and bonding states of the carbon materials. SEM was utilized to examine the surface morphology and pore structure of the adsorbents. Zeta potential analysis was conducted to assess the surface charge characteristics of BC and ABC. FTIR spectroscopy was performed to identify the functional groups present on the adsorbent surfaces. Comparative adsorption studies were carried out to evaluate the effectiveness of BC and ABC in removing turbidity and hardness from various water samples. The water samples included groundwater and river water collected from New Dari village, Dali, Siang, Aalo, Pasighat and Leparada districts as well as from different regions of Jonai in Assam. Batch adsorption experiments were conducted under varying conditions to optimize the treatment process. The experimental parameters investigated included adsorbent doses (ranging from 0.01 to 0.04 g/L), temperatures (25°C to 45°C), and agitation times (10 to 60 min).

The results revealed significant differences between BC and ABC, highlighting the impact of chemical activation on the adsorbent properties. XRD analysis showed that the crystalline sizes of BC and ABC were 57.41 nm and 24.71 nm, respectively, indicating a reduction in crystallite size upon activation. This decrease in crystallite size suggests an increase in the

surface area and porosity of ABC compared to BC, potentially enhancing its adsorption capacity. Zeta potential measurements provided insights into the surface charge characteristics of the adsorbents. BC exhibited a surface charge of -36.2 mV, while ABC showed a slightly more negative charge of -39.6 mV. The increased negative surface charge of ABC may contribute to enhanced electrostatic interactions with positively charged contaminants, improving its adsorption performance. According to the SEM pictures, bamboo fibres and parenchyma cells, among other structural characteristics, were preserved when carbonized BC was pyrolyzed at 400°C. Additionally, the longitudinal section of the BC revealed well-built, big, regular, and cleanly ordered pores that measured less than 5 mm. Large macropores oriented parallel to the fibres were retained after BC was activated using an HNO_3 at 400°C. Additionally, a number of nanosized pores may have formed on the surface of the AC as a result of internal bonding breaking. The activated carbon's SEM pictures reveal a slightly expanded view of numerous thick, circular pores that may be macropores, resulting in branching micropores inside the carbon. The adsorption studies demonstrated the superior performance of ABC compared to BC in removing turbidity and hardness from water samples. Under optimal conditions, ABC achieved up to 100% removal of both turbidity and hardness. The enhanced adsorption capacity of ABC can be attributed to its increased surface area, improved pore structure, and modified surface chemistry resulting from the chemical activation process. The effects of various experimental parameters on the adsorption performance were investigated. Increasing the adsorbent dose from 0.01 to 0.04 g/L led to improved removal efficiencies for both turbidity and hardness, likely due to the increased availability of adsorption sites. Temperature variations between 25°C and 45°C showed a moderate impact on adsorption performance, with slightly higher removal efficiencies observed at elevated temperatures. This suggests that the adsorption process is endothermic in nature. The agitation time study revealed that the adsorption process reached equilibrium within 60 minutes, with the majority of contaminant removal occurring within the first 30 minutes.

This study demonstrates successful synthesis and application of bamboo-derived activated carbon for groundwater treatment, specifically targeting turbidity and hardness reduction. The use of waste bamboo as a precursor for activated carbon production aligns with sustainable development goals by utilizing abundant and renewable resources. Furthermore, the study showcases the role of nanotechnology in enhancing the efficiency of water treatment processes, as demonstrated by the nanoscale crystallite sizes of the synthesized adsorbents. Future research directions may include investigating the adsorption mechanisms in greater detail, exploring the removal of other water contaminants, and scaling up the production and application of bamboo-derived activated carbon for large-scale water treatment operations. Further, studies on the regeneration and reuse of the adsorbent would be valuable in assessing its long-term economic viability and environmental sustainability. This study contributes to the growing body of knowledge on sustainable water treatment technologies and underscores the importance of utilizing renewable resources in addressing global water pollution challenges. The successful application of bamboo-derived activated carbon for turbidity and hardness reduction in groundwater treatment opens up new avenues for the development of efficient, cost-effective, and environmentally friendly water purification solutions.

Keywords: *Bamboo charcoal, bamboo activated carbon, water treatment*

EXAMINING THE CHARACTERISTICS OF GROUNDWATER QUALITY IN FLUORIDE-ENRICHED HARD ROCK REGION IN VELLORE DISTRICT TAMILNADU, INDIA USING HYDRO-GEOCHEMICAL AND MULTIVARIATE STATISTICAL TECHNIQUES

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Groundwater is an essential resource that sustains human life, agricultural activities, industrial processes, and ecosystems. It serves as a critical source of drinking water for millions worldwide, emphasizing the importance of its protection and sustainable management. However, groundwater faces growing threats from over-extraction and contamination, endangering its availability for future generations. Among various contaminants, fluoride is a naturally occurring geogenic pollutant at presents a significant challenge, impacting groundwater quality more profoundly than industrial pollutants. Geogenic fluoride pollution, particularly in arid and semi-arid regions, is a growing concern. Fluoride contamination in groundwater has far-reaching implications, often surpassing the impact of industrial pollutants. Excessive fluoride concentrations pose serious health risks, such as dental and skeletal fluorosis, necessitating stringent monitoring and management to ensure the sustainable use of this invaluable resource. This study focuses on investigating groundwater quality in a fluoride-enriched region of Vellore district, Tamil Nadu, India.

Groundwater quality data from 30 wells were obtained from the Central Ground Water Board (CGWB) between 2022 and 2023. The data obtained was categorized into two seasons, pre monsoon and post monsoon. On analysis it revealed that 60% of the samples exceeds the permissible fluoride limit of 1 mg/L according to World health organization (WHO). The study also examines the hydro-geochemical processes and mechanisms influencing groundwater chemistry and employs advanced exploratory data analysis techniques, including structural equation modeling (SEM), to validate the findings. Hydrogeochemical analyses indicate that groundwater in the region is predominantly of the $NaHCO_3$ (sodium bicarbonate) and NaCl (sodium chloride) types, attributed to rock-water interactions and anthropogenic sources, respectively. These interactions result in most groundwater samples exhibiting alkaline characteristics. Further to provide a comprehensive understanding of groundwater quality, the study utilized advanced multivariate statistical methods, including Cluster Analysis (CA), Factor Analysis (FA), Multiple Linear Regression (MLR), and Structural Equation Modeling (SEM). These methods enabled the categorization, identification, and modeling of factors contributing to groundwater quality and fluoride contamination. Cluster Analysis (CA) classified the sampling locations based on water quality and physico-chemical parameters, grouping them according to similar characteristics. This method proved effective in identifying regional variations and provided a clearer understanding of the underlying factors influencing groundwater quality. It also facilitated the linking of physicochemical attributes to their sources, distinguishing between natural processes, such as rock-water interactions, and anthropogenic influences, such as agricultural runoff or urban activities.

Cluster of TDS, TH, Ca, Mg, Cl, and SO_4, indicates water with higher hardness and salinity. Additionally, a cluster of F, Na, and HCO_3 reflects natural weathering activities, while another cluster, consisting of pH, K, and NO_3, highlights the influence of agricultural activities in the region. The classification enabled the targeted identification of areas in need of intervention, helping to prioritize regions that require focused attention for remediation or further study. Factor Analysis (FA) simplified the dataset by transforming correlated variables into a smaller set of uncorrelated factors, thereby reducing the dimensionality of the data while retaining essential information. The factor loadings revealed distinct influences on groundwater quality: Factor 1 showed strong associations with chloride (Cl), calcium (Ca), and magnesium (Mg), indicating contributions from mineral dissolution and rock-water interactions. Factor 2, on the other hand, was characterized by high loadings for sodium (Na), bicarbonate (HCO_3), and sulfate (SO_4), suggesting influences from anthropogenic sources, such as agricultural activities or industrial processes, as well as evaporation.

These findings highlight the different hydro-geochemical processes that contribute to the quality of groundwater in the region. The Multiple Linear Regression (MLR) model provided further insights into the factors contributing to contamination, offering a highly accurate method for identifying both environmental and geogenic sources of fluoride enrichment. The model highlighted the complex interplay between natural processes and human activities in shaping groundwater chemistry, demonstrating how these factors together influence fluoride levels. Structural Equation Modelling (SEM), a robust multivariate statistical technique, was employed to construct and validate models linking observed and latent variables. This approach facilitated the direct analysis of relationships between independent and dependent variables, offering a comprehensive understanding of the mechanisms influencing groundwater quality. The SEM results demonstrated excellent goodness-of-fit indices, with values of 0.98 for the pre-monsoon period and 0.97 for the post-monsoon period. These high indices highlight the reliability and effectiveness of SEM in modeling the complex dynamics of groundwater quality across seasons. The study also highlights seasonal variations in fluoride concentrations and identifies the key factors influencing groundwater quality in the Vellore district. The use of an integrated approach combining CA, MLR, and SEM to assess the groundwater quality in the study area reveals that the water chemistry is primarily influenced by rock-water interactions and the dissolution of evaporites. This study enhances our understanding of groundwater chemistry and highlights the urgent need for regular monitoring of fluoride contamination and its flow patterns in affected regions. Additionally, it provides valuable insights into preventive measures that should be implemented for wells impacted by fluoride dispersion from the source rock.

Keywords: *Fluoride, Hydro-geochemistry, Factor Analysis, Multiple Linear Regression, Structural Equation Modeling*

INTEGRATED ASSESSMENT OF GROUNDWATER QUALITY USING EWQI AND VARIANCE DECOMPOSITION METHOD TO EVALUATE FLUORIDE-INDUCED HEALTH RISKS

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Groundwater (GW) is an invaluable resource that provides a reliable source of freshwater for multiple activities such as agriculture, industry, and domestic use. The World Health Organization (WHO) reports that over 750 million people worldwide struggle to access safe drinking water. In emerging economies like India, groundwater is a primary source of potable water. Contamination affects one-quarter of India's groundwater sources, impacting approximately 200 million people. Therefore, understanding the quality of drinking water is crucial for sustainable development in both urban and rural areas. GW contamination from both natural and man-made sources is currently posing a serious threat to India's Gangetic plains. Growing GW withdrawals, water scarcity, fast development, widespread industrialization, and urbanization are all contributing factors to the GW quality decrease. Numerous contaminants and trace elements, including fluoride and nitrate, are introduced as a result of these operations, and they pose a major risk to human health. Therefore, a thorough evaluation is required to quantify the level of GW pollution.

To fill this gap, 59 groundwater samples were gathered from tube wells and hand pumps of various depths in the Sirdala block in the Nawada district of Bihar during the pre-monsoon season A portable digital meter (PSCTestr35) was used to test physical parameters including pH, EC, and TDS as soon as the sample was collected. Ion chromatography was used to investigate the principal cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (F^{-}, Cl^{-}, HCO_3^{-}, NO_3^{-}, and SO_4^{2-}). An entropy-based water quality index (EWQI) was used to evaluate the groundwater's suitability for human use. The entropy-weighted water quality index (EWQI) provides a comprehensive measure by integrating all physicochemical data into a single representative value that reflects overall water quality. This study assesses human health risk assessment (HHRA) related to fluoride and two distinct age groups: adults and children. Additionally, for oral health risk models, the relative contribution and interaction of input factors were evaluated using a variance decomposition-based Sobol sensitivity technique. Three distinct scores such as FOE (first order effect), SOE (second order effect), and TE (total impact) were assessed for various demographic age groups. Also, to understand the spatial variation and dynamics of groundwater quality, groundwater contamination, and its associated health risk the spatial maps were depicted using ArcGIS.

Ionic dominance in groundwater was shown to follow the following sequence: cations: Na^{+} > Ca^{2+} > Mg^{2+} > K^{+} and anions: HCO_3^{-} > Cl^{-} > SO_4^{2-} > NO_3^{-} > F^{-}, according to a descriptive examination of the hydrochemistry of groundwater samples. The nature of groundwater is slightly alkaline in nature and the concentration of fluoride exceeded the permissible limit of 1.5 mg/l in 42.37% of the total groundwater samples. The Entropy Weighted Water Quality Index (EWQI) is used in this study to measure the drinking water quality. The study region's groundwater samples had EWQI values ranging from 23.70 to 453.38. According to these findings, one of the study's groundwater samples was classified as having extremely poor

quality (rank-5), meaning it is not at all advised for human consumption. One sample that was deemed unsafe for consumption and with poor water quality (rank-IV) was identified. Roughly 8% of the samples were categorized as fair grade water (rank-III), meaning that they are just somewhat fit for human consumption. However, before fair-quality water is utilized for residential purposes, pretreatment is advised. 56% of the samples had excellent water quality, while about 32% of the samples were classified as good quality. Drinking water with a high F^- content may have a detrimental effect on human health and cause serious sickness. Hazard quotient (HQ) values were used to weigh the possible health impacts of F^-. No negative health consequences are anticipated if the calculated HQ is less than 1, and consumers are at serious risk if the HQ is more than 1. Hazard quotient fluoride (HQF) values varied between 0.24 and 6.71 for children, 0.160 and 4.47 for adults. The average value of HQF for children is 1.12 and for adults is 0.74. HQF > 1 was reported for 35.59% and 15.25%, of the samples for children and adults. Fluoride concentration (Cw) is particularly sensitive, according to the FOE, which is followed by exposure frequency (EF), intake rate (IR), and body weight (BW). According to the SOE scores, the most crucial input criteria for determining the danger to children's oral health are IR and Bw. The interactions Cw–IR for adults had the greatest Sobol score, followed by those for children. Additionally, the findings indicate that the oral risk is higher in the children's groups than in the adult groups.

The nature of groundwater is slightly alkaline in nature and the concentration of fluoride exceeded the maximum permissible limit of 1.5 mg/l in 42.37% of the total groundwater samples. The majority of the groundwater in the examined area had fair to excellent water quality, according to the analysis of EWQI values, making it fit for human consumption. The HQ value for F^- indicates that 35.59% and 15.25%, of the samples, for children and adults exceed the acceptable limit respectively. Additionally, the study investigates if the SSA approach can be used to another pollutant and whether it is feasible to examine the impacts of various input parameters for the health risk model. Improving the quality of groundwater is essential for protecting public health, particularly for vulnerable groups like children. These results highlight the need for careful monitoring and management techniques to protect groundwater quality from various contamination sources.

Keywords: *Groundwater quality, EWQI,* Sobol sensitivity *analysis, human health risk, Gangetic Palin*

A COMPARATIVE STUDY OF BIOFILTER, VERMIFILTER, AND MACROPHYTE-ASSISTED VERMIFILTER FOR TREATMENT OF CATTLE FEEDLOT WASTEWATER

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Macrophyte-assisted vermifiltration (MaVF) is an emerging technology for the treatment of cattle feedlot wastewater, proving to be efficient and sustainable compared to conventional methods. Contaminants released from untreated cattle feedlot wastewater are released into surface water, percolating into groundwater, leading to groundwater pollution. The contaminants present in cattle feedlot wastewater comprises of organic matter, nutrients and antibiotics. Antibiotics are one of the constituents frequently found in cattle feedlot wastewater, which poses a serious health concern. Moreover, the persistence of these contaminants in water and soil systems can have long-term ecological impacts, including toxicity to aquatic life and alterations in nutrient cycling. Antibiotics present in cattle feedlot wastewater pose significant environmental risks, including the development of antibiotic resistance in microorganisms. The wastewater containing the antibiotics and antibiotic resistance genes (ARGs) is further released into wastewater treatment plants (WWTPs). MaVF is a sustainable recent technology introduced for the treatment of wastewater, but a comparative analysis between different MaVFs and other biological treatment systems remains unexplored. Thus, in the present study, we performed a comparative analysis between three different technologies- biofilter (BF), vermifilter (VF), and macrophyte-assisted vermifilter for the treatment of cattle feedlot wastewater. The removal efficiency of Chemical Oxygen Demand (COD), Total Nitrogen (TN), ammonia, Total Phosphorous (TP), and antibiotics in the influent (i.e., cattle wastewater) through different bioreactors was evaluated. Three horizontal subsurface flow MaVFs were set up, namely T1, T2 and T3. T1 was MaVF planted with *Canna indica,* T2 was vermifilter bioreactor, and T3 was biofilter. The species of earthworms introduced in VF and MaVF were *Eisenia fetida*, commonly found in tropical areas. Synthetically prepared cattle wastewater containing antibiotics were applied to these systems through gravity feeding at a hydraulic loading rate (HLR) of 0.6 m^3/m^2/day. The bioreactors were examined for 120 days, and the effluent was analysed for different water quality parameters.

The results indicated substantial removal rates in different water quality parameters, including antibiotics. The average COD removal efficiency for T1, T2, and T3 were 60.2±1.9%, 52.9±1.1% and 42.4±1.2%, respectively. The average DO in T1, T2 and T3 effluent was 7.4 mg/L, 4.6 mg/L, and 3.06 mg/L respectively. The pH for influent wastewater was in the range of 9.16±0.4, whereas the effluent pH ranged between 8.46-8.97 for all the reactors. Both macrophyte-assisted and conventional filters contributed to the buffering capacity of the system, though no significant difference in pH regulation was observed between the reactors. The removal efficiency of TN for T1, T2, and T3 were 28.3±1.4%, 19.6±1.2% and 17±1.4% respectively while for ammonia, T1 demonstrated higher removal efficiency (53.4±1.4%) in comparison to T2 (38.6±1.8%) and T3 (27.8±1.2%). The superior nitrogen removal in T1 is likely due to the nitrification-denitrification processes enhanced by *Canna indica* and further phytoaccumulation of nutrients in macrophytes. The plant's root structure supports a diverse microbial community that converts ammonia and organic nitrogen into nitrate, followed by denitrification to nitrogen gas. The limited microbial colonization in T2 and T3 restricted nitrogen removal efficiency in those systems. Removal efficiency for TP for T1, T2, and T3 was 34±1.2%, 25±1.2%, and 21±1.4%, respectively. Observational analysis revealed the efficiency of MAVF in comparison to VF and BF in terms of clogging. The superior performance of T1(MaVF) in comparison to T2 and T3 can be attributed to the presence of an extensive and dense root structure by *Canna indica*, providing a larger surface area for attachment of microbes, increasing the microbial activity. In the preliminary analysis, it was observed that MAVF reactors were more efficient in antibiotic removal than VF and BF. However, further quantitative analysis is needed to fully understand the mechanisms and extent of antibiotic removal. The environmental and economic benefits of MaVF systems make them a viable alternative to conventional wastewater treatment methods. Using locally available macrophyte species further enhances the sustainability of this approach by reducing costs and ensuring adaptability to regional conditions. Modularization of MaVF systems could facilitate broader applications and provide higher removal efficiencies for organics and antibiotics while extending their lifespan.

Future research should focus on expanding the scope of this study by evaluating additional macrophyte species and optimizing operational parameters such as hydraulic loading rates and retention times. Long-term monitoring of MaVF systems is also essential to assess their durability and performance under varying environmental conditions. Furthermore, advanced analytical techniques should be employed to quantify antibiotic removal and understand the underlying mechanisms in greater detail. By addressing these research gaps, Macrophyte assisted vermifiltration technology can be developed into a robust and sustainable solution for managing cattle feedlot wastewater and mitigating its environmental impacts. Thus, it can be concluded that if modularized, the application of MAVF systems for higher removal efficiency of organics and antibiotics and expanded life span.

Keywords: *Canna indica, Macrophyte, Vermifiltration, Cattle-feedlot wastewater, Antibiotics, Organics*

HYDRO-GEOCHEMICAL INVESTIGATIONS AND SUITABILITY OF GROUNDWATER FOR DRINKING PURPOSES IN INDORE DISTRICT, MADHYA PRADESH, INDIA

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Water covers approximately 71% of the Earth's surface, largely in seas and oceans, with minor proportions as groundwater (1.7%), glaciers, and atmospheric vapours. Groundwater is a vital source of drinking water for nearly one-third of the global population. Despite its abundance, challenges related to freshwater scarcity and contamination persist worldwide. Key water quality parameters, including Electrical Conductivity (EC), pH, Dissolved Oxygen (DO), Chlorides, and microbial contamination, impact human health and ecosystem sustainability. Globally, over one billion people lack access to safe drinking water, with rural populations being disproportionately affected. In India, groundwater meets 85% of the public water demand, but contamination from pathogens, agricultural runoff, and industrial pollutants poses significant challenges. In this paper we investigate the hydro-geochemical characteristics of groundwater and surface water in Manglia Village, located in the Indore District of Madhya Pradesh, to evaluate its suitability for drinking purposes. Indore spans 530 km^2 and is geographically positioned between latitudes 22°48′00″N to 22°50′00″N and longitudes 75°54′00″E to 75°56′30″E, bordered by the Chambal River to the west and the Kshipra River to the east. The Deccan Traps, which are the predominant rocks in the district, have wide variation in the water bearing properties of the different units constituting them. The massive basalts, their weathered zones and secondary porosities and the vesicular basalts with their minutely connected and partially filled vesicles play an important role in determining the occurrence, movement and storage of groundwater. These invariably form potential aquifers. In the alluvial areas, the occurrence of groundwater is governed by sand/clay ratio. The sand beds generally form good aquifers, but due to the limited thickness and erratic occurrence in the form of lenses, the ground water structures in them are poor to moderately productive. During the post-monsoon season, 19 water samples, including groundwater, surface water and 11 (5 sites) soil samples, were collected within a 5-kilometer radius of Manglia Village from bore wells and surface water sources. The samples were analyzed for pollution indicator ions and trace metals. Ion chromatography (IC) determined the concentrations of anions (Cl^-, SO_4^{2-}, NO_3^-), while Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) was used for trace metal analysis. The soil texture was analyzed using of the sieve test and the laser diffraction method. Soil samples were digested using the Multiwave PRO microwave for chemical analysis. All analyses were conducted in triplicate to ensure accuracy and reliability. The pH, EC and DO of water samples ranged from 6.82 to 7.6, 808 to 2640 μS/cm, and 0.94 to 3.10 mg/L, with average values of 7.14, 1516 μS/cm, and 1.77 mg/L, respectively. Anion concentrations in groundwater were as follows: chloride (Cl^-) ranged from 45 to 460 mg/L, sulfate (SO_4^{2-}) from 1 to 130 mg/L, and nitrate (NO_3^-) from 0.2 to 4.9 mg/L, with average values of 215 mg/L, 48 mg/L, and 1.51 mg/L, respectively. Surface water samples follow similar trends as groundwater, with chloride ranging from 45 to 306 mg/L, sulfate from 24 to 36 mg/L, and nitrate from 0.7 to 3.2 mg/L, with average values of 155 mg/L, 31 mg/L, and 1.6 mg/L, respectively. All anion concentrations were within permissible limits established by the Bureau of Indian Standards (BIS, 2012). Trace metal concentrations in groundwater showed arsenic (As) levels ranging from 3.3 to 9 ppb, iron (Fe) from ND to 2910 ppb, manganese (Mn) from 1 to 5696 ppb, nickel (Ni) from 1.41 to 9.41 ppb, lead (Pb) from 4.2 to 7.98 ppb, zinc (Zn) from 44 to 304 ppb, and copper (Cu) from 0.6 to 15 ppb. Average concentrations of above metals (in same sequence) were 6.5, 442, 604, 5.41, 6.09, 130, and 5.2 ppb, respectively. Surface water samples revealed similar patterns, As, Fe, Mn, Ni, Pb, Zn, and Cu ranged from 3.3 to 7.9 ppb, 200 to 950 ppb, 14 to 364 ppb, ND to 10.7 ppb, 4.3 to 6.7 ppb, 42 to 406 ppb, 4.2 to 46 ppb, with respective averages of 5.5, 610, 207, 10.7, 5.4, 202, and 22 ppb. All measured trace metals except Fe and Mn were within permissible limits as prescribed by the BIS, 2012. High concentrations of iron generally cause inky flavour, bitter and astringent taste. It can also discolour clothes, plumbing fixtures and cause scaling which encrusts pipes. Excessive concentration may promote bacterial activities in pipe and service mains, causing objectionable Odours. Trace metal concentrations in soil samples showed variability, with arsenic, cadmium, lead, chromium, nickel, zinc, copper iron, aluminium, and manganese ranged from 114 to 169 mg/kg, 30 to 43 mg/kg, 107 to 310 mg/kg, 430 to 699 mg/kg, 512 to 736 mg/kg, 489 to 1017 mg/kg, and 512 to 736 mg/kg, 205 to 270 mg/kg, 179 to 286 mg/kg, and 6 to 23 mg/kg respectively. In the soils samples clay contents ranged from 4.3 to 24.0%, silt and sand contents had wider ranges of volume percent; silt contents ranged from 32.6 to 75.4%; while sand contents ranged from 8.1 to 38.8% and gravel percentage varied from 0.2 % to 37.6% in the study area. However coarse size fractions increase with depth in these soils with reduction in fine size fractions. Based on textural classification of soil samples, the soil of the study area is mainly silty loam type. It is concluded that all the measured ions and trace metals are within the permissible limit except iron and manganese. However, the water quality monitoring, including physicochemical and trace metal parameters, can identify potential risks early and it should be monitored regularly.

Keywords: *Water quality, groundwater, drinking water, Indore*

POTASSIUM RETENTION AND TRANSPORT IN AGRICULTURAL SOILS UNDER TREATED WASTEWATER IRRIGATION: MECHANISMS AND ENVIRONMENTAL IMPLICATIONS

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Potassium (K) is an essential macronutrient for plant growth, animal health, and human nutrition. It plays a significant role in various physiological functions, including enzyme activation, photosynthesis, and water regulation in plants. In agricultural soils, the availability of potassium is primarily governed by the soil's buffering capacity and retention properties, which determine its mobility and subsequent uptake by plants. The retention of potassium in soil is a complex process influenced by multiple physical, chemical, and biological factors. Traditionally, potassium is supplied to crops through chemical fertilizers; however, with growing concerns regarding sustainable agricultural practices and resource conservation, alternative sources of nutrients are being explored. One such alternative is the use of treated wastewater (TWW), which contains essential nutrients, including potassium, and can serve as a supplementary nutrient source for crop production. To evaluate the feasibility of using TWW as a potassium source, it is crucial to understand the interactions between potassium and soil, particularly its retention mechanisms and transport behaviour in the vadose zone. This study aims to investigate these aspects by analysing soil samples collected from agricultural fields. The physicochemical properties of the soil were assessed to determine key factors influencing potassium retention. A series of controlled batch experiments were conducted to examine potassium retention under varying conditions, including pH (ranging from 2 to 10), contact time (from 0 to 24 hours), and isotherm behaviour at room temperature. The adsorption kinetics were studied to determine the rate at which potassium binds to soil particles. Additionally, a column experiment was performed to analyse potassium transport under dynamic conditions. The experiment utilized a 0.01 M NaCl background solution containing 25 ppm potassium, applied under a constant hydraulic head of 50 mm. The experimental setup consisted of cylindrical polyvinyl chloride (PVC) columns with an inner diameter of 5 cm, a column length of 25 cm, and a soil fill depth of 20 cm. The soil was packed in column to achieve a bulk density of 1.37 g/cm^3. All potassium concentrations were measured using flame photometry and ion chromatography. The study revealed that potassium retention in soil is influenced by pH conditions. Under acidic conditions, potassium retention was lower due to electrostatic repulsion. Since potassium carries a positive charge, and acidic environments are also characterized by an abundance of hydrogen ions (H^+), strong repulsion forces hinder potassium adsorption. This leads to higher potassium mobility and potential leaching risks in acidic soils. The kinetic analysis demonstrated that potassium retention follows a second-order kinetic model, suggesting that the adsorption process is primarily governed by chemical interactions rather than simple diffusion. Furthermore, isotherm studies indicated that the Freundlich isotherm model provided the best fit for potassium adsorption data, highlighting the heterogeneous nature of potassium binding sites within the soil matrix. For transport analysis, the experimental data were simulated using the STANMOD software to model potassium movement through soil. The results indicated that the presence of competing cations, such as sodium, calcium, and magnesium, in TWW effluent reduces potassium retention capacity in the soil matrix. This

effect enhances potassium mobility, increasing the likelihood of leaching into deeper soil layers and potentially contaminating groundwater. The use of TWW for irrigation has both beneficial and adverse implications for potassium dynamics in agricultural soils. On the positive side, TWW enhances potassium availability, reducing the reliance on synthetic fertilizers and contributing to improved soil fertility. However, excessive potassium accumulation can disrupt nutrient balance, negatively affecting the uptake of other essential cations such as calcium and magnesium. This imbalance can have implications for plant health and crop yields. Potassium dynamics also play a role in shaping microbial communities in the soil, potentially altering nutrient cycling and organic matter decomposition. The long-term application of TWW for irrigation requires careful management to prevent soil degradation and ensure sustainable nutrient availability while mitigating risks to water quality and ecosystem health. This research highlights the complex interactions between potassium, soil properties, and TWW application in agricultural systems. The study underscores the importance of understanding soil-specific retention mechanisms and transport dynamics to optimize nutrient management strategies. While TWW serves as a valuable resource for potassium supplementation, its use must be carefully managed to balance agronomic benefits with environmental risks. The insights gained from this study provide a foundation for developing best practices in wastewater reuse, contributing to sustainable agriculture and resource conservation. Policymakers, and agricultural practitioners, can utilize these findings to improve wastewater management strategies, ensuring that nutrient benefits are maximized while minimizing ecological risks. By integrating sustainable irrigation practices, we can enhance soil fertility, promote efficient nutrient use, and mitigate potential threats to groundwater quality and ecosystem stability.

Keywords: *Nutrients, retention, transport, treated wastewater, potassium*

HYDROGEOCHEMISTRY AND LEAD CONTAMINATION OF GROUNDWATER IN GUWAHATI CITY, ASSAM, INDIA

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Water is a basic human right. Assessing and predicting quality of groundwater is crucial in managing groundwater availability effectively. Groundwater is an essential resource. However, landuse and landcover changes facilitated by population growth, over exploitation, urbanization, industrialization and agricultural practices have overwhelming impacted this vital resource. Population density, landuse changes and complex geology pose greater problems in urban areas compared to rural. Both point and non-point sources contribute to greater water quality degradation in urban areas. Leakage from sewer mains, industrial effluents, urban runoff and household discharges contribute to the hydrogeological challenges faced by urban groundwater systems. Pollution of groundwater by dissolved trace elements has been recognized as a major threat to safe drinking water. The pollution of groundwater by dissolved trace elements has raised serious global concerns due to their persistence, carcinogenicity, and environmental impacts. While the presences of certain trace elements are deemed essential for human health, their presence above guideline values is a major threat to human health and the ecosystem. Groundwater contamination due to arsenic and fluoride has been widely reported over the past decade, emergent contaminants like Pb in groundwater has only been recognized more recently. More than 80% of urban and rural population in India relies on groundwater for meeting their water needs. However, groundwater in most cities across India are contaminated with trace elements like arsenic, fluoride, lead, zinc cadmium, mercury etc. Communities consuming such contaminated water face severe health consequences.

The presence of arsenic (As) and fluoride (F) in groundwater of Guwahati city, the gateway to the northeastern part of Assam, India has been widely reported. A limited number of studies have also reported the presence of trace elements like lead (Pb), cadmium (Cd) and iron (Fe) in groundwater. This study is thus an attempt to access the groundwater hydrogeochemistry in Guwahati city to evaluate the origin and geochemical mechanism driving groundwater quality and lead (Pb) contamination in groundwater of Guwahati City, Assam, India. 61 groundwater samples were collected from shallow tubewells and dugwells (depth <50 m) from across the study area**.** The water samples were collected in cleaned 500 ml PE (polythene) bottles, which were washed in the laboratory with 10% nitric acid (HNO_3), and then rinsed with ultrapure water few times. Samples designated for trace elements analysis were preserved with 7M HNO_3. The analysis of cations and trace elements was conducted using inductively coupled plasma mass spectrometry (ICP-MS, NexION 350, PerkinElmer Instrument, USA), while anions were analyzed using ion chromatography (IC, Thermo Scientific Dionex Integrion RFIC system, USA). All the laboratory analyses were conducted at the Global Centre for Environmental Remediation (GCER), The University of

Newcastle, Australia.The concentrations of major cations followed the order calcium (Ca^{2+}) > sodium (Na^{+}) > magnesium (Mg^{2+}) > potassium (K^{+}) while chloride (Cl^{-}) is the most dominant anion in the groundwater. Piper plot demonstrated that the groundwater is predominantly of Ca–HCO_3 typealong with mixed Ca–Mg–Cl, Na–K–HCO_3, and Ca–Cl types, indicating the dominance of alkaline earth over weak acids. Groundwater hydrogeochemistry is mainly controlled by rock water interactionsand evolves through the processes of silicate weathering, carbonate weathering, and cation exchange. Alarmingly, 54% of samples exceeded the permissible limits of 10µg/L set by both World Health Organization (WHO) and Bureau of Indian Standards (BIS), indicating serious concerns for the local inhabitants. Lead concentrations ranged from 3.05 µg/L to 74 µg/L, with a mean of 13 µg/L. Lead is a naturally occurring toxic metal, typically sourced from both geogenic and/or anthropogenic sources. It is used for various purposes such as automobile fuels, paint, and batteries, and can be found in wastewater. High Pb concentrations in drinking water can have serious health implications, such as the disruption of the biosynthesis of hemoglobin, increased blood pressure, renal damage, disruption of the nervous systems, neurological damage, and diminished learning abilities in children. Spatial distribution maps of Heavy Metal pollution (HPI) indicates wide-spread groundwater contamination in the study area, except for isolated pockets with good to excellent groundwater in the central portion of the study area.Regular monitoring and intervention of groundwater sources in the hotspot areas are essential for long-term use. The findings of this study will assist policymakers in devising strategies for sustainable management of groundwater in the study area and regions facing similar challenges.

Keywords: *Groundwater, Hydrogeochemistry, Lead Contamination, Piper Plot, Management*

ASSESSING GROUNDWATER CONTAMINATION IN MADHYA PRADESH: SOURCES, IMPACTS, AND REGULATORY RESPONSES IN A RAPIDLY INDUSTRIALIZING LANDSCAPE

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Groundwater contamination in Madhya Pradesh, a rapidly industrializing state in India, has become a pressing environmental concern. This review paper comprehensively examines the prevalent sources, pathways, and impacts of groundwater contamination arising from industrial activities within the state. Specific focus is placed on industries such as chemical manufacturing, textiles, pharmaceuticals, and metal processing, which are known contributors to contamination. The paper delves into the various contaminants released by these industries, including heavy metals, organic compounds, and inorganic substances. Additionally, it explores the geological and hydrological factors that influence the movement and distribution of contaminants in the unconfined aquifers. An overview of the potential environmental and health risks associated with groundwater contamination is discussed, highlighting the potential implications for agriculture, drinking water supplies, and human well-being. Finally, the paper provides a review of existing regulations, monitoring practices, and remediation technologies employed in Madhya Pradesh to address groundwater contamination. By synthesizing the current knowledge and research, this review aims to contribute to a better understanding of the issue. It allows decision makers to make informed policy decisions for sustainable industrial development and groundwater protection in the region. Groundwater contamination is challenging to detect due to its subsurface nature, making monitoring efforts expensive and time-consuming. Addressing these challenges requires improved pollution control strategies, stringent wastewater management policies, and enhanced groundwater monitoring systems.

Madhya Pradesh, a state with a low industrial development rate, has several large and medium-scale manufacturing centres in Indore, Gwalior, Bhopal, and Jabalpur. Government-sponsored industries include paper milling, cement production, and heavy electrical items. Private sector facilities produce sugar, textiles, lumber, flour, and seed and vegetable oils. Other products include fertilizer, synthetic fibres, and chemicals. The hand-loom industry has flourished, with saris made in Chanderi, gold and silver thread embroidery in Bhopal, and carpets woven in Gwalior. Gwalior artisans also produce handmade pottery. Jabalpur and Sagar are known for manufacturing bidis, hand-rolled cigarettes. These industries produce different wastes such as organic wastes, heavy metals (Pb, Hg, Cd, Cr, As, Ni, and Zn), and harmful chemicals. Due to the industrial area and their waste releases the groundwater is contaminated, and the land is polluted. Dewas is such area located in Ujjain Revenue Division, is situated on the Malwa plateau in West-central Madhya Pradesh, India situated between 20°17´ and 23°20´ North latitude and 75°54´ and 77°08´ East longitude. Large-scale concentrated sources of pollutants, such as industrial discharge and subsurface chemical injection, are evident in the groundwater (Kori, et al., 2020). The Mandideep industrial area in Madhya Pradesh, located near Bhopal, was the focus of a study conducted from 2017 to 2018. The study analyzed physico-chemical parameters of ground water, following standard guidelines and Central Pollution Control Board guidelines. The results showed high contamination in ground waters, with nitrate concentrations ranging from 3.74 mg/l to 27.88 mg/l, and fluoride concentrations ranging from 0.23 mg/l to 1.11 mg/l. Another study analysed the physico-chemical characterization of groundwater in a village near the Malanpur and banmore industrial area in Bhind and Morena, Madhya Pradesh, from April 2018 to March 2020. The samples were analyzed for parameters such as pH, total dissolved solids, total hardness, calcium, magnesium, sodium, potassium, chloride, sulphate, and fluoride. The study also found that the dominant presence of fluoride, salt, sodium, and calcium had severe effects on teeth, skeletal, kidney, and rural people. The high levels of ions in the groundwater were attributed to the seepage of industrial effluent discharged without treatment on the land. The study suggests a proper management plan to improve groundwater quality for human health and sustainable development.

Considering these we calculated the Water Quality Index (WQI) based on acceptable and permissible limits for each parameter, and we have taken the applicable averages of these values to calculate the normalized index. A groundwater quality investigation conducted across four industrial regions in Madhya Pradesh Dewas, Mandideep, Malanpur, and Banmore reveals significant deviations in physico-chemical parameters from the acceptable drinking water limits. Based on the WQI, we have classified groundwater risk into three zones: low-risk (WQI < 0.35), moderate-risk (WQI 0.35–0.70), and high-risk (WQI > 0.70). Analysis of acceptable WQI values indicates that all four regions fall within the high-risk zone, with values ranging from 0.72 (Mandideep) to 0.89 (Banmore), indicating severe groundwater contamination. However, based on permissible WQI standards, all regions are categorized under moderate risk, with values between 0.53 (Mandideep) and 0.65 (Malanpur). This deterioration in groundwater quality is likely attributed to industrial activities, including the discharge of untreated or partially treated effluents, which directly or indirectly impact aquifer systems. The findings underscore the urgent need for comprehensive groundwater management strategies, stricter industrial wastewater regulations, and enhanced monitoring frameworks to mitigate contamination risks and safeguard groundwater resources for sustainable use.

Keywords: *Groundwater contamination, industrial pollution, heavy metal contamination, Madhya Pradesh*

ASSESMENT OF GROUNDWATER QUALITY WITH SPECIAL REFERENCES TO FLOURIDE CONCENTRATION AROUND BHIWAPUR, NAGPUR DISTRICT, MAHARASHTRA, INDIA

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Groundwater is an important source of freshwater for world's population. It is used for domestic, agricultural manufacturing and industrial purposes. The groundwater regime of any area is controlled by parameters like lithology, structure, geomorphology, slope land use/land pattern etc. Quality of water plays an important role in promoting agricultural production and standard of human health for assessment and management of groundwater resources, it is essential to understand the hydrogeological and hydrogeochemical properties of aquifer. The geochemical composition of groundwater is mainly influenced by natural factors such as wet and dry deposition of atmospheric salt, precipitation, evapotranspiration, soil matrix, rock water interaction, residence time etc. Assessment and classification of groundwater based on its quality can be obtained by analyzing its chemical characteristics. Variations in ion chemistry of groundwater are used to identify geochemical processes that control groundwater quality. Presence of low or high concentration of certain ions is a major issue as they make groundwater unsuitable for various purposes. Fluoride is such one ion that causes problem to people's health. The studies' main objectives are to define major hydrogeological processes, assess groundwater quality and pinpoint village where groundwater is suitable or unsuitable for drinking water purposes in the study area.

The study area is a part of Bhiwapur taluka adjoining villages WGM-2 Watershed which is situated at about 60 km SE to Nagpur district headquarters. The Maroo is main river which flowing NE direction. In this area mainly comprises rock types of Granatic gneiss, Migmatite Gneiss, Amphibolite, Quartzites which is of Amgaon gneissic group of Archean age. Depth of dug well is 8 to 17 mbgl. Diameter of well is between 3 to 5 m and yield of well is 50 to 100 m^3/day. While depth of borewell ranges from 60 to 70 mbgl. Hydrological data collected in study area was carried out during post monsoon season of year 2023. Total 21 villages samples are taken for analysis. Out of 21 samples 7 samples from borewell and 14 samples from dugwell are analyzed. Major chemical parameters were analysed in laboratory.

The result was evaluated in accordance with World Health Organization and standard specification of BIS Standards. Total 21 samples analysis concentration of F-result village wise is Bhagabori 0.53mg/l, Borgaon-1.30mg/l, Chikhali-0.5mg/l, Dongargaon -1.48mg/l, Jaoli- 1.20 mg/l, Kinhala-0.53mg/l, Mangali-0.55 mg/l,Manora-1.90 mg/l, Mendala-0.44mg/l, Murhapur-1.30 mg/l, Nakshi-0.54 mg/l,Pandharabodi-1.30mg/l,Botezari-1.70mg/l, Ranmangali-1.30 mg/l, Sarandi-0.81 mg/l, Seloti-0.95 mg/l,Somnala-1.90mg/l, Tas-1.50 mg/l,Chichada-2.0mg/l, Wadadha-0.27 mg/l, Taka-1.70mg/l. Out of 21 samples 16 villages having F^- concentration range between 0.27 mg/lit to 1.50 mg/l is in permissible limit. While 5 samples show F^- concentration range is 1.60 to 2.0 mg/l. these villages are F^-concentration above permissible limits, so groundwater of these sources is not suitable for drinking purposes.

The main rock formation in water sampling study area are Archeans and it comprises of granitic gneisses, amphibolite, quartzite, migmatite gneiss. It seems more appropriate that rock rich in fluoride minerals have contributed to the enriched fluoride content of groundwater during the course of weathering of rock. Dissolution activity of fluoride minerals is more important for fluoride concentration in groundwater rather than fluoride -bearing minerals present in rock. Thus, concentration of fluoride in ground water is depends on concentration of fluoride -bearing minerals in rock types. Their decompositional, dissociational and dissolutional activities along with residence time of the chemical reaction are important. In acidic medium (acidic pH), fluoride is absorbed in clay; however, in alkaline medium it is desorbed and, thus alkaline pH is more favorable for fluoride dissolution activity. In present case all water samples were found alkaline in nature and their pH value varied from 7.4 to 8.4. The aqueous ionic concentration of groundwater also influenced the fluoride solubility behaviors; for example, in presence of excessive sodiumbicarbonates in groundwater, the dissociation activity of fluoride will be high, and this can be expressed as CaF_2+2$NaHCO_3$=$CaCo_3$+2Na+2F+H_2O+CO_2. Mineral composition of these rocks is plagioclase feldspar, anthrophyllite, garnet, mica, epidote, hornblend, orthopyroxenes, biotite and illimanite and all these minerals are fluoride bearing minerals. Weathering of these rock and prolonged residence time leads to occur high fluoride concentration in groundwater. It is observed that in study area fluoride concentration occurs in groundwater is due to natural cause where principal source of F-in water are fluoride bearing minerals present in rocks. Most of villages in study area groundwater are suitable for drinking & domestic purposes.

Keywords: *Geoenvironmental, fluoride concentration, Bhiwapu, ion exchange, Water quality*

ASSESSMENT OF HYDROCHEMISTRY AND SOURCE IDENTIFICATION OF GROUNDWATER CONTAMINATION ALONG THE COASTLINE OF ODISHA, INDIA USING GEOSPATIAL AND STATISTICAL TOOLS

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Groundwater is an essential resource for drinking, irrigation, and industrial activities, particularly in coastal regions where surface water availability is often limited. However, the quality of groundwater in such areas is significantly influenced by both natural and anthropogenic factors. The present study aims to analyze the groundwater geochemistry in parts of Jagatsinghpur district, Odisha, with a focus on identifying the geochemical processes influencing groundwater composition and potential contamination sources. Jagatsinghpur district is situated on the east coast of India, forming part of the fertile plains of the Mahanadi delta. The region experiences tropical monsoonal climatic conditions, with a significant influence from seasonal variations in precipitation and tidal interactions due to its proximity to the Bay of Bengal. The district's fertile soils and abundant groundwater resources provide favorable conditions for agricultural activities, making it essential to evaluate groundwater quality and potential contamination threats. To conduct the assessment, a total of 62 groundwater samples were collected from various locations across the study area during both the pre- and post-monsoon seasons of the year 2023. These samples were analyzed for various physicochemical parameters, including pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and concentrations of major cations and anions sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), chloride (Cl^-), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-). The analytical procedures followed standard protocols as recommended by the American Public Health Association (APHA, 2017). Water samples were filtered, preserved, and analyzed using titrimetric, spectrophotometric, and flame photometric techniques. Statistical analyses, including correlation matrices, cluster analysis, and dendrogram construction, were employed to identify trends and potential contamination sources. The Water Quality Index (WQI) method was also utilized to assess the overall suitability of groundwater for human consumption. The electrical conductivity (EC) of groundwater in the study area exhibited a wide range, varying from 287 μS/cm to 37,586 μS/cm during the pre-monsoon season and from 336 μS/cm to 39,339 μS/cm in the post-monsoon season. This substantial variation indicates diverse hydrochemical processes affecting groundwater quality. The higher EC values suggest significant dissolved ion content, which may arise from seawater intrusion, agricultural runoff, or rock-water interactions. The dominance order of major cations in the groundwater samples was found to be $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while the anion composition followed the order $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$. The elevated sodium and chloride concentrations indicate a considerable influence of saline water intrusion, which is a common issue in coastal aquifers subjected to over-extraction and altered hydraulic gradients. A strong positive correlation ($r > 0.9$) was observed between chloride concentration and other parameters such as EC, sodium, calcium, and magnesium in both seasons. This strong correlation suggests that seawater intrusion plays a predominant role in controlling the groundwater chemistry in the study area. The intrusion is likely exacerbated by excessive groundwater extraction for irrigation and drinking water supply, which leads to reversed hydraulic gradients, allowing seawater to encroach into the freshwater aquifer. The correlation between chloride (Cl^-) & sulfate (SO_4^{2-}) ranged from r = 0.1 to r = 0.88 from the pre- to post-monsoon season. This variation suggests that additional factors, such as agricultural activities and soil leaching, influence groundwater chemistry, particularly during the post-monsoon period. The increased use of chemical fertilizers post-harvest may contribute to higher sulfate concentrations in the groundwater. Agricultural practices significantly impact groundwater quality in the region. The use of chemical fertilizers, pesticides, and herbicides can introduce various contaminants, including nitrates and phosphates, into the groundwater system. The relatively high concentrations of NO_3^- observed in some samples indicate potential leaching from agricultural fields. Post-monsoon variations in groundwater chemistry further suggest that irrigation return flow and soil leaching contribute to elevated solute concentrations. Increased rainfall during the monsoon season enhances the mobilization of agricultural chemicals, leading to their percolation into the groundwater system. To evaluate the suitability of groundwater for human consumption, the Water Quality Index (WQI) was calculated based on weighted averages of key water quality parameters. The WQI values were categorized into different classes ranging from excellent to unfit for consumption. The results indicated that a significant proportion of groundwater samples fell into the poor to very poor categories, particularly in regions experiencing higher EC and chloride concentrations. This assessment highlights the need for stringent water quality monitoring and management strategies. Cluster analysis and dendrogram techniques were employed to identify key factors influencing groundwater quality. The analysis revealed distinct clusters, indicating multiple sources of contamination. The findings of this study indicate that groundwater quality in Jagatsinghpur district is influenced by multiple geochemical processes, with seawater intrusion being a significant factor. The impact of agricultural activities further exacerbates water quality deterioration, particularly during the post-monsoon season. Given the critical dependence of local communities on groundwater resources, it is imperative to implement sustainable groundwater management strategies. This extended analysis provides a more comprehensive understanding of groundwater quality dynamics in Jagatsinghpur district, emphasizing the need for effective management interventions to mitigate contamination risks.

Keywords: *Groundwater chemistry, ion exchange, saltwater intrusion, cluster analysis, coastal aquifers*

FATE OF ORGANO-ARSENIC COMPOUNDS WITH NATURAL MINERALS AND SOILS: INSIGHTS FROM ROXARSONE STUDIES

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Arsenic poisoning in drinking water is a significant global environmental crisis, impacting millions annually, with sources of inorganic arsenic stemming from both geogenic and anthropogenic origins. While substantial research has been conducted on the fate, transport, and speciation of inorganic arsenic in various geochemical conditions, studies on organo-arsenic compounds remain limited. Evidence suggests that inorganic arsenic (As(III) and As(V)) can be effectively removed by iron minerals such as hematite and magnetite. Organo-arsenic compounds, including those adsorbed onto iron minerals like hematite and goethite, exhibit adsorption behaviors influenced by molecular size, methyl group content, and soil characteristics, including Fe and aluminum content. Adsorption is inversely related to total organic carbon (TOC) in the soil. Desorption of these compounds varies with anions such as sulfate, phosphate, and chloride, and microbial or photodegradation can convert organo-arsenic to inorganic arsenic, with potential biotransformation occurring in reverse by bacteria. Roxarsone (4-Hydroxy-3-nitrophenyl arsonic acid) (ROX) is an organo-arsenic compound used as feed additives to improve the quality and pigmentation of meat in poultry and swine farms. In this study the sorption of roxarsone on naturally occurring non-iron minerals: K-feldspar, serpentine, calcite, gypsum; iron minerals: hematite, magnetite and maghemite and clay colloids: bentonite and kaolinite, were done for the groundwater matrices. The non-iron minerals used in this study were natural and bought from Hindustan Minerals, Kolkata. Then these samples were crushed for the experiments. Iron minerals were synthesized in the AquaNano Lab by wet chemical synthesis methods. The soil samples: alluvial soil, red soil and black soil are field samples collected from different parts of India. The soil samples were collected from the field removing the top soil in the field and then air dried and sieved in the lab for further experiments. Batch experiments were conducted for 24 hours. The experiments were conducted for 10 mg/L ROX solution in groundwater matrices. The pH of the solutions after interaction were near neutral. The final concentrations of ROX after 24 hours were determined using UV-Vis spectrophotometer in AquaNano Lab. Results suggested that ROX had minimal to zero sorption for the non-iron minerals. Magnetite showed the highest sorption in case of ROX with the sorption capacity of 55.99%. The sorption capacity of ROX in decreasing order as follows: Magnetite > maghemite > hematite. The clay colloids had zero to minimal interactions with the ROX. Bentonite and kaolinite had zero sorption of ROX. The results revealed that ROX was not interacting with major rock forming non-iron minerals and soils suggesting adverse leaching to the subsurface level and posing a greater threat to the subsurface groundwater contamination and transport which warrant further investigation.

Keywords: *Organo-arsenic, roxarsone, sorption, geochemical interactions, groundwater contamination, iron minerals, soil characteristics, environmental fate and transport*

WATER QUALITY ANALYSIS OF NAINITAL LAKE BY INTEGRATING SATELLITE DATA AND LABORATORY EXPERIMENTS

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Nainital Lake is one of the pristine freshwater sources in the Kumaon region of Uttarakhand, India, and the sole source of drinking water for the local population. It has been a significant tourist spot for decades. According to the census report of 1981, the population of Nainital district is 27,002, while the 2011 census reported 3 time increase in the population of Nainital district, which is 954,605. Also, according to the tourist bureau statistics record, there is almost twice the increase in the number of tourists from 4.17 lakh in 1988 to 7.84 lakh in 2023; these lead to anthropogenic load in the lake, which degrades its water quality. The average rainfall in the Nainital region is around 2500 mm and the additional water source of the lake is from two springs, Chunadhara and Pardadhara. Although these natural inflows support the lake, unregulated urban runoffs, sewage discharge, and heightened sedimentation have disrupted its biological equilibrium. We have employed an integrated method that combines satellite remote sensing and laboratory studies to continuously monitor water quality indicators, including temporal changes in water clarity, suspended sediments, and critical physicochemical parameters.

For this study, we are integrating two approaches to easily monitor and analyze the water quality of the Nainital Lake. The first approach is to utilize the satellite data; we have leveraged the high-resolution Sentinel-2 multispectral satellite data for our study. Initially, we planned a preliminary analysis with an index-based approach in which we calculated the Modified Normalized Difference Water Index (MNDWI) and Normalized Difference Suspended Sediment Index (NDSSI). MNDWI is derived from green (Band 3) and shortwave infrared (SWIR, Band 11), which measures water clarity by suppressing non-water features whose higher values denote lower turbidity. The NDSSI is derived from red (Band 4) and near-infrared (NIR, Band 8) bands measuring the suspended sediment concentration, where higher values indicate increased loads due to runoff or human activities. We did a time series analysis of the Nainital Lake water quality based on these indexes to obtain the temporal variations in water quality from 2017 to 2024. This duration significantly alters the human-induced pollution load in the lake due to the COVID-19 pandemic. So, we did a double-period water quality analysis using these indices that have been undertaken, looking at a three-year pre-COVID period of March 2017-2019 against the period 2022-2024 to examine the impacts incurred during the lockdown of COVID-19. In the second approach, we have planned to do a laboratory-based water quality analysis. For that, we collected 12 water samples from the 12 different locations of the Nainital Lake. We analyzed physicochemical properties: Electrical Conductivity (EC), pH, Dissolved Oxygen (DO), and Oxidation-Reduction Potential (ORP). This investigation showed significant changes in the water quality and degrading nature of the Lake's self-sustaining capability.

After both these approaches, we aim to build a correlation equation developed by machine-learning algorithm using satellite and ground truth data to obtain the water quality by analyzing the satellite data. Initial trends indicate distinct patterns that have emerged between the pre-and post-COVID periods. Pre-COVID (2017-2020): Higher NDSSI values during monsoon captures showed increased sedimentation, while fluctuating MNDWI values suggested alterations in water clarity due to tourism and urban runoff. COVID Period (2020–2021): Lower values of NDSSI and higher values of MNDWI would indicate enhanced water quality due to decreased human interference around the lake. Post-COVID (2022–2024): There is a partial recovery to pre-COVID conditions that may be due to increased anthropogenic stressors. From the laboratory analysis, we found that the pH values ranged from 5.16 to 8.4, reflecting localized variations caused by organic matter breakdown and human waste outflow. Dissolved oxygen (DO) concentrations varied from 0.4 to 8.2 mg/L, with specific areas exhibiting hypoxic conditions, presumably attributable to nutrient enrichment and microbial activity. Apart from this, we are focusing on the analysis of TOC, especially for the chlorophyll study, turbidity, and nutrient levels, which seem to be the major causes affecting Nainital Lake's self-cleaning cycle. Furthermore, we will include these lab results to validate satellite observations.

Keywords: *Lakes, Water quality, remote sensing, Nainital*

INVENTORY OF RADON ABUNDANCE IN GROUNDWATER ALONG THE YAMUNA RIVER, INDIA

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Climate change has led to higher dependence of anthropogenic activities on groundwater. This demands the regular monitoring of groundwater source and quality. Recently, the abundance of radon (Rn) in groundwater has received global attention due to its geogenic source as well as adverse effects on human health. The higher exposure to radon via directly injected water or inhaled gas has proved to be carcinogenic in nature. The international organizations like US Environmental Protection Agency, European Atomic Energy Community have set the maximum concentration for safety level of radon in water to 11 Bq/L. This highlights the need to understand the source and abundance of radon in regional groundwater to avoid higher annual dose effect. The large tropical river basins host dense population due to rich groundwater resources. However, the groundwater in these large tropical river basins interacts with diverse lithology leading to higher possibility of radon exposure. In India, the large river basins of the Himalayas (Ganga, Yamuna, Brahmaputra and Indus) are well known for their dense population and agricultural intensive land use. However, there are only few reports on the radon abundance though it has significant human health impact. The available literature on radon concentration in groundwater of India or the Himalayan terrain shows observations mainly focusing on certain villages or in patches of major cities. With this in view, the present study investigated the radon concentration in groundwater of the Yamuna River basin which hosts rich groundwater resources, diverse climate and topography suitable for larger livelihood. This study provides for the first time an inventory on the status of radon concentration in the entire stretch of Yamuna River. The objectives of this study were to identify the spatial distribution variability of radon, understand the lithological controls on radon abundance, fingerprint the groundwater - river water interactions, and record the groundwater contamination status for radon along the Yamuna River.

River Yamuna originates from the Yamunotri Glacier located at an altitude of about 6300 m above msl in Uttarkashi district of Uttarakhand, India near Bandarpooch peak of the Himalayas. It flows through several states like Punjab, Haryana and Delhi before joining the Ganga River at Prayagraj, Uttar Pradesh. In addition, the major southern tributaries like Chambal, Ken and Betwa flow through the states of Rajasthan and Madhya Pradesh before joining the main channel of Yamuna River. The other tributaries of Yamuna River include the rivers like Tons, Giri, Asan, Bata, Hindon, Sindh, etc. The overall length of Yamuna River system from its origin to the joining of Ganga at Prayagraj is about 1,376 km while the river basin covers an area of about 3,66,223 km^2. The region experiences different climatic conditions with its upper reaches exhibiting cold winter and mild summer whereas in the downstream region and southwestern tributaries exhibit seasonal climate similar to major parts of Peninsular India with hot summer, relatively mild winter. The lithology is mainly dominated by silicate rocks like granites, gneiss, schists, etc. while the carbonate rocks are also present in patches throughout the basin. For this study, the groundwater samples were collected from about seventy locations adjacent to the main channel and major tributaries of the Yamuna River during June-July, 2024. About 250 ml of groundwater sample was collected at each station in a tightly sealed glass bottle. The shallow depth groundwater (<30 m) was sampled mainly using handpumps from Janaki Chatti (upper reaches) to Prayagraj (lower reaches) along the Yamuna River. Before the sample collection, the water was pumped for a longer period to avoid the previously stored water in surface. The glass bottle was also rinsed onsite thoroughly before filling with the groundwater sample for analysis. The collected groundwater samples were analyzed for radon abundance within few hours of collection which was usually within three to four hours. The radon concentration in groundwater samples were measured using RAD7 detector (Durridge Ltd.). The RAD7 instrument is a highly efficient portable alpha detector and uses passive implanted planer silicon semiconductor detector to measure alpha activity in gaseous samples. The radon concentration is then obtained from the measured alpha activity. The instrumental set-up was well purged before analysis. The measured radon concentrations in groundwater along the Yamuna River were in the range of 1.29 - 84 Bq/L during the sampling period. The lower radon abundances were found in the downstream stations which could be due to the clayey lithology. The lower radon concentration in groundwater along the river channel could also be due to the mixing of river water which are generally less enriched with radon. The higher abundances of radon were observed in the groundwater located at upper reaches of Yamuna River which may be attributed to the decay of naturally distributed uranium in source rocks. However, the average radon concentration in measured groundwater samples is found to be slightly higher than the global safety level. The generated database on radon abundance in groundwater along the Yamuna River is one of the useful tools to explore the present status of water contamination and to develop a mass awareness for sustainable water utilization in the Himalayan River basins. The government departments may utilize the radon database as an environmental tracer to demarcate the groundwater sensitive zones in the Himalayan River basins as it is a major health hazard.

Keywords: *Radon concentration, groundwater assessment, water rock interactions, river basin*

GEOSPATIAL ANALYTICS FOR ANALYSING FLUORIDE CONCENTRATIONS AND GROUNDWATER QUALITY STATUS IN PARTS OF NALGONDA, TELANGANA, INDIA

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The most reliable freshwater source in the world is groundwater. Because around 2.5 billion people worldwide depend on groundwater, its sustainability and quality are vital. Access to safe drinking water is a fundamental human right across the globe and in India, 85% of drinking water supplies are dependent on groundwater. The groundwater resources are not equally distributed or of sufficient quality, which causes shortages and issues with suitability for intended uses. Further, variations in groundwater supply and quality are influenced by both natural and anthropogenic factors. The vulnerability of water borne diseases are significantly influenced by the quality of groundwater. Fluoride is one of the major contaminants among the many water quality indicators that has drawn attention and causes considerable health dangers. A prime example of this is Nalgonda, in Telangana, which was previously the epicentre of fluorosis in India and is known for having high rates of the disease due to contaminated groundwater. High fluoride concentrations in groundwater, that occur naturally, pose a health risk to approximately 180 million people potentially affected worldwide, primarily in the global south. Within a certain range, fluoride (F^-) in groundwater can be good for human health but, when the concentrations are too high or too low, it can have negative effects. A number of factors affect groundwater quality in terms of suitableness that can be evaluated using water quality indices (WQI) and other water quality indices. In this direction, this study envisages evaluating the impact of factors affecting the status of the water quality using spatial analysis tools.

The study area chosen for the research is severely fluoride affected parts of Nalgonda district with four sub-districts (mandals). The Study area falls under semi-arid regions of the country. The four mandals (sub-districts) of the district were chosen to conduct the research, namely., Marigudda, Munugode, Chandur and Chityal. There are 17 villages within these mandals, which are susceptible to serious fluorosis as a result of drinking groundwater. The South-West Monsoon season is from June – September, Winter is January – February, Pre-Monsoon is from March – May, and Post-Monsoon (North-East Monsoon) is from October – December. The Principal Aquifer in Dindi watershed is Banded Gneissic complex. The Specific Yield in the aquifer varies from 1% - 4%. The recharge from rainfall is reported to be in the range of 5% – 12%.

The water quality parameters of 19 groundwater samples during pre and post monsoon seasons of the years 2018 to 2022 were used for the analysis. The groundwater quality parameters were analysed for pH, Electrical conductivity, Total dissolved solids, Sodium, Potassium, Calcium, Magnesium, Chloride, Bicarbonates and carbonates, Sulphates, Nitrates, Fluoride and Total Hardness. These parameters were further analysed by generating WQI. To determine whether the groundwater samples are suitable for irrigation, indicators such as the sodium adsorption ratio (SAR), electrical conductivity (EC), percentage of sodium (Na%),

residual sodium carbonate (RSC), residual sodium bicarbonate (RSBC), permeability index (PI) and magnesium ratio (MR) were estimated. These indicators were then attributed to spatial distribution analytics for determining groundwater vulnerability. The study utilized spatial interpolation method that effectively interpolates the groundwater water quality index, resulting in the creation of spatial distribution maps.

The results indicate that the groundwater is contaminated by high fluoride, total dissolved solids, nitrates and salinity ions. The findings show that in this area, fluoride determines about 80% of the WQI, rendering it unfit for human consumption. The WQI indicates that the groundwater is in poor to very poor condition, however, the fluoride concentration is within the acceptable bounds. When the fluoride concentrations are reduced to the lowest possible levels, the WQI is excellent to good quality. Since all villages in the study area rely on groundwater and 19 wells fall within unfit category water quality ratings, population of nearly 60,000 individuals are vulnerable to waterborne diseases consuming this groundwater.

Using the groundwater in this region with high magnesium concentration for prolonged irrigation may result in progressive degradation of soil structure, decreased soil permeability, and marked decrease in crop productivity. In this study, Residual sodium carbonate (RSC) and bicarbonate concentration (RSBC) measurements provide more accurate assessments than salinity relative to salt (SAR), particularly at lower salinities levels. Calcium and magnesium carbonates tend to precipitate out in waters with a high bicarbonate concentration. Utilizing excess of this groundwater can affect natural soil structures, leading to oxidative and alkaline stress, ion toxicity and crop yield deficits as well as nutritional deficiencies in both soil and crop yields. Furthermore, salinization interferes with nitrogen absorption by plants, slowing their growth and lower productivity.

Nalgonda District is well known for its fluoride contamination. By creating suitable artificial structures and desilting local natural tanks, rainwater harvesting and implementation of Tank filling schemes can increase the groundwater availability while simultaneously decreasing fluorosis incidences among its local population. In order to take additional action to improve the condition of groundwater quality, the spatial approach employed in this study seems suitable for evaluating the crucial parameters associated with groundwater quality in other hard rock regions affected by fluoride.

Keywords: *Groundwater quality mapping, geospatial analytics for WQI, fluoride concentrations, irrigation suitability indices, Nalgonda fluorosis*

ASSESSMENT OF GROUNDWATER VULNERABILITY IN JHARKHAND REGION OF INDIA USING DRASTIC MODEL

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In areas like Jharkhand, India, where groundwater is the main supply for a variety of social demands, assessing groundwater vulnerability is essential for efficient management of water resources. The danger of contamination that groundwater resources confront as a result of a mix of natural and human activity processes is known as groundwater vulnerability. Evaluating this susceptibility is essential to managing water resources effectively and preventing pollution. The state of Jharkhand, in eastern India, is distinguished by its varied terrain, which includes dense forests, mineral-rich plateaus, and a complex web of rivers. Groundwater is essential to Jharkhand's agriculture, industry, and home needs because it is an agrarian state. But a combination of natural and human-caused factors is putting this vital resource in jeopardy more often. To make sure that groundwater is shielded from pollution and misuse, it is imperative to assess its vulnerability. Groundwater vulnerability in Jharkhand is impacted by a complex web of interrelated causes, including human activity, land use patterns, and geological features. Evaluating groundwater vulnerability is crucial to maintaining sustainable management and safeguarding this priceless resource. A significant supply of drinking water, agriculture, and a number of industrial operations are all supported by groundwater. Besides a variety of human activities, including inappropriate waste disposal, industrial discharges, and agricultural runoff, as well as natural processes like soil erosion and geochemical leaching can contaminate it. By identifying regions that are most vulnerable to contamination, groundwater vulnerability assessment facilitates targeted interventions and preventive actions. Groundwater vulnerability evaluations are a vital component of land use planning, helping to direct choices about industrial siting, zoning, and agricultural methods. Policymakers and other stakeholders can put policies in place that reduce threats to groundwater quality by identifying the locations that are most vulnerable to pollution. The creation of environmental norms and regulatory frameworks to protect water resources is also supported by this evaluation. Furthermore, because contaminated groundwater can have far-reaching effects on ecosystems and communities, it is essential for maintaining environmental sustainability and public health. In the long term, thorough evaluations of groundwater risk facilitate well-informed decision-making and proactive resource management. In addition to promoting environmentally responsible development, it helps guarantee that groundwater will always be a dependable source of clean water for present and future generations.

This study intends to identify the unique vulnerabilities of Jharkhand's groundwater systems through a thorough analysis of the parameters of the Drastic model. The Drastic model, which takes into account a wide range of variables such as depth to water table, recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity is one of the most well-known techniques for assessing groundwater susceptibility. The Drastic model analyses a number of important factors, such as hydraulic conductivity, recharge, topography, impact of the vadose zone, depth to the water table, and aquifer and soil media. When taken as a whole, these components provide a thorough grasp of the hazards that Jharkhand's groundwater resources confront. It was developed as a qualitative

tool to identify areas at risk of groundwater pollution based on various hydrogeological parameters. The acronym DRASTIC stands for Depth to Water table, Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity. Shallow water tables are generally more susceptible to contamination as pollutants have a shorter distance to travel before reaching the groundwater. The depth to the water table is a critical factor in assessing vulnerability. Recharge refers to the rate at which water replenishes the aquifer. Areas with low recharge rates may be more vulnerable to contamination as there is less dilution of pollutants. The characteristics of the aquifer material, such as its permeability and porosity, influence how easily contaminants can move through it. Highly permeable aquifers are more vulnerable to rapid contaminant transport. The type of soil through which water percolates before reaching the aquifer affects vulnerability. Different soils have varying capacities to filter and attenuate contaminants. Topography plays a role in directing the flow of groundwater. Contaminants may travel more rapidly downhill, affecting vulnerability in certain topographic settings. The vadose zone is the unsaturated zone above the water table. It filters and transforms contaminants before they reach the groundwater. Understanding the impact of this zone is crucial for assessing vulnerability.

DRASTIC model and the overlay sum weighted approach are used to identify the Jharkhand groundwater vulnerable areas. The region is categorized into five groups by the final vulnerability map according to the DRASTIC index values: low (75 - 107.83), moderate low (107.84 - 117.11), moderate (117.12 - 127.1), moderate high (127.11 - 138.16) and high (138.17 - 166). The visualization indicates that the majority of Jharkhand's low-vulnerability zones are found in the state's northern and central regions including portions of the districts of Hazaribagh, Giridih and Dumka. Deeper water tables, slower recharge rates and less porous aquifer media and soil help these places by lowering the danger of contamination. On the other hand, large areas of the state's southern regions such as East Singhbhum, West Singhbhum and Southern Jharkhand are concentrated in high vulnerability zones which are more prone to groundwater contamination due to their extremely shallow water tables, high rate of recharge, highly permeable soil and aquifer materials. While moderate and moderate low exposure zones include a number of localities including Palamu, Garhwa and Ranchi, moderate high vulnerability areas are also noteworthy, encompassing portions of Lohardaga, Simdega and Bokaro. Policymakers and environmental managers may use this evaluation as a vital tool to help them prioritize and put groundwater conservation measures into action. The results emphasize the necessity of taking prompt action in high-vulnerability areas to stop pollution and guarantee long-term groundwater management across Jharkhand.

***Keywords*:** *Groundwater, vulnerability, DRASTIC model, overlay sum weighted approach, DRASTIC index, Jharkhand*

Theme 6

GROUNDWATER MODELING AND MANAGEMENT

ANALYTICAL SOLUTION TO MODEL FLOW BEHAVIOR IN UNCONFINED DUAL PERMEABILITY AQUIFERS

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Groundwater is a key resource that is crucial in supplying water for drinking, agriculture, and industrial activities. The unconfined dual-permeability aquifers are particularly important because of their unique structures, consisting of two continua namely a porous matrix continuum that stores water and exchanges it with the fracture continuum, and a fractures continuum with higher permeability. This framework permits dual-permeability models to simulate preferential flow, where fracture networks respond more rapidly than the porous matrix to external disturbances such as pumping wells, rainfall infiltration, and river flooding. The flow behavior in such systems is complex and is significantly influenced by various factors like precipitation patterns, land use changes, pumping rates, and boundary conditions. Unconfined aquifers are crucial for controlling water exchange between surface and subsurface sources, as well as in the recharge of confined aquifers, and the contaminants attenuation processes. They serve as key freshwater resources but are highly vulnerable to surface pollution. Understanding the interactions between the matrix and the fracture zones is crucial for effective management of groundwater. Comprehensive analytical solutions incorporating critical factors like precipitation, unsaturated flow, water table variation and variable pumping rates are limited in the existing literature, notwithstanding their importance. Such model developments and incorporation of these challenges into analysis necessitate the use of analytical models that describe the flow behavior in unconfined dual-permeability aquifers with good accuracy. This paper addresses these gaps through the development of an analytical model using the Laplace transform method together with GITT. This is expected to go a long way in enhancing predictions and management strategies of groundwater resources toward sustainable water management practices.

The present study develops an integrated approach to analytically and numerically model the dynamics of groundwater flow in unstressed dual-permeability aquifers. An analytical solution for the pressure head is developed in both the porous and fracture matrices by applying GITT, coupled with the Laplace transform that generally leads to a framework for solving complex boundary value problems. The analytical solution developed for a dual-permeability model has excessive contrasts of hydraulic properties in the interaction of fracture and matrix. GITT projects complicated governing equations with critical boundary conditions representing source and sink terms standing for precipitation and variation of the water table in the aquifer. The solution of the auxiliary problem for the homogeneous boundary condition is used by GITT, while the filtered or steady-state solution is used for the nonhomogeneous boundary. In the Laplace transform, the time dependence is considerably simplified, the equations are converted into algebraic form, and then the application of the Inverse Laplace Transform obtains the solution in the original time domain. The numerical-analytical framework provides, in an effective way, the heterogeneity of the system. It ensures that the obtained results are representative of real conditions with greater accuracy than numerical approaches. Numerical simulations are performed to compare the numerical results with the model in question through the application of the finite difference method by means of MATLAB software. It is a tool utilized as a numerical solution to compare with the analytical result in order to assess its accuracy and reliability. The FDM discretizes the spatial and temporal domains so that scrutiny of groundwater flow dynamics in detail for different scenarios can be performed. The numerical method gives a good insight, but emphasis is laid on the analytical solution due to its precision in predicting flow behavior under various conditions: All values of various parameters and coefficients like hydraulic conductivity, specific liquid capacity, and transfer coefficient of liquid are borrowed from the available literature for the solution. These parameters are basically required to assess the impact of precipitation, fluctuating water table, unsaturated flow, and variable pumping rates in groundwater flow.

The various results from the analytical model describe the interaction between fracture and matrix with dual-permeability in unconfined dual-permeability aquifers. Hereby, the model takes into account variable boundary conditions, fluctuating water tables, source/ sink terms, and pumping rates essential for the management of groundwater. A comparison is carried out between pressure head profiles obtained from the GITT analytical solution to numerical simulations using the finite difference method in MATLAB. These solutions are in excellent agreement with each other, especially for longer times, hence confirming the reliability of the GITT approach coupled with the eigenvalue problem. For higher values of the exchange term coefficient, pressure head equalization between the porous matrix and fracture continuums occurs more rapidly.

This present research provides substantial insight through a comprehensive analytical methodology that can be used to explain the behavior of groundwater flow in unconfined dual-permeability aquifers. The incorporation of these key factors-precipitation, unsaturated flow, fluctuating water table, and pumping rate into the analytical solutions hints at the limitation of previous models. The solution, by the GITT technique, the Laplace transform method, etc., allows for analytical solution and thus gives a very good model of the interaction between matrix and fracture systems with essential handling of complex boundary conditions. The developed analytical model provides an accurate prediction of groundwater behavior and hence emerges as a reliable tool for practical application to environmental and geotechnical engineering. These numerical solutions, by the finite difference method using MATLAB, would be used for comparison with the analytical results, so that this model can perform well in different scenarios and be stable and adaptable. This research will contribute to enhancing the prediction capability of the response of aquifers under various factors, such as precipitation, which in turn will be vital in improving strategic groundwater management. Additionally, the outcome will form the foundation for further analysis into more complicated aquifer systems, promote understanding of the dynamic nature of groundwater flow, and serve as a basis for sustainable management of water resources.

Keywords: *Analytical solution, dual-permeability model, generalized integral transform technique, finite difference method, laplace transform, matrix-fracture interaction*

ASSESSMENT AND PREDICTION OF CIPROFLOXACIN ANTIBIOTIC IN GROUNDWATER DUE TO PHARMACEUTICAL WASTE DISPOSAL IN MUSI RIVER, HYDERABAD

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Groundwater is a major water source for domestic, agricultural, and industrial purposes. The quality of groundwater is crucial for its several uses. However, expanding industrial sectors is causing severe environmental issues to surface and sub-surface water bodies. Their contamination by industrial effluents is one of the major issues. These effluents include untreated discharge from industries. In the present study, the impact of pharmaceutical discharge in surface water and its effect on groundwater is examined. For this, the study area of Greater Hyderabad is chosen. In Hyderabad, several industries are located near the bank of Musi River and these industries are responsible for its contamination. The available studies show that the river is heavily polluted with pharmaceutical waste. It leads to an overabundance of antibiotics in the river water. The presence of these antibiotics is also a threat to the groundwater bodies in the vicinity of the Musi River. The excessive antibiotics in the water promote the spread of antimicrobial resistance bacteria (AMR). It affects aquatic fishes and as a result, humans become resistant to antibiotics. Ciprofloxacin antibiotic contamination in groundwater is a major health concern. In this study, groundwater contamination due to ciprofloxacin antibiotic is predicted using MODFLOW and MT3DMS models. To conduct this study, initially, 26 water samples at different locations of Musi River were collected and these samples were tested in the laboratory to estimate the ciprofloxacin contamination using UV-Visual spectrophotometer at 278 nm wavelength. The laboratory results showed that the river water is heavily polluted by active pharmaceutical ingredients (API) and the average ciprofloxacin concentration is 6 ppm in the river water. Moreover, soil samples were collected using the reverse rotary drilling technique from every 0.6 m of depth to obtain stratigraphy modeling data and to determine the distribution of soil in the study area. The hydraulic conductivity of soil was determined using the falling head permeability test. For various input parameters of the model, hydrological data was taken from CGWB (Central Groundwater Board) and WRIS (Water Resource Information System) reports. Further, ciprofloxacin transport in the groundwater of the study area is modeled in the GMS (Groundwater Modeling System) software. For this, a conceptual model of Hyderabad city is set up in the GMS. To conduct groundwater flow modeling, MODFLOW model and for contaminant transport, MT3DMS model were used. The double-beam spectrophotometer was used to quantify the concentration of ciprofloxacin antibiotic for 26 river water samples. The spectra of ciprofloxacin show maximum absorbance at 278 nm wavelength. Similarly, all collected samples were analyzed precisely in a UV-visual spectrophotometer. Absorbance values were noted for each sample. The concentration of contaminant was computed by using a straight-line equation from the calibration curve. Average ciprofloxacin concentration was computed as 6 ppm from all 26 samples. The hydraulic conductivity of sediments was determined by using the falling head permeability test. The initial water level (h1) was marked and the valve was open for 2 min 15 seconds. Reading of the final water level (h2) was noted down, and then the hydraulic conductivity (k) was calculated by the using falling head permeability equation. A Conceptual model is created for the study area using GIS shape file and by delineating its boundaries with all source and sink. Various coverages were added for respective feature objects (viz. boundary of feature object, Sources and sink, Recharge and Layer Properties). Thereafter, the model was converted to MODFLOW. A steady-state conceptual model approach was used to develop contaminant transport plumes across the river concerning different stress periods and to predict further groundwater contamination in the next upcoming years. The sources for input data were collected from authentic Govt. organizations. The origin coordinates for Hyderabad district, study area was covered between 17°23'11" N and 78°30'12" E.The developed flow models show the present groundwater flow direction, i.e. from Hussain Sagar Lake. The depth of the water table is higher in the northern part (Hussain Sagar Lake) and sequentially lower down towards the southeast (Peerzadiguda) side. Hence, the groundwater is flowing from the north to southeast direction. Four different scenarios were taken at a regular interval of 10 years, starting from 2022. To develop the flow model, the hydraulic conductivity (0.275 m/day) and transient values for recharge were added to simulate the results. The results of the study show that the groundwater regions is likely to get contaminated with ciprofloxacin in the future. This case study not only highlights the complexities associated with antibiotics pollution but also serves as a model for assessing similar risks in other regions. Given the alarming trends in antibiotics contamination and its potential health implications, our findings advocate for enhanced regulatory frameworks and community awareness programs to mitigate the risks associated with the contaminated groundwater. It also emphasizes the need for stricter regulations to control the discharge of antibiotics into the environment, particularly from sources like pharmaceutical industries and hospitals. Additionally, it calls for community-level awareness programs to educate the public on safe disposal practices, pollution prevention measures, and the importance of protecting groundwater resources.

Keywords: *API (Active Pharmaceuticals Ingredients), GMS (Groundwater Modeling System) Ciprofloxacin, MODFLOW, MT3DMS*

GIS-BASED GROUNDWATER POTENTIAL ANALYSIS FOR SUSTAINABLE EXTRACTION AND RECHARGE PLANNING: A CASE STUDY FROM NORTH CHENNAI, TAMIL NADU, INDIA

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Water is one of the basic requirements for living. Out of all the earth's water resources, only 3% is present as fresh water. While the majority of freshwater is present in the form of ice, nearly 30% is present in groundwater, and less than 1% is present as surface water in the form of lakes and rivers. Around the world, groundwater provides a reliable source for water supply systems. It is one of the primary sources of irrigation and ecological support in addition to drinking water. Generally, groundwater is considered less polluted than other sources of available water due to lack of direct contact. Still, in recent decades, groundwater quality has been decreasing due to its high demand. Water scarcity is also a growing concern nationally and internationally, with regions depending on groundwater facing considerable pressure from population growth, industrial demand, and over-extraction.

The study area combines five zones in Chennai Corporation, Tamil Nadu, namely Thiruvottiyur, Manali, Madhavaram, Tondirapet, and Royapuram, called North Chennai. It lies within the boundaries of 13.0483° N to 13.2460° N latitudes and 80.2574° E to 80.3521° E longitudes, covering an area of 68.33 km^2. It is a residential zone within the Chennai Metropolitan area. It is characterised by its vibrant port activities, dense population, and extensive industrial establishments like significant power plants, refineries, and factories, making it a pivotal contributor to the region’s economy. The urban sprawl and heavy industrial activity in the North Chennai region have significantly strained local natural resources, particularly groundwater, often outpacing natural recharge rates. This over-reliance on groundwater, combined with limited surface water availability, alongwith fluctuating monsoon-dependent recharge rates, puts tremendous pressure on its groundwater resources. Due to industrial emissions and wastewater discharge, the region is susceptible to air and water pollution, making pollution control and sustainable resource management essential for its future.

In this study, the Groundwater Potential Zone has been identified through a spatial data model of QGIS (quantum geographic information system) using different primary thematic layers like soil map, geology, land use land cover, slope map, relative relief, dissection index, geomorphology, drainage density, drainage frequency and drainage texture. First of all, various data or maps were collected like LULC (land use land cover) map from ESRI (environmental system research institute), DEM (digital elevation model) with a resolution of 30 metres from USGS (United States Geographical survey), soil map from FAO (food and agriculture organisation), geology and geomorphology maps from BHUKOSH. It takes a combination of datasets, plugins, and tools to create thematic layers in QGIS, such as soil maps, geology, land use/land cover (LULC), and others. While QGIS's Raster Calculator or SAGA GIS Terrain Analysis can determine slope and relative relief by processing elevation data (DEM), the Semi-Automatic Classification Plugin (SCP) helps with LULC classification by processing satellite images. A Raster Calculator can be used to combine slope and relative relief data to create a Dissection Index.

The Geomorphometry and Gradient Metrics plugin in QGIS can be used to evaluate geomorphology layers. After digitizing stream networks or performing hydrological research using Hydro tools, users can utilize Line Density tools to determine drainage density, frequency, and texture. Hence, these operations collectively enable the creation of the above-mentioned 10 primary thematic layers. The various thematic layers have been classified into 4 categories, namely: Drainage (density, frequency, texture), Slope (relative relief, dissection index, slope), Natural resource (geology, geomorphology, soil map), and LULC. In this study, a GIS approach termed weighted overlay analysis has been used to evaluate several spatial parameters by giving each one a proportionate priority. In order to make spatial judgments, this strategy incorporates multiple layers, each of which represents a unique criterion (such as soil type, elevation, or land use). Based on its applicability or impact on the analytical goal, each layer has been classed into a common scale (e.g., 1 to 10). Each layer has then been given a weight to represent its significance or impact in relation to the other layers. After classification, suitable weights have been assigned to them according to their importance in groundwater potential zones. All thematic layers have not been superimposed at a time but done in the above-mentioned categories, thus obtaining 4 intermediate thematic layers. This has been done so that errors can be pointed out accurately. Next, the 4 thematic layers have been superimposed to form a groundwater potential map.

The study produced a detailed map identifying zones of low, medium, and high groundwater potential across North Chennai. Areas with a high potential for recharging and those appropriate for sustainable groundwater extraction have been highlighted on the map. The study is expected to assist initiatives to decrease water table loss, lessen saline intrusion, and sustainably balance groundwater resources by identifying regions susceptible to over-extraction and emphasizing possible recharge zones.

Keywords: *Groundwater potential, North Chennai, QGIS, extraction and recharge planning*

RIVER AQUIFER EXCHANGE DYNAMICS IN VARUNA RIVER THROUGH DIFFERENTIAL FLOW GAUGING AND NUMERICAL GROUNDWATER MODELLING

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Thomas C. Winter explained that the connection between groundwater (GW) and surface water (SW) bodies in various landscapes is dynamic. This interaction between rivers and aquifers is referred to as River Aquifer Exchanges (RAE). The exchange processes are bidirectional and depend on the hydraulic gradient between the surface water bodies and the adjacent aquifer. There are several methods to quantify River Aquifer Exchanges (RAE), ranging from field techniques to analytical and numerical approaches. At the point scale, RAE is typically measured using seepage meters, temperature loggers, and mini piezometers. For small segment scale measurements, the hydraulic gradient is used to calculate Darcy's flux, and geochemical tracers may be employed. At the reach and larger scale, measurements are usually conducted through water balance calculations between two gauged stations. However, available research on determining RAE through numerical modeling is primarily limited to a regional scale and often overlooks small-scale dynamics. Field-based methods can be exhaustive and require extensive data collection. To address this gap, this research examines River Aquifer Exchanges (RAE) in a small groundwater-fed river by integrating Differential Flow Gauging (DFG) observations into a calibrated groundwater flow model.

In this study, a comprehensive local scale model has been developed to simulate a 34.6 km stretch of the Varuna River Basin (VRB) using the MODFLOW-NWT software. This model employs a parent-child modeling approach, allowing for a detailed representation of groundwater interactions within the specified area. To establish accurate boundary conditions for this localized model, a regional scale model of the lower middle Ganga Basin was utilized. This broader model provided the necessary hydrological context and data to ensure precise simulations. The river itself has been modeled using the Streamflow Routing (SFR2) package, which effectively integrates the hydrological fluxes generated by the area's hydrological model. This integration is crucial as it allows for the assessment of how surface water and groundwater interact within the basin. To calibrate the model accurately, transient groundwater observations were collected from 36 strategically placed open wells throughout the river section. These observations provided valuable data regarding the aquifer parameters and riverbed conductivities. In addition, transient data from eight specific cross-sectional areas were gathered to support the calibration process. Measurements of the groundwater table were taken meticulously with a measuring tape, supplemented by precise positioning data obtained from a Differential Global Positioning System (DGPS) unit (Sokkia GRX2). The assessment of river discharge at the eight cross-sections was conducted using an Acoustic Doppler Current Profiler (ADCP) (Sonotek-M9), a sophisticated instrument that measures water velocity and discharge in rivers. This data is essential for understanding the hydrodynamics of the river and its relation to the surrounding groundwater system. To refine the aquifer parameters and achieve a high level of accuracy, the particle swarm optimization algorithm was applied. This advanced computational technique helped minimize the root mean squared error between the observed data and the simulated results, thereby enhancing the overall reliability of the groundwater model within the Varuna River Basin.

Analysis of the data indicates that during the lean flow period, the average groundwater (GW) table in the study area is consistently measured at approximately 10.2 meters below ground level. This depth reflects variations in groundwater levels that experience increases between 0.05 meters and 0.3 meters in response to heightened aridity in the region. Additionally, it has been observed that the stage of the Varuna River exhibits a downward trend as temperatures rise, suggesting a correlation between higher air temperatures and decreasing river stages. In June, the Varuna River recorded its lowest stage, with measurements ranging from 68.279 meters above sea level (m asl) down to 62.805 m asl. This significant drop indicates a substantial reduction in water availability during a critical period. Correspondingly, measurements from nearby wells revealed fluctuating water levels between 66.16 m asl and 71.45 m asl, which highlights a pronounced hydraulic gradient during the pre-monsoon season. Such gradients are indicative of the dynamic interactions between surface water and groundwater during this time.

The alluvial deposits in the Varuna River Basin (VRB) demonstrate a significant heterogeneity, which is particularly evident in the calibrated properties of the aquifer, including hydraulic conductivity and storage coefficients. These variations affect not only the movement of water through the soil but also the overall water retention capabilities of the aquifer. Average losses or gains at each river section exhibit variability, ranging from 6.9% to 12.06% of the total inflow from preceding sections. Interestingly, there is an overall average gain of approximately 9.92%, indicating that, on average, more water enters the aquifer than exits it during the dry flow period in the monitored sections. As the measurement periods unfolded, the contribution from RAE became increasingly significant, particularly during the intervals from May to June 2022 and from January 5 to February 17, 2023. This trend underscores the aquifer's reliance on base flow during the dry season, whereby groundwater replenishes surface water sources to maintain flow levels in the river.

Further analysis of simulated RAE data illustrates a complex and dynamic interaction between surface water (SW) and groundwater (GW) within the region. Notably, most sections of the river exhibit a pattern of losing water to the aquifer during the rainy season. After the monsoon, the rate of interaction at these losing reaches begins to diminish, while the contribution of groundwater to the river in the lower reaches increases, indicating a shift in the hydrological dynamics post-rainy season. Ultimately, the overall patterns of RAE dynamics witnessed in the Varuna River are characterized by losing reaches that experience low seepage rates, signifying the need for careful management of this valuable water resource. In the Varuna basin, the River Aquifer Exchange (RAE) is particularly noticeable in the lower reaches of the river, especially after the confluence of its two tributaries. The upper reaches of the river system are shallow and often disconnect from the groundwater during the pre-monsoon season. In contrast, the lower reaches primarily receive groundwater from the adjacent aquifer. However, the exchange rate is relatively low due to the reduced hydraulic conductivity of both the shallow aquifer and the riverbed. Additionally, the calibrated hydraulic conductivity of the riverbed indicates significant heterogeneity.

Keywords: *Varuna River basin, river aquifer exchanges, MODFLOW, differential flow gauging, particle swarm optimization, parent-child models*

ASSESSMENT AND PRIORITIZATION OF GROUNDWATER QUALITY PARAMETERS USING MCDM TECHNIQUES

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Groundwater is crucial for drinking, domestic, industrial, and agricultural needs. The rapid growth of population and urbanization reduces the water recharge areas. The over-drafting of groundwater may increase the chance of water contamination due to deeper layers having different geological formations and it also increases the cost of water usage. The decline of water level promotes deeper excavation due to poor groundwater recharge. The groundwater development has reached more than 70 per cent in most parts of the country and now moving to the dark zone, which indicates the decline of groundwater level, to fulfil the demand. This overdevelopment exposes different aquifer layers, degrading water quality, and resulting in contamination that can be harmful to health, crop yields, and ecosystems directly or indirectly. So, there is a need to evaluate the groundwater quality and suggest remedies to minimize the wastage of groundwater based on qualitative evaluation. It supports sustainable water use, helps to assess compliance with regulatory standards, and also helps in the prevention of health risks. Regular groundwater quality assessments are essential for maintaining agricultural productivity and effective water resource management, thus safeguarding the overall integrity and safety of water resources. The qualitative evaluation of groundwater is a comprehensive process, conducted to measure the physical parameters such as pH, Ec, turbidity, total dissolved solids, ions and other parameters such as heavy metals etc. Previous studies on groundwater quality in Varanasi reveal significant concerns regarding water contamination due to anthropogenic and natural factors. High concentrations of parameters like total dissolved solids (TDS), nitrate (NO_3^-), fluoride (F^-), and heavy metals such as lead (Pb) and arsenic (As) have been reported, often exceeding permissible limits set by the WHO and BIS. Rapid urbanization, unregulated industrial discharge, and improper waste management are primary contributors to groundwater pollution. In various studies it was found that the Ganga River system and fluctuating water tables, influence the groundwater quality of Varanasi, leading to spatial variability across the region. Evaluating the water quality of Varanasi now becomes crucial due to rapid urbanization, industrial discharge, and agricultural runoff, which degrade groundwater. Ensuring safe water becomes vital for public health, sustainable development, and addressing contamination risks of this densely populated region. In this study, the water quality of the study region was evaluated by developing a water quality index and ranking the site of observation well for evaluating the potential area of water contamination. The study also aims to identify the factors contributing to the variation of groundwater quality parameters, determine the sources of contamination, and assess the impact of specific drivers. These findings emphasize the need for robust water quality management strategies to safeguard public health and sustainable water use in Varanasi. This research considered 15 physical parameters of water quality to develop an index using different MCDM techniques, to evaluate the water quality. The water quality was analyzed through AHP, TOPSIS and Fuzzy AHP MCDM techniques. These techniques, help in developing the Water Quality Index (WQI) by assigning weights to key parameters (water quality) based on their significance. They prioritize locations by ranking groundwater quality across sites, offering a systematic, objective, and efficient approach

compared to traditional methods. These MCDM technique-based models have been developed to identify the impacts of different influencing parameters on the overall WQ potential. Techniques like TOPSIS and Fuzzy TOPSIS help in ranking the well (location) and others (AHP, Fuzzy AHP and Entropy) are used to develop the water quality index. Ranking of wells helps in prioritizing for management and the water quality indices (WQIs) give a numeric value to summarize the overall quality status compared to quality standards by aggregating multiple physicochemical data into a single value. Results of analysis carried under the study highlight that nitrate (NO_3^-) and TDS are the most critical parameters determining the water quality of the study area, with weights of 0.15 and 0.13, respectively. The wells near urban clusters and industrial zones, such as the Varuna River basin and Cantonment regions, fall under 'moderate to poor' water quality category and southern Varanasi, indicates better water quality. Water quality index developed under the study are expected to help in the design and monitoring of water conservation structure. The results indicate varying degrees of water quality across different areas of Varanasi, highlighting regions with critical quality concerns. The observed variations in groundwater quality across the region highlight the significant impact of human activities, such as untreated wastewater, agricultural runoff, and unregulated industrial discharge. The use of AHP-TOPSIS methods for evaluating the Groundwater Quality Index (GWQI) has effectively identified priority areas for intervention and provided a valuable approach to developing sustainable groundwater management strategies. This study underscores the need for regular monitoring and management strategies to ensure safe drinking water and sustainable groundwater use.

Keywords: *WQI, AHP, TOPSIS, Fuzzy AHP, Fuzzy TOPSIS*

GROUNDWATER CHARACTERIZATION THROUGH MODELING EXERCISE IN THE UPPER PART OF AJOY-DAMODAR INTERFLUVE OF WEST BENGAL, INDIA

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The study focuses on simulating groundwater flow in the shallow aquifer zone beneath the upper part of the Ajoy-Damodar interfluve in the state of West Bengal. This region is of significant hydrogeological interest as it encompasses the renowned Raniganj Coalfield, where mine dewatering remains a critical challenge in numerous open-cast mines. The study area includes the Gondwana group of rocks in the west and extends to the older alluvium deposits in the east. The aquifer system is primarily composed of Gondwana sandstone horizons interspersed with shales and overlaid by laterites. The simulation aims to better understand the groundwater dynamics of this region, particularly in relation to mining activities. To develop the conceptual groundwater flow model, the study area was bounded by three major rivers: Barakar River to the west, Ajoy River to the north, and Damodar River to the south. The eastern boundary is defined by a transition from older to younger alluvial deposits. The model was constructed using the MODFLOW computer code, which is widely used for simulating groundwater flow. Boundary conditions were incorporated to account for the hydrological inputs from the rivers, and relevant hydrogeological parameters, including hydraulic head data from both central and state government agencies, were used. The model has been run in both steady-state and transient-state conditions to simulate varying groundwater flow scenarios. The groundwater flow model was successfully calibrated and validated, providing insights into the flow dynamics within the shallow aquifer zone. The model accurately represented the regional groundwater behavior and responded to changes in boundary conditions. The results showed the influence of the Barakar, Ajoy, and Damodar rivers on groundwater flow, as well as the impact of lithological transitions in the east on the groundwater regime. However, the lack of detailed micro-level water data, particularly around the coal mining pockets, posed a limitation in fully capturing the groundwater flow dynamics in these localized areas. The developed groundwater flow model serves as a valuable tool for understanding the groundwater dynamics in the Ajoy-Damodar interfluve, especially in the context of coal mining activities in the region. While the model has been calibrated and validated successfully, the absence of high-resolution, micro-level water data around the coal mining areas remains a significant limitation. Further studies incorporating more detailed hydrogeological data would enhance the accuracy of the model and its applicability in addressing mine dewatering challenges and other groundwater management issues in the region.

Keywords: *Groundwater characterization, groundwater flow model, boundary conditions and MODFLOW computer code*

EVALUATING STATUS OF GROUNDWATER DYNAMICS USING GEO-SPATIAL WATER LEVEL FLUCTUATION MAPPING FOR DINDI WATERSHED

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In Telangana region, during the last few decades, there was a steep decline in the area irrigated under tanks and the negligible increase in irrigation under Major and Medium irrigation projects which led to over exploitation of ground water. One such case study is the Dindi watershed where the groundwater status is over exploited. A new Lift irrigation project is in pipeline called the Sri Ramaraju Vidyasagar Rao Dindi Lift Irrigation Project (SRVR DLI Project) which envisages to provide irrigation and drinking water to the most severely affected areas by fluoride and the drought prone areas of Devarakonda and Munugodu constituencies of Nalgonda District.

Groundwater has become the sole source of irrigation in non-command regions due to frequent failures of the hydrological cycle. Because to the hydrogeological complexity and lack of understanding of the aquifer systems, groundwater availability has been overstated. The groundwater table fluctuation technique is one of the effective approaches for evaluating groundwater availability in India's hard rock regions. Water table maps are essential tools for managing water resources in arid and semi-arid regions. Due to the numerous observation wells, it might be difficult to spatially evaluate water table oscillations and determine time series changes in static groundwater levels at the watershed scale. Furthermore, a spatial framework analysis of the data with reference to a global datum is required in order to comprehend the groundwater dynamics of the watershed. In this context, a case study has been carried out in one of the watersheds in the hard rock areas of Telangana state (Dindi watershed, Nalgonda district) with a purpose to analyze dynamics and interaction aspects of aquifer system. The study area falls under semi-arid class, and is covered mostly by hard rocks, feasible for bore wells. As groundwater irrigation is common in the study area, it may cause groundwater level decline due to over exploited stage of groundwater development. Extensive extraction of groundwater for irrigation and other uses is exerting stress on the resource. Therefore, formulation of a robust groundwater management policy is essential for long term sustainability of aquifer systems in this region. To facilitate this, initially the dynamics of groundwater aquifer systems need to be understood. For the purpose, analysis of long-term groundwater levels has been carried out in one of the watersheds known as the Dindi watershed. Long term groundwater level and quality data from this watershed for thirty-five well-locations have been analyzed in time and space for any trends or fluctuations. Based on elaborate analyses, useful inferences on groundwater trends and water quality fluctuations in the study area are identified and presented in the paper.

In the previous few decades, the Telangana region has seen a sharp decrease in the area irrigated under tanks and a small growth in irrigation under Major and Medium irrigation projects, which has resulted in overuse of ground water. An instance of this can be found in the Dindi watershed, where the overexploitation of groundwater has occurred. There's a new lift irrigation project in the works called the Sri Ramaraju Vidyasagar Rao Dindi Lift Irrigation Project (SRVR DLI Project). Its goal is to supply drinking water and irrigation to

the areas of Nalgonda District that are most vulnerable to drought as well as the area's most severely affected by fluoride. The Telangana state groundwater department with NIH has considered the area of Dindi to study the impact of LIS on groundwater status of the region. Specific objectives are developed to study the issues of micro-basins as representative studies in Krishna River basins of Telangana. The objectives are achieved with the use of various statistical tools and designing case-based data products to prepare ground water model development for Dindi micro-basin in Krishna River basin. Therefore, the objectives of this study are to assess the long-term changing pattern of rainfall using statistical analysis; to study the declining water levels in aquifers based on observed Groundwater levels; and to identify the sectors under water-stressed regions for planning sustainable groundwater development and management.

The study area is a command watershed which has an area of 2334 km^2. The study area falls under semi-arid regions of the country. The South-West monsoon season is from June – September, Winter is from January – February, Pre-Monsoon is from March – May, Post-Monsoon (North-East Monsoon) is from October – December. The Piezometric static Groundwater level observations of 35 monitoring stations have been used for statistical analysis of groundwater dynamics for Telangana State Groundwater Department. Rainfall data has been collected from concerned department and utilized. In this study, AGHW modelling has been used to prepare dynamic piezometric surfaces to categorize the study area into different zones based on transient water level measurements. Trend is analyzed for these zones based on change detection concept where the areas are observed to be expanding or reducing in a particular Groundwater level zone.

The changes in rainfall trend can have a significant effect on the watershed conditions and groundwater availability. Hence, for the watershed considered the rainfall trend analysis is carried out to check the changes in the long-term rainfall. If there are significant changes then it is quantified by the statistical tests performed. The Aquifers largely gets recharged in the monsoon season and aided to some extent in the post-monsoon season. Hence, to analyze the behavior of groundwater levels AHGW tool have been used to observe the distribution of transient groundwater levels in study area for Pre-Monsoon, Monsoon and Post-Monsoon seasons for the year 2015 – 2018 having consistent data. The groundwater aquifers are classified based on water level variation characteristics into 8 classes. 150-180 m, 180-210 m, 210-240 m, 240-270 m, 270-300 m, 300-330 m, 330-360 m, 360-390 m above MSL. 360-390 m range are shallowest aquifers and 150-180 m range are deepest aquifers. Use of geospatial applications such as ArcHydro Groundwater tools can effectively help in visualizing the categorization of Piezometric heads of aquifers. The dynamics of groundwater stressful regions can be identified by long term aquifer information mapping. The spatial rainfall distribution using iso-hyetal procedures can help in understanding the variations and trend in rainfall pattern and its impact on groundwater recharge. It is found through this study that although monsoon rainfall trend is towards above normal, there is a decline in post-monsoon recharge. This may be attributed to the decreasing rainfall trend along with the extensive groundwater exploitation in post-monsoon season for agricultural and drinking purposes. This is evident from the results of AGHW modelling which shows that the zones with shallow groundwater levels (300-390 m above MSL) is decreasing and the zones with deeper groundwater levels (150-240 m above MSL) is expanding over past few years.

Keyword: *Groundwater, Arc-Hydro, trend analysis, GIS, watershed,*

EFFECTS OF WATER EXTRACTION ON MAXIMUM LONGITUDINAL PLUME LENGTH: A NUMERICAL INVESTIGATION FOR CONTAMINANT SITE REMEDIATION

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Contaminated sites pose significant threats to groundwater resources. In India, 240 such sites have been identified in the year 2022, and the number is likely to increase owing to increasing crude oil consumption and its storage facilities. Globally, non-aqueous phase liquids (NAPLs), including petroleum hydrocarbons and chlorinated solvents, have been thoroughly investigated through extensive projects. Due to their persistence and potential to form long contaminant plumes that degrade groundwater resources, NAPLs pose significant challenges. However, subsurface modelling of NAPLs in India remains limited, with most studies focusing only on pollutants near the groundwater table. While many studies have examined contaminant transport under natural conditions, few have analysed the impact of external stresses such as water extraction on subsurface conditions. Groundwater extraction, commonly practiced for water supply, can significantly alter hydraulic gradients and flow patterns within an aquifer, potentially affecting the migration of contaminant plumes. Addressing this research gap, this study numerically investigates the effects of water extraction on the maximum longitudinal plume length ( ) of a contaminant plume generated by a contaminant source. By simulating various scenarios of groundwater extraction, we aim to provide insights into how water extraction effects the contaminant plume dynamics.

A three-dimensional numerical model was developed using MODFLOW-2005 for simulating groundwater flow and MT3DMS for modelling contaminant transport. The model represents a homogeneous, isotropic, and fully saturated aquifer with uniform hydraulic properties, consistent with the analytical model. The domain dimensions were selected to capture the full extent of the contaminant plume under steady-state conditions. To ensure computational efficiency, several model domains with different grid discretization were tested. The final model employed a refined grid in the vicinity of the contaminant source and extraction wells to accurately capture steep concentration gradients, flow velocities. Boundary conditions were specified as constant head boundaries to maintain a uniform flow across the domain. Model validation was performed by comparing the numerical plume length estimates ( ) with the analytical solution. Our numerical model demonstrated 97.3% accuracy with the analytical solution, validating its suitability for scenario analysis. Simulation scenarios were devised to quantify changes in by varying three main parameters: 1) Spatial locations of extraction wells: Wells were placed at different positions along and perpendicular to the groundwater flow direction, both inside and outside the analytical plume extents; 2) Extraction rates: Pumping rates were varied from low to high values to assess the sensitivity of to the intensity of water extraction, and 3) Number of extraction wells: Scenarios included single well extraction and multiple wells operating simultaneously, with total extraction rates kept constant for comparison. These scenarios aimed to assess the direct and indirect impacts of water extraction on plume dynamics and to identify optimal strategies for plume management. The simulation results demonstrate that the placement and operation of extraction wells significantly influence the contaminant plume length ( ). When extraction wells are located within the plume specifically along the centre of the model domain where they directly intersect the contaminant plume decreases exponentially with increasing pumping rates. This reduction is attributed to the direct removal of contaminants through pumping and the enhanced dispersion caused by increased groundwater velocities near the well.

In contrast, extraction wells situated outside the plume, particularly those positioned farther from the contaminant source, have a minimal effect on reducing . In some instances, a slight increase in plume length was observed, likely resulting from alterations in the hydraulic gradient that promote downstream migration of the plume. These wells primarily influence groundwater flow patterns without effectively removing contaminants, leading to negligible or even adverse effects on plume length. Additionally, the use of multiple extraction wells resulted in a smaller reduction in compared to a single well operating at an equivalent total extraction rate. The reduced effectiveness is attributed to the distribution of pumping rates among multiple wells, which leads to lower individual well capacities and decreased contaminant capture due to lower contaminant concentrations at each well location. This finding suggests that consolidating extraction efforts into a single, strategically placed well within the plume may be more effective for plume reduction than dispersing the extraction across multiple wells.

Our findings categorize the impacts of water extraction on into two types: 1) Direct contaminant extraction: Significant reduction in plume length occurs when wells are strategically placed within the plume and operated at sufficient pumping rates to capture and remove contaminants, and 2) Indirect mixing effects: Wells located outside the plume primarily influence groundwater flow patterns, inducing mixing but not effectively removing contaminants, resulting in negligible changes to . In some cases, these mixing effects led to slight increases in plume length, indicating potential unintended consequences of poorly placed extraction wells.

This study highlights the critical importance of well placement and pumping rates in controlling contaminant plume migration. Integrating water extraction into contaminant transport modelling is essential for accurately predicting plume behaviour and designing effective remediation strategies. The numerical models developed in this research serve as powerful tools for preliminary assessments, enabling stakeholders to evaluate various remediation scenarios before committing to costly field interventions.

Strategic placement of extraction wells within the contaminant plume can significantly reduce plume length, mitigating risks to downgradient water users and environmental receptors. Conversely, poorly planned groundwater extraction may fail to control plume migration and could exacerbate contamination spread. While pump and treat remediation methods are extensive and expensive, the insights gained from this study facilitate more targeted and cost-effective remediation efforts. By precisely determining the extent of subsurface contamination and optimizing well configurations, practitioners can enhance the efficiency and effectiveness of remediation programs.

Keywords: *Contaminant transport, groundwater extraction, plume length, numerical modelling, MODFLOW, MT3DMS, NAPLs, contaminated site modelling*

3-D GROUNDWATER FLOW MODELING IN YAMUNA MICRO-WATERSHED USING FEFLOW

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Over the period, northwest India has emerged as one of the most groundwater (GW) overexploited regions due to its geological, climatic, and anthropogenic complexities. Over-pumping of resources to meet the enhanced agricultural, domestic, and industrial demands, coupled with continuously changing climatic patterns, has amplified the GW scarcity and deepened the water table in the region unexpectedly. The GW estimations have been studied using the in-situ and GRACE estimations, flux-based numerical models, and data-driven modeling techniques. Spatial and temporal coarse resolution and noise contamination, data-oriented results, and being a more complex physical system, the GW balance assessment poses a great challenge to acquire a real picture of its variability and flow patterns. Numerical models have demonstrated their efficacy in modeling by employing complex mathematical algorithms to represent the GW flow intricacies and dynamics. Over time, various models (e.g., FEFLOW, MODFLOW, GMS) have been developed to simulate GW flow and solute transport within aquifer systems. The robustness and reliability of these models are defined by their ability to incorporate geological heterogeneity, address boundary conditions, and their governing equations.

The current study utilizes the finite element modeling approach using FEFLOW (version 8.1). FEFLOW provides the ability to create finite element unstructured grids which helps to represent the complex and irregular geometries of the natural system with its multidimensional modeling capabilities. For regions with complex hydrogeological characteristics such as fractured rock systems, layered aquifers, or areas with significant heterogeneity and anisotropy—FEFLOW's precision in handling spatial variability offers an advantage. Hence, this study aims to develop a 3-D finite element GW model for a micro watershed in the Yamuna sub-basin to simulate the transient GW flow and its budget in the region. The study area, with an area of 4,418 km^2, has an aeolian-alluvium dominance with the presence of silt-sand and quartzite with predominant quaternary formations.

A 3-D transient state finite element model is developed for the multilayered aquifer system containing four major aquifers. The GW is abstracted from ten blocks represented administrative boundary-wise accessed from CGWB while monitored through 237 monitoring wells over the period from 2015 to 2024 from state and central GW stations. The 2-D model domain was generated based on the hydraulic gradient in the watershed region, with the river boundary on the east side of the boundary. A high-resolution 2-D finite-element mesh is generated using triangular prism discretization and projected to 3-D with 11 layers using their available elevation (X, Y, and Z) to effectively capture the complexity of the geological structures. Borehole log data are incorporated to achieve accurate vertical discretization of model layers. The rivers and lineaments are refined more with the local refinement property for intricate analysis.

The model includes 18,918 nodes and 37,085 elements per layer. The top elevation of the model varies from 287.0 m to 438.5 m from the mean sea level. After meshing, the model properties were assigned as an unconfined phreatic first and other dependent layers with a fully saturated water table. The top unconfined layer was assigned a default residual water depth of 0.5 m to avoid any dry cells in the first slice during simulation. The western no-fluid flux boundary is likely chosen due to geological constraints or the absence of significant flow across this boundary. Meanwhile, the eastern fluid transfer (3^{rd} kind flow Cauchy) boundary conditions (BC), align with the Sahibi River's water level at 238.99 m, simulating a controlled, consistent exchange with surface water that can impact local hydraulic gradients and flow paths near this boundary. The north and south boundaries are assigned constant head (first kind flow Dirichlet) BC.

Constant zone material properties were provided for every layer with four aquifers in 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} (aquifer 1), 7^{th} (aquifer 2), 9^{th} (aquifer 3), and 11^{th} (aquifer 4) layers. Horizontal hydraulic conductivity (Kx=Ky) values were assigned based on the transmissivity values provided by the authorities, divided by the thickness of the aquifers. The vertical conductivity (Kz) is given a factor of 1/10 of the horizontal values. Average precipitation and evapotranspiration data were acquired from satellite data Global Precipitation Measurement (GPM) and MODIS respectively for around 200 points in the model domain from 2015 to 2024 and were calculated as inflow-outflow, applied on the top layer using the inverse distance interpolation method. The lack of pumping well information has motivated to calculate the source-sink property for selected elements in different depths with the pumping volume information provided block-wise by CGWB authorities.

The model is simulated for the steady and transient conditions. To simulate the reliable GW flow, model calibration is important, hence FEPEST is used. Since the model is most sensitive to permeability, K values were chosen for the calibration along the X, Y, and Z axes. The parameter definition is provided for the Kx, Ky, and Kz layerwise with the Kriging (internal) interpolation technique. The model is optimized with 20 iterations with a regularization setting for the high-parameterized model. The model is calibrated by assigning the pilot points across the model, presenting the spatial heterogeneity in the K values. The model is calibrated to achieve the least root mean square error and best fit the observed and simulated heads. The model is validated from 2015 to 2024 under transient conditions, employing the calibrated conductivities and heads from steady state as initial conditions. The transient data for other boundary conditions were employed and simulated for the transient state. The model aims to gain accuracy with a 95% confidence interval and simulate the hydraulic heads and GW imbalance in the watershed region.

Keywords: *Groundwater, numerical modeling, finite element, simulations, flow dynamics*

EFFECTIVE GROUNDWATER MONITORING NETWORK FOR MODELLING AND MANAGEMENT AT MICRO-WATERSHED SCALE

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Effective groundwater monitoring networks are essential, as comprehensive information obtained from observation wells offers critical insights into the dynamics of hydrogeological systems and serves as a foundation for numerous applications such as modeling, and management. The network design, namely the selection of positioning and number of monitoring wells, is crucial in any study that involves modeling and prediction utilizing geographical data. It is essential to comprehend the variability of groundwater levels, specifically the depth to groundwater (DTW) across various scales, as this knowledge will aid in developing policies for the effective planning and management of the deteriorating groundwater resource at several levels. Moreover, the efficacy of a groundwater model is contingent upon the quality of the input data utilized. Consequently, inadequately distributed monitoring wells may result in erroneous conclusions or a distortion of the regional perspective. This study focuses on efficient groundwater monitoring network capturing the spatiotemporal variability at micro-watershed level for intensive hydrologic monitoring and evaluation for science-based management and planning, with a focus on groundwater extraction and recharging.

The study area consists of the Illirsinga, Kodhibhanga, and Rasol micro-watersheds in the Hindol region. It is situated 30 kilometers to the west of Dhenkanal Urban in the state of Odisha, India. The region is bounded by south-western mountains, that form a watershed between the Brahmani and Mahanadi rivers, with a narrow intermountain valley in the west, a perennial drainage ditch, in the north, and undulating plain in the south-east. It exhibits diverse topography, ranging from 90 to 630 meters above sea level, and lacks perennial streams. The region has a semi-arid climate that is influenced by the recurring appearance of the monsoon, which brings rainfall from mid-June to mid-October. The average annual precipitation is approximately 1300 mm, with over 80% occurring during the monsoon season. The average yearly temperature is 31.5˚C. However, during the summer months of March to May, the daily maximum temperature can reach up to 48˚C. Currently, the study area contains only one well, named Rasol National Hydrological Stations (NHS) within the long-term groundwater monitoring network of NHS in India, captured from the India Water Resources Information System. Henceforth, it was necessary to enhance the groundwater monitoring network to focus on groundwater recharge and extraction for micro-watershed planning and management. The dynamics of groundwater flow has been captured via a preliminary observation well network with a cluster of 13 wells, distributed enough to ensure sufficient spatial coverage, and, utilized to monitor groundwater levels to investigate the effectiveness of the current groundwater network. The measurement of the depth below an arbitrary place and the groundwater level is conducted in meters using a Groundwater Level Indicator. Additionally, the elevation of that arbitrary point above the mean sea level (msl) is measured using a Handheld GPS device.

Geostatistical sampling is a method for creating a sample network that employs statistical and spatial analysis to identify ideal sampling sites. To determine where to place more sampling points, a geostatistical model called the model variogram is employed. These are chosen according to the established selection criteria by minimizing the maximum kriging variance. It is contingent upon the covariance model and the arrangement of data and unaffected by the actual values in data. The geostatistical sampling design relies on the predicted standard error as a selection factor for choosing the location of additional points of sampling. Regardless of the data, two identical sample location distributions will yield the same kriging variance for a given covariance model. The mathematical-statistical description and numerical analysis of two-dimensional Gaussian distributed realizations demonstrate the validity of kriging variance. The prediction error variance is independent of the data values; hence the kriging variance remains an accurate evaluation of local uncertainty, even when fluctuations in particular regions are greater or lesser than in others. Nonetheless, these conclusions are inapplicable to the non-Gaussian scenario. Additionally, the results are compared with stratified, and cluster sampling to assess the heterogeneity in the DTW variability, consequently distinguished as an internally homogenous cluster.

The Geostatistical Sampling Design is executed in the Esri Environment using an ArcGIS Tool "Densify Sampling Network." The semi-variogram is revised at each densification phase, resulting in varying outcomes based on the consecutive addition of points. Consequently, it led to monitoring efficient network with the lowest average standard error. Additionally, this network also captures the distinctness of each well and its seasonal DTW variability. This study aimed to establish a groundwater level monitoring network to determine if an extensive design can provide valid spatial estimates of groundwater levels, capturing spatiotemporal variability in the micro-watershed scale. We examined the geostatistical sampling by densifying the network by placing additional sites depending on the semi-variogram model. This methodology resulted in verifying the spatiotemporal variability of DTW. The seasonal fluctuations in the water levels of groundwater demonstrate the potential variations in the specific yield within this study region by examining the distinctness of each well. This monitoring network provides information that offers valuable insights into the spatial variability of evapotranspiration and recharge fluxes over the aquifer system. Such a monitoring network can assist in the intervention emphasis on groundwater recharge and extraction.

Keywords: *Groundwater, monitoring network design, geostatistical sampling, spatiotemporal variability*

PARTICIPATORY GROUNDWATER MANAGEMENT TOWARDS SUSTAINABLE DEVELOPMENT OF AN AQUIFER – A CASE STUDY AQUIFER FROM SATARA DISTRICT, MAHARASHTRA, INDIA

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Groundwater is an essential shared resource, critical for various user groups, yet its depletion is becoming a major concern in Maharashtra due to erratic monsoons and over-exploitation of aquifers. In response, a participatory groundwater management initiative was launched in a portion of the BM-85 watershed in Satara district. The project developed an Integrated Groundwater Management Action Plan (GWMAP), utilizing a comprehensive approach that incorporated remote sensing, hydrometeorological, hydrological, hydrogeological, hydro-chemical, and geophysical analyses. The study area, located in the basaltic Deccan Trap formations, experiences a semi-arid climate with an average annual rainfall of 367.5 mm, and the aquifers are predominantly unconfined. This case study describes the methodology used for aquifer delineation, employing geospatial tools, multi-criteria analysis, and hydrogeological surveys. The implementation of the GWMAP was guided by scientific data alongside a deep understanding of the local social structure, integrating both natural and social sciences in a community-based groundwater management program. A base map was created using the Survey of India topographic map (47K/5 at 1:50,000 scale), and spatial analyses—such as slope and precipitation maps—were performed using GIS software. Other key analyses, including geomorphology, drainage patterns, and groundwater potential, were also carried out using GIS tools. A baseline survey was conducted to gather demographic data, assess the status of domestic water supply, identify agricultural practices, and evaluate existing water conservation structures. Social science surveys, in collaboration with local support organizations, assessed the community's social and economic conditions. Hydrogeological surveys helped determine groundwater potential and informed management strategies. Historical data, combined with field surveys, enabled the development of hydrogeological maps that identified high-potential groundwater zones and evaluated aquifer controls. Aquifer characteristics, including specific yield (0.0015 to 0.03) and transmissivity (77.62 to 232.26 m^2/day), were derived from aquifer pumping tests (Theis, 1935; Cooper & Jacob, 1946). The occurrence and distribution of groundwater in the area were analyzed through a detailed study of well inventories. The average well density is 4.7 wells per square kilometer. Of the 412 open wells, 389 are used for irrigation, with 294 equipped with electric motors and 48 with diesel engines. Additionally, 70 wells are no longer in use, while 23 wells serve domestic and drinking water needs. Well depths range from 5 m to 21 m below ground level (bgl), and diameters vary between 6 m and 13 m. Water levels fluctuate between 0.5 m and 17 m bgl during winter and 3.5 m to 20.5 m bgl during summer. Seasonal water level variations from pre-monsoon to post-monsoon were observed to range from 2 m to 13 m. Water level fluctuations indicate the seasonal regeneration of groundwater, with variations ranging from 5 to 8 m over the last decade. Wells fully penetrating the aquifer yield between 40 to 100 m^3/day in winter, with a decrease to 0 to 40 m^3/day in summer. Groundwater exists under unconfined water table conditions, with aquifer depths limited to 15 meters below ground level. The region has 97 irrigation borewells, whose yields vary from 5 to 60 m^3/day in winter and 0 to 30 m^3/day in summer. Approximately 30% of the wells yield high quantities, while 40% of borewells become defunct annually due to groundwater depletion. Vertical Electrical Soundings (VES) at 68 locations revealed the aquifer is predominantly occupied by vesicular zeolitic basalt, with resistivity values ranging from 20 to 40 Ωm, followed by fractured basalt with resistivity values between 40 and 70 Ωm. Chemical analysis of water samples was performed, and a Piper diagram was used to interpret water quality. The results indicated that groundwater in the area is suitable for drinking, with Total Dissolved Solids (T.D.S.) and other constituents within permissible limits. All data were geo-referenced and integrated into a GIS platform, facilitating the creation of thematic maps for aquifer management. The study identified two primary aquifer types: phreatic aquifers in weathered vesicular basalt and fractured massive basalt, with the former being dominant. A water balance was computed for the aquifer using 75% dependable rainfall, alongside cropping data from the agricultural department. The water account indicated a deficit of 54 million cubic meters (ham), with the aquifer's development stage at 112%. To address this deficit and ensure sustainable groundwater use, the GWMAP integrates both supply-side and demand-side strategies, such as water-saving technologies, improved irrigation practices, crop planning, and local regulations to reduce overuse. Ongoing monitoring of groundwater levels and rainfall provides the community with vital data to track aquifer status. Demand-side measures, such as crop diversification, efficient irrigation practices, and self-regulation, are gradually being adopted by farmers. While the changes are beginning to show positive results, continued collective efforts will help achieve long-term groundwater sustainability. A holistic approach to groundwater management is crucial, considering factors such as slope, geomorphology, lineaments, soil, and land use. Long-term planning must also address future irrigation and drinking water needs. The success of this initiative hinges on effective demand management, including participatory groundwater management, community-based monitoring, water budgeting, and self-regulation. This case study highlights the importance of integrating both supply-side and demand-side measures, alongside active community involvement, for successful groundwater management. It also recommends sharing groundwater resources among neighbouring villages and promoting the conjunctive use of groundwater and surface water to ensure sustainability in the long term.

Keywords: *Groundwater management, aquifer, remote sensing, water budgeting, participatory groundwater management*

A FINITE VOLUME METHOD-BASED NUMERICAL MODEL FOR COUPLED SUBSURFACE FLOW AND CONTAMINANT TRANSPORT DYNAMICS

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Groundwater is a critical resource for agriculture, industry, and human consumption. However, it is facing continuous threats of contamination and overexploitation, under the complexities of the changing climatic scenarios. Effective management of this essential resource relies heavily on our ability to model subsurface flow and transport dynamics accurately. Mathematical models are essential for predicting the flow dynamics and contaminant migration under various hydrodynamic conditions and developing remediation and disposal policies for contaminants to ensure the long-term sustainability of groundwater systems. These models are indispensable tools in groundwater contaminant hydrology for forecasting the impacts of various extraction scenarios, assessing contamination risks, and planning remediation strategies. Despite significant advancements, the existing coupled subsurface models often fail to achieve mass conservation while simultaneously simulating the flow and transport mechanisms. Partially coupled models handle flow and transport sequentially, using the output from the flow models to drive the transport model. This approach can lead to inaccuracies where the interactions between flow dynamics and transport mechanisms are dominant. Fully coupled models, which solve the flow and transport equations simultaneously within a single framework, often suffer from high mass balance errors and computational inefficiencies. To address these limitations, it is necessary to develop a mass-conservative, fully coupled subsurface flow and transport model, incorporating advanced computational techniques like an adaptive time-stepping algorithm for computational efficiency.

In the present study we have developed a robust, adaptive, and mass-conservative, one-dimensional (1D) coupled model to simulate the complex subsurface flow and transport phenomena. The Finite Volume (FV) method is used to discretize the governing equations of flow and transport for the developed modeling framework. The FV method ensures mass conservation across the computational domain thereby, enhancing the applicability of the developed model for accurate predictions. The nonlinearity of the flow and transport equations is handled using the modified Picard iteration scheme in the mathematical formulation of the developed modeling framework. Within the unsaturated zone of the subsurface media, the non-linear relationship between the pressure head and the soil-water characteristics parameters - moisture content ( ), hydraulic conductivity ( ), and specific moisture capacity ( ) are expressed using the empirical van Genuchten-Mualem model. An adaptive time-stepping algorithm is implemented in the modeling framework to address the computational challenges associated with fully coupled models. This algorithm dynamically adjusts the time-step size during the simulation based on the evolving behavior of the solution, thereby ensuring smooth convergence of the Picard iteration scheme and significantly enhancing the computational efficiency without compromising accuracy.

The integration of a contaminant transport model with a density-dependent flow model in the present research work aims to predict the complex interactions between groundwater flow dynamics and contaminant migration in variably saturated subsurface media. Application of the FV method for the coupled 1D modeling framework ensures minimum mass balance errors as the FV discretization scheme is inherently mass-conservative. The developed 1D model is validated against the standard benchmark problems from the literature which confirms its applicability for accurate modeling of complex subsurface flow and contamination transport phenomenon. The present model is deemed crucial for developing effective strategies for groundwater management under increasing extraction activity and contamination risks. In the future, we aim to extend the applicability of the developed model to three-dimensional domains for solving practical problems on complex subsurface phenomena, including saltwater intrusion, contaminant flow and transport, and nutrient leaching.

Keywords: *Coupled models, finite volume method, subsurface flow, contaminant transport, mass conservation, picard iteration scheme, adaptive time-stepping algorithm*

A STUDY OF PRE- AND POST-MONSOON WATER LEVEL AND WATER LEVEL FLUCTUATION OF NORTHERN PART OF WRJ-2 WATERSHED, NAGPUR DISTRICT, MAHARASHTRA STATE

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A majority of water problems in India are related to groundwater as India is the largest consumer of groundwater in the world. Groundwater is a major source of irrigation and industrial uses in India. It is the main source of water for agriculture, municipal and industrial use. A total of 93% geographical area of Maharashtra State is covered by hard rocks, out of which the Deccan basalt constitutes about 82% of the geographical area. Due to its hard and compact nature, the *occurrence* and *storage* of groundwater in the Deccan basalt is very limited, which is a reason for its poor to moderate yield. The groundwater in the basaltic terrain occurs in the multi-layered sequence of lava flows. Aquifers in the Deccan basaltic terrain generally occur as (i) aquifers in which storage space exists by virtue of weathering and porphyritic and vesicular zones. (ii) aquifer in which storage space exists due to the structural features such as columnar joints, fractures, faults, etc., and (iii) aquifer which occurs at relatively greater depth, where groundwater occurs under confined state. The heterogeneous nature of the Deccan Trap is responsible for the variable occurrence and distribution of groundwater. The present study area is the WRJ-2 Watershed, which is included in Survey of India toposheets 55K/11 and 55K/7 and bounded by latitude 21°17'30" - 21°29'00" N and longitude 78°30'00"-78°59'15" E. The WRJ-2 watershed has a total area of 219.86 km^2 and is included in the critical category, after groundwater assessment. The entire area of watershed WRJ-2 is covered by the Deccan basaltic lava flows of Upper Cretaceous to lower Eocene age. The study area has been drained by the Jam River and its tributaries. The overall pattern of drainage is dendritic which testifies the presence of hard rock in the area. The general slope of the ground is towards the south. The northern part of the watershed WRJ-2 falls mostly in the runoff zone. A percolation tank is also present in the Northern part of the study area. Stratigraphically this area comprises eight lava flows of Sahyadri Group, which is further categorized as Karanja Formation. Out of the eight lava flows exposed in the area, seven flows are massive and one flow is unclassified basalt.

A detailed hydrogeological study has been carried out in the area and regular pre- and post-monsoon water level monitoring has been carried out. The average static water levels in the post-monsoon season range between 2.1 to 20.50 m bgl, whereas in pre-monsoon season it varies between 5.2 to 20.50 m bgl. The seasonal water level fluctuation ranges between 2 to 4 m. The average yield of the dug wells ranges between 60 and 100 m^3/day during post-monsoon, while it ranges between 18 and 50 m^3/day during pre-monsoon season. The geomorphology of the area is suitable for groundwater management and provides a scope for further groundwater management as the population in the area is growing enormously thus posing an increased demand for groundwater extraction. As the shallow aquifers are dried in summer, the dependability on the deeper aquifers has increased. The present study would help to analyze the pre- and post-monsoon water levels and their fluctuation in the northern part of the watershed. The study area comprises of vast belt of orange and citrus cultivation, resulting in over-exploitation of groundwater in the area. The study incorporates, the water level fluctuation and water level trends in the northern part of watershed WRJ-2, concerning the growing over-exploitation of groundwater due to citrus cultivations in the area.

Geographic information system is used as a tool to identify and study the groundwater fluctuation, geology, and hydrogeology of the area. Preparation of geological and geomorphological maps based on field observations and existing data has been done. A detailed study of the yield and water level fluctuation of the monitoring stations is carried out during pre-monsoon and post-monsoon periods in the study area. The groundwater management of the study area is carried out on a ridge to valley-based concept. Also, the data from the actual field survey has been collected after studying various irrigation and public wells in the study area. For the effective groundwater management of the study area, the area should be thoroughly investigated considering geological, hydrogeological aspects, and aquifer parameters, in the Deccan basaltic terrain of multi multi-layered aquifer system in the present area. The artificial recharge measures suitable in the area are suggested to arrest surface water and soil runoff.

Keywords: *Groundwater, Deccan trap, watershed, over-exploitation, heterogenous, critical, water level*

UNVEILING THE HIDDEN WATERS: INTEGRATING SWAT-MODFLOW FOR MAHANADI RIVER BASIN'S WATER DYNAMICS

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Climate change aided with rapid urbanization has significantly impacted the regional water table. This has altered the water dynamics and intensified water scarcity across the globe. With dwindling resources and untimely rains, as cities expand and populations grow, the demand for water increases, often outpacing the available supply. This situation is further complicated by the alteration of natural hydrological cycles due to climatic changes, which can lead to reduced groundwater recharge, increased surface runoff, and pollution of water sources. Consequently, there is an urgent need for a comprehensive hydro-climatological assessment of all components of the hydrological cycle, including precipitation, evaporation, infiltration, and runoff. Such an assessment is crucial for developing sustainable water resources management strategies that can ensure a reliable water supply, and predict drought and flood events, while also protecting the environment and maintaining the balance of natural ecosystems. By understanding and managing the intricate dynamics of regional hydrology, policymakers, and water managers can implement effective measures to mitigate the impacts of climate change on water resources and promote long-term sustainability.

Understanding the interaction between surface water and groundwater is crucial to deciphering the complexity of the hydrological cycle. SWAT-MODFLOW is a widely employed integrated model to effectively couple surface water with groundwater to simulate their interaction processes. In this study, SWAT-MODFLOW has been applied to the mighty Mahanadi River basin, located on the eastern coast of India to simulate the Surface water groundwater dynamics. For the development of the SWAT (Soil and Water Assessment Tool) model, a variety of data sets have been utilized to ensure a comprehensive and accurate representation of the study area. These datasets include the Digital Elevation Model (DEM), stream density, soil characteristics, Land Use and Land Cover (LULC), and slope. The integration of these diverse data sources allowed for the detailed classification of the entire basin into 30 sub-basins and 806 Hydrologic Response Units (HRUs). This classification was crucial for understanding the spatial variability and hydrological processes within the basin.

Climate data played a significant role in the simulation of surface runoff. The climate data included parameters such as rainfall, maximum and minimum temperatures, wind speed, solar radiation, and relative humidity. These parameters were used to simulate surface runoff over a 23-year period, from 2000 to 2023. The initial two years, 2000 and 2001, were designated as a warm-up period to stabilize the model and ensure accurate simulations for the subsequent years. In addition to the SWAT model, a groundwater model (MODFLOW) was developed to simulate groundwater flow and interactions within the basin. The MODFLOW model was constructed using aquifer characteristics, including aquifer thickness, hydraulic conductivity, and specific yield data. These characteristics were essential for accurately representing the groundwater system and its dynamics. The entire basin was discretized into a grid with a spatial resolution of 1000 x 1000 meters, which provided a detailed representation of the groundwater flow system. To understand the linkage between surface water and groundwater processes, the HRUs of the SWAT model were linked to the grid cells of the MODFLOW model. This linkage was crucial for capturing the interactions between surface runoff and groundwater recharge. The outputs of both the SWAT and MODFLOW models were validated using observed data. Surface runoff data from 18-gauge stations and groundwater recharge data from various wells were used for this validation process. The validation ensured that the models accurately represented the hydrological processes within the basin. The analysis of LULC changes over time was a significant aspect of this study. Using MODIS (Moderate Resolution Imaging Spectroradiometer) data, the time-dependent trend in LULC was analyzed from 2001 to 2020. The analysis revealed notable changes in the LULC within the basin. Water bodies and urban areas showed an increase of 2% and 3%, respectively, indicating urban expansion and changes in water management practices. Conversely, barren land decreased by 14%, suggesting a shift towards more vegetated or developed land uses.

The water balance analysis of the basin provided insights into the overall hydrological dynamics. The analysis indicated a negative soil water content of -1133.61 mm, which suggested net water loss through runoff and evapotranspiration. This negative balance highlighted the importance of understanding and managing water resources to mitigate water scarcity and ensure sustainable water use. One of the key findings of the study was the higher water discharge observed in sub-basin 22, where the Hirakud dam is located. The discharge rate in this sub-basin was 227 mm in 2002, which increased significantly to 614 mm in 2023. This substantial increase in discharge rate indicated that sub-basin 22 had become a flood-prone zone. The construction of the Hirakud dam and subsequent changes in land use and hydrological processes likely contributed to this increased flood risk. Largely, the study provided valuable insights into the hydrological processes and changes within the basin over the 23-year period. The integration of SWAT and MODFLOW models, along with comprehensive data sets and validation, ensured a robust analysis of surface and groundwater interactions. The findings highlighted the importance of continuous monitoring and adaptive management to address the challenges of water resource management in the face of changing climate and land use patterns. This integrated approach will provide a detailed understanding of groundwater recharge and stream flow dynamics, allowing them for the estimation of key hydrological cycle components. These results will offer insights into water storage dynamics within the concerned basin, providing crucial information to support policymaking and ensure the sustainable management of water resources in the future.

Keywords: *Mahanadi river basin, SWAT-MODFLOW, hydrological cycle, surface runoff, groundwater recharge*

FLOW MODEL FOR GROUNDWATER RECHARGE POTENTIAL

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Groundwater is a vital freshwater resource globally, equally important as surface water. Over-exploitation due to increasing water demand from population growth has led to water stress in several regions. This paper focuses on delineating the recharge potential of an area using advanced technologies such as GIS, remote sensing, and modeling. The primary factors contributing to groundwater depletion include improper land use and land cover, hydrogeology, lithology, salinity constraints, and water pollution. To address these challenges and implement appropriate measures, it is crucial to assess the recharge potential of specific areas. The Analytical Hierarchy Process (AHP) model, integrated with GIS, is employed for decision-making to identify high-risk areas experiencing rapid depletion, suitable for artificial recharge. In this study, various thematic layers have been developed using satellite imagery to analyze factors such as slope, drainage density, and geomorphology for zoning areas with low recharge potential. These methods facilitate the collection of historical data to predict and estimate future groundwater level fluctuations in the region.

Keywords: *Analytical Hierarchy Process, GIS, remote sensing, groundwater*

PRIORITIZING GROUNDWATER POTENTIAL AND SOIL EROSION-PRONE ZONES USING MORPHOMETRIC, HYPSOMETRIC AND COMPOUND FACTOR APPROACHES IN THE BEAS BASIN, HIMACHAL PRADESH

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One of the most crucial techniques for evaluating drainage and sub-watershed prioritization for groundwater potential and soil erosion of watersheds is the use of remote sensing and GIS. This study focuses on the Beas River Basin, from its origin up to Pong Dam (Kangra district), Himachal Pradesh, covering an area of 12,370 square kilometers. This study uses morphometric, hypsometric, and compound factor techniques to identify zones that are prone to groundwater potential and erosion using digital elevation models (DEM) and Arc GIS tools. Using remote sensing and GIS techniques, morphometric measurements that is, linear, areal, and relief features were assessed for a thorough analysis of the Beas River Basin. The USGS earth explorer provided the SRTM- DEM with a 30 m resolution for the Beas River Basin morphometric investigation. Linear, bifurcation ratio (Rb), mean bifurcation ratio (Rbm), stream length (Lu), stream numbers (Nu), stream order (So), and mean stream length. Overland flow length (Lg), circulatory ratio (Rc), form factor (Ff), shape factor (Bs), elongation ratio (Re), compactness coefficient (Cc), drainage density (Dd), stream frequency (Fs), drainage texture ratio (Rt), and infiltration number (If) in the Areal aspects Relief (Rf), relative relief (R), relief ratio (Rh), ruggedness number (Rn), mean relief (Hm), maximum relief (Hmax), minimum relief (Hmin), and hypsometric integral (HI) are among the morphometric parameters reviewed in this study. There are five sub-watersheds within the watershed i.e. SW1, SW2, SW3, SW4, SW5 and SW1, SW2, SW3, SW4 and SW5 having areas of 3175.13, 2367.64, 1795.0.72, 1775.53 and 3256.18 km^2 and having perimeter for sub-watersheds 352.73, 269.00, 221.47, 259.82 and 367.98 km. For the estimation of the ranking technique for soil erosion calculate the Linear aspect and areal aspect for calculating the compound factor after the calculation of the compound factor prioritize the ranking for soil erosion. Similarly for the estimation of prioritizing groundwater potential zones calculate the Linear aspect i.e. Mean bifurcation ratio (Rbm), in the areal aspect, circulation ratio (Rc), drainage density (Dd), stream frequency (Fs), drainage texture ratio (Rt), form factor (Ff), shape factor (Bs), and elongation ratio (Re) infiltration Number (If) and relief aspects i.e. relief ratio (Rh) and ruggedness number (Rn) with Compound factor ranking technique approaches to determine and prioritize the groundwater potential zones. The morphometric, compound factor (CF), and hypsometric integral (HI) parameters were all effectively calculated. The ground water potential and soil erosional susceptibility of the basins were evaluated using the hypsometric integral (HI) and compound factor (CF) ranking approaches. The methodology for this study is STRM Data, GIS software, study area extraction, stream networks, sub-basins, morphometric analysis i.e. (Linear aspect, areal aspect, relief aspect) and then compound factor for analysis of both groundwater potential zoning and soil erosion prone zone areas. Results for this study depend upon two factors i.e. compound factors and the hypsometric integral approach. Following the evaluation of factors, priority zones are allocated to each sub-watershed for areas susceptible to groundwater potential and soil erosion-prone areas. This study using ArcGIS tools and different methodologies showed as a result that all of the sub watersheds i.e. SW1, SW2, SW3, SW4 and SW5 having high or low infiltration, high or low groundwater potential zones, high or low erosive levels of soil and also having high or low permeability. The average of all these parameters for each watershed is calculated to determine the priority. To better planning and management, the study shows that remote sensing data and geographic information systems are viable for analyzing and estimating the stage and rate of soil erosional processes and groundwater potential zones in a Himalayan watershed. To manage groundwater zones and soil erosion-prone area activities at the appropriate locations within the study area, the results have aided in the qualitative discussions and prioritizing the sub-watershed for sustainable groundwater potential zones and soil erosion-prone area zones and management. We are able to establish the priority ranks and categorize the sub-watershed into three groups based on the calculated results: low, moderate, and high priority. The distribution of its natural resources and the identification of major watersheds or sub-watersheds must be prioritized to implement effective and sustainable watershed management strategies. A key methodology approach for a better understanding of hydrological challenges and efficient catchment management planning is the use of RS and GIS for morphometric evaluation and prioritizing sub-catchments according to their groundwater capacity and susceptibility to soil erosion. The study's findings can be used to inform plans for flood prevention, watershed management, and water resource conservation.

Keywords: *Catchment, morphometric analysis, hypsometric analysis, compound factor, Beas River basin, ground water potential, soil erosion, sub basin prioritization*

MATHEMATICAL MODELLING OF GROUNDWATER FLOW IN HETEROGENEOUS SOIL USING THE FINITE DIFFERENCE METHOD

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Modelling the groundwater flow is a key requirement of proper water resource management in arid and semi-arid regions, where groundwater is the principal source for irrigated agriculture. The goal of the paper is the establishment of a mathematical model simulating the process of flow of groundwater in heterogeneous soils using the Finite Difference Method. Variability in hydraulic soil properties plays a significant role in the groundwater flow pattern, making this complexity appear necessary to incorporate it into modelling efforts. Groundwater is an essential resource supporting ecosystem functions, agricultural activities, and human endeavours; hence, understanding the dynamics of its flow is fundamental to its sustainable management. The study aims to create a robust three-dimensional (3D) groundwater flow model that incorporates spatial variations in hydraulic conductivity and evaluates how these variations, alongside different boundary conditions, affect groundwater flow behavior. The governing equations for steady-state groundwater flow are derived from the fundamental principles outlined in the continuity equation and Darcy's law, which serve as the basis for the model. Using the Finite Difference Method, the research successfully discretizes such governing equations in a manner that allows a three-dimensional simulation of groundwater flow. There are three different cases for hydraulic conductivity variations: constant, linear, and exponential variations, each representing distinct realistic real-world scenarios common to the field of subsurface hydrology. Simulations under different boundary conditions, such as Dirichlet and Neumann types, are run to ensure the reliability of the model. These are important in defining how the outer boundaries of the system affect the flow of groundwater. From the study, there are significant insights into hydraulic head distribution across the modelled area. It is noticed that the hydraulic heads have a wide range of distributions based on the imposed boundary conditions. For example, the hydraulic head values on the boundaries may be given through Dirichlet boundary conditions. The Dirichlet boundary conditions may tend to yield a relatively uniform hydraulic head distribution over the model domain. The Neumann boundary conditions are flux inputs on the boundaries and usually lead to higher hydraulic head variability in terms of influences of flux-based factors. Furthermore, the study highlights the impact of heterogeneity in soil properties on groundwater flow dynamics. By introducing spatially variable hydraulic conductivities into the model, the researchers uncover notable changes in flow patterns. When applying linear variations in hydraulic conductivity, gradual shifts in groundwater flow patterns are observed, indicating a smoother transition in flow dynamics. Alternatively, the inclusion of exponential functions implies a steeper variation that identifies certain zones that can dry out or have their groundwater accumulate. Such discovery is essential in determining changes due to soil property variations impacting groundwater availability and movement with better management practices. The study emphasizes that soil heterogeneity needs to be incorporated into the groundwater flow models; in fact, such factors may improve predictive capabilities in the simulations considerably. The Finite Difference Method simulates the complex groundwater scenario effectively; however, there are limitations with the study regarding computational efficiency when model complexity increases. This aspect emphasizes the demand for realistic modelling approaches that reflect the complex nature of subsurface hydrological systems. In this regard, the study becomes invaluable in advancing the understanding of groundwater flow in heterogeneous soils, as any consideration in variations of hydraulic conductivity determines overall flow dynamics. The developed FDM model turns out to be a useful tool for predicting groundwater behaviour, which is important for the sustainable management of water resources, especially in areas facing problems related to variable soil conditions. Therefore, this research has significant implications for water resource management strategies, as it gives a better understanding of how groundwater systems behave under different scenarios. Future research efforts should look forward to further extending the model to incorporate additional complexities, such as interactions with various soil properties and the incorporation of seasonal variations in groundwater recharge. Testing the applicability of the model in different geographical contexts would also be important since it would enhance the utility of the model in addressing a wide range of water resource management challenges faced globally. Overall, this study is a testament to the importance of mathematical modelling in understanding and managing groundwater resources, contributing valuable insights that can aid decision-making processes in sustainable water management practices.

Keywords: *Groundwater flow, heterogeneous soil, Finite Difference Method, hydraulic conductivity, water resource management*

TEMPORAL ANALYSIS AND PREDICTIVE MODELING OF GROUNDWATER DYNAMICS IN SAMBHAL DISTRICT, UTTAR PRADESH, INDIA

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Groundwater constitutes an indispensable resource pivotal for sustaining agricultural productivity, potable water supply, and industrial operations. Understanding its dynamics is essential for sustainable resource management and mitigation of water scarcity challenges. The current investigation targets the dynamics of groundwater in Bahjoi, situated within the Sambhal District of Uttar Pradesh, India (latitude: 28.41, longitude: 78.63). The study spans from 2001 to 2022, encompassing key variables such as rainfall, minimum and maximum temperatures, and groundwater levels during the pre-monsoon season. The overarching objective is to elucidate trends and predict groundwater levels employing advanced statistical techniques and machine learning methodologies. Analytical tools such as the Mann-Kendall test, Sen’s slope estimator, and a random decision forest model were deployed. The dataset underwent rigorous preprocessing, including the handling of missing values using Inverse Distance Weighted (IDW) interpolation in ArcGIS and the application of Kalman smoothing for noise reduction.

Rainfall and temperature datasets were sourced daily from the Indian Meteorological Department (IMD) and aggregated to seasonal averages. Employing reliable methods for data aggregation ensures the precision of the analysis and provides an accurate basis for subsequent modeling. The IDW interpolation method was utilized to estimate missing values based on spatial proximity, enhancing the dataset's reliability. Kalman smoothing was applied to mitigate data noise and refine temporal patterns. Correlation analyses using Pearson and Spearman coefficients provided insights into interdependencies among variables. Temporal trends were assessed through the Mann-Kendall test and Sen’s slope estimator, while the Innovative Trend Analysis (ITA) method augmented the trend identification process. A random decision forest model was implemented to forecast groundwater levels, integrating rainfall, maximum temperature (Tmax), and minimum temperature (Tmin) as predictors. The model’s efficacy was gauged using metrics such as R-squared (R^2), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE).

The correlation analysis revealed varied degrees of association among the parameters under investigation. This step is integral for delineating the interplay between climatic variables and groundwater levels, forming the groundwork for robust predictive modeling. Rainfall exhibited a weak positive correlation with groundwater levels, with Pearson’s coefficient recorded at 0.12 and Spearman’s rank correlation at 0.15, implying a limited direct influence. Tmax demonstrated a more substantial positive correlation, with Pearson’s coefficient at 0.31 and Spearman’s rank correlation at 0.29, underscoring its influence on groundwater dynamics through processes such as evaporation and aquifer recharge. Conversely, Tmin showed negligible correlation, with coefficients approximating zero, indicating a minimal role in groundwater fluctuations. Trend analysis yielded significant insights into long-term variability. Identifying trends over decades is crucial for planning adaptive measures and understanding the impact of climatic variations on groundwater systems. Rainfall displayed a marginally declining trend, as evidenced by a Mann-Kendall Z-score of -0.42 and a Sen's slope of -0.0028 mm/year. Tmax exhibited a decreasing trajectory with a Z-score of -0.22 and a Sen's slope of -0.0150 °C/year, suggesting potential climatic shifts. In contrast, Tmin presented an upward trend, marked by a Z-score of 0.32 and a Sen's slope of 0.0016 °C/year. Groundwater levels showed a pronounced increasing trend, with a Z-score of 4.76 and a Sen's slope of 0.3581 m/year, indicative of substantial recharge mechanisms or reduced abstraction pressures. The ITA method corroborated these findings, highlighting consistent increases in groundwater levels alongside relatively stable rainfall and temperature dynamics.

The study period exhibited considerable variability in groundwater levels, ranging from a minimum of 8.65 meters below ground level (mbgl) in 2002 to a maximum of 15.95 mbgl in 2021. This variability underscores the complex interrelations among climatic inputs, recharge mechanisms, and human activities affecting groundwater. This variability reflects a complex interplay of factors, including recharge rates, water extraction practices, and prevailing climatic conditions. Lower levels during the early 2000s likely resulted from elevated extraction rates and suboptimal recharge, whereas higher levels in recent years suggest improved water resource management practices or favorable natural recharge conditions. The random decision forest model demonstrated robust predictive capabilities, achieving an R^2 value of 0.78, RMSE of 0.81 mbgl, and MAE of 0.58 mbgl. These results signify the potential of machine learning frameworks in decoding intricate environmental systems and providing actionable predictions. These metrics underscore the model's ability to effectively capture the intricate relationships between groundwater levels and influencing variables. The model forecasted a groundwater level of 13.92 mbgl for 2023, aligning well with observed trends and validating its reliability. The relatively weak correlation between rainfall and groundwater levels emphasizes the significant role of non-rainfall factors, such as soil characteristics, aquifer properties, and anthropogenic activities, in shaping groundwater dynamics.

This investigation underscores the efficacy of integrating statistical and machine-learning approaches for groundwater analysis and prediction. Such integration paves the way for comprehensive strategies to address pressing water resource challenges in a changing climatic scenario. The Mann-Kendall test and Sen's slope estimator provided robust tools for identifying temporal trends, while the random decision forest model delivered reliable predictions. The findings illuminate the critical role of temperature and non-rainfall variables in influencing groundwater levels. The upward trend in groundwater levels during the pre-monsoon season suggests enhanced recharge conditions or moderated abstraction, offering valuable insights for sustainable water resource management strategies. Future research could incorporate additional parameters, such as land use changes, aquifer properties, and socio-economic factors, to further refine the understanding of groundwater system dynamics and improve predictive accuracy.

Keywords: *Random Decision Forest, Mann-Kendall Test, Sen's slope, inverse distance weighted*

GROUNDWATER PUMPING INDUCED STREAMFLOW DECLINE

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The Ganga and Indus River basins, which support a significant portion of the global population and are intensively irrigated, have emerged as a hotspot for groundwater depletion. These regions supply essential groundwater and surface water resources that underpin food production, irrigation, and drinking water. Groundwater, in particular, helps stabilize river flows during dry seasons, ensuring that water is available even when rains are scarce. However, over the past few decades, a troubling trend has emerged: groundwater levels and streamflow in these basins are falling alarmingly, threatening water supplies, food production, and the ecosystems that depend on the rivers.

The situation is especially dire in the Ganga River Basin (GRB). Summers before the monsoon, once a time of relief, now bring record-low water levels. The cause? Over-extraction of groundwater, where it is being pumped out faster than it can be replenished. This is not just draining underground aquifers but also disrupting the natural flow of groundwater into streams, which is crucial for keeping rivers flowing during dry seasons. As groundwater contributions dwindle, streams are drying up, creating significant water management challenges, particularly during the dry season when rivers rely heavily on baseflow—the part of streamflow fed by groundwater. This drop in water availability has enormous consequences: millions face water shortages, and river ecosystems are at serious risk.

Unfortunately, many large-scale hydrological models do not fully capture the complex interactions between groundwater and surface water, especially lateral groundwater flow, which moves sideways and feeds rivers. To address this gap, we used the ParFlow-CLM model. This advanced hydrological model stands out for its ability to simulate groundwater and surface water dynamics in great detail, down to a 5 km resolution. It can simulate water movement above and below ground, capturing the complex relationships between groundwater, soil moisture, evapotranspiration, and surface water.

In our study, we applied the ParFlow-CLM model over 50 years (1970–2021) to explore a range of hydrological variables—stream discharge, evapotranspiration, soil moisture, total water storage, and water table depth. We ensured our model was reliable by validating it against real-world data: streamflow records from the Central Water Commission (CWC), groundwater level data from the Central Ground Water Board (CGWB), and GRACE satellite measurements that track changes in groundwater storage. We also used data from the Minor Irrigation Census to understand how human activities, especially groundwater pumping for irrigation, have contributed to these trends. Bringing all this data together helped us better understand how water systems are changing in the Ganga and Indus basins.

Our main goal was to uncover how declining streamflow is directly linked to reduced river groundwater contributions. The results are precise: human activities, particularly unsustainable groundwater pumping for irrigation, significantly deplete groundwater levels and reduce river flow during dry periods. Since the 1970s, when large-scale groundwater extraction ramped up for agriculture, baseflow has steadily dropped. This decline disrupts the natural balance between streams and aquifers, putting many rivers at risk of becoming "losing streams," where, instead of groundwater flowing into rivers, river water is absorbed back into the ground, further draining both surface and groundwater resources. Our study highlighted specific sections of the Ganga River and its tributaries that are either gaining or losing water, showcasing the uneven and complex nature of groundwater-surface water interactions.

Although climate change plays a significant role in determining the contribution of groundwater to streamflow variability, the primary driver of the decline in groundwater discharge is the excessive pumping of groundwater for irrigational practices. The steady drop in baseflow undermines the long-term stability of river systems. It highlights the urgent need for a more integrated approach to managing water resources, considering both surface water and groundwater systems. This is especially important in areas where groundwater depletion is accelerating due to human activity and increasing climate stress. Our research offers a pathway for more sustainable water management in two of the world's most critical river basins, aiming to secure water resources for future generations.

If these trends continue, the Ganga and Indus basins face the risk of severe water crises and potentially devastating impacts on food security, economic stability, and the health of ecosystems. Our research underscores the urgent need for policies that integrate surface and groundwater resources management and consider the spatial variability of groundwater-surface water interactions. In short, to protect the future of water in these basins and the millions of people who rely on them, we must act now, rethinking how we manage this precious resource in the face of mounting pressures from humans and the environment.

Keywords: *Groundwater depletion, Streamflow variation, Ganga River Basin, Groundwater discharge, Groundwater-surface water interactions, Integrated groundwater modelling.*

NUMERICAL MODELING ON THE TRANSPORT OF BENZENE UNDER VARIABLE-DENSITY FLOW

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Benzene, a volatile and toxic aromatic hydrocarbon, is a persistent environmental pollutant with significant consequences for human health and ecological stability. Because of its carcinogenic characteristics, even minimal concentrations of benzene in soil and groundwater can present significant threats to public health, requiring effective predictive models to evaluate and alleviate its effects. This study examines the intricate mechanisms of benzene transport in variable-density flow systems, particularly those affected by seawater intrusion in coastal aquifers. Coastal habitats, where freshwater and seawater mix together, display unique density gradients, creating more complexities for modeling pollutant transport. The transport of benzene in subsurface environments is influenced by many physical and chemical processes, including dissolution, sorption, retardation, and volatilization. These processes collectively influence the mobility and bioavailability of benzene in groundwater. Comprehending these transport mechanisms are essential for creating efficient numerical models that can forecast the behavior of benzene and suggest successful remediation approaches. Numerical modeling is an effective instrument for simulating intricate relationships among flow dynamics, pollutant transport, facilitating thorough risk assessment and the development of corresponding remedies.

This study investigates the transport dynamics of benzene in variable-density flow systems by integrating the governing equations of flow with benzene's advection-dispersion mechanisms. The model integrates density gradients produced by fluctuations in benzene concentration, facilitating more precise simulations of actual scenarios, where seawater intrusion influences groundwater density. Coastal aquifers are particularly influenced by density-driven flows resulting from the interaction between freshwater and intruding seawater. These interactions establish distinct transport conditions for toxins such as benzene, which must be considered to forecast contamination plume dynamics effectively. The foundation of the current numerical modeling technique relies on the finite volume method, which is utilized to discretize the governing equations for flow and transport. The flow model is coupled with the transport model, indicating that the flow field calculated from density variations due to seawater intrusion and benzene concentration gradients directly affects benzene transport. The velocity field obtained from the flow model functions as an input for the transport model, further connecting the physical and chemical mechanisms that regulate benzene transportation. This connection is crucial for precisely capturing the interactions between flow dynamics and contaminant transport under a variable-density flow.

Boundary conditions are carefully defined to represent the intricacies of the natural system. A constant head boundary condition is established at the upper boundary of the flow model, simulating a steady-state flow condition driven by external hydrological inputs. No-flow boundary restrictions are imposed on the left, right, and bottom boundaries of the model to restrict the system and facilitate a concentrated examination of transport processes within a specified area. In the benzene transport model, a temporally variable boundary condition is assumed at the source zone at the upper boundary. All remaining boundaries for the transport model are assumed to be Neumann boundary conditions, signifying impermeable or reflective obstacles that limit the passage of benzene beyond the model region. The model development of the study integrates hydrodynamic processes, including advection and dispersion, and chemical interactions under hydro-geochemical settings pertinent to benzene transport. In the study, a series of simulations are performed to analyze the impact of density variations on benzene transport, exploring scenarios with varying levels of seawater intrusion and benzene concentration. These simulations illustrate the influence of density gradients on dispersion and advection, affecting benzene plume expansion and the efficacy of natural attenuation. The findings suggest that elevated density gradients, either by intensified saltwater intrusion or benzene levels, augment the advection-dispersion of benzene, potentially resulting in more broad contaminated plumes. This finding directly impacts risk assessment and the formulation of remediation solutions, highlighting the necessity of considering density-driven flow mechanisms in the evaluation of pollutant transport within coastal aquifers.

Although prior studies have investigated benzene transport in freshwater environments, research on variable-density systems is still scarce. This study addresses a gap in the field and establishes a framework for future research on pollutant transport in coastal aquifers affected by seawater intrusion. The results elucidated herein augment the comprehension of benzene behavior in variable-density settings and contribute to the formulation of predictive models that can direct environmental management and policy. The study's findings about the interaction of flow dynamics, benzene transport, and natural attenuation mechanisms can enhance the development of more efficient monitoring and remediation strategies in coastal areas susceptible to pollutant intrusion. This study illustrates the effectiveness of numerical modeling in explaining the complex relationship between variable-density flow and benzene transport. The study presents a comprehensive tool for simulating benzene dynamics in density-driven flow environments by coupling flow and transport models. This research enhances the understanding of contaminant transport in coastal aquifers, improving predictions and mitigation strategies for harmful compounds such as benzene on human health and the ecosystem.

Keywords: *Numerical modeling, variable-density flow, benzene, finite volume method, advection-dispersion*

GROUNDWATER MANAGEMENT USING COUPLED MESHLESS NUMERICAL MODELS AND MACHINE LEARNING TECHNIQUES

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Groundwater is under increasing stress due to population growth, climate variability, and rising demand, making effective assessment and management essential, and necessitating advanced predictive tools for sustainable management. Current groundwater assessment heavily relies on numerical models to predict groundwater level and flow. The numerical models are based on solving partial differential equations to represent aquifer physical processes, and need intensive meshing, complex data inputs, and substantial computational resources, restricting their ability to represent complex geometry. Further, the meshing process in the traditional models requires high preprocessing and finetuning efforts. Meshless methods are more flexible numerical methods that use scatter points in the domain boundary instead of grids, which simplifies handling complex geometries, reduces preprocessing, and improves boundary representation. However, issues such as the requirement for extensive field data and accurate measurements are not alleviated in meshless methods. The present study aims to overcome traditional numerical methods' limitations by combining the strengths of numerical models with emerging artificial intelligence (AI) techniques to create robust predictive models for groundwater quantity modeling.

The simulation model is developed by coupling the Meshless Radial Point Collocation Method (RPCM) with Long Short-Term Memory (LSTM) networks to predict Groundwater Levels (GWL) accurately. RPCM is a strong-form meshless method with the advantages of simpler adaptive analysis, direct discretization, a straightforward modeling approach, and computational efficiency. RPCM is proven to be reliable for spatial prediction of groundwater levels. LSTM is a form of deep learning AI technique suited for time-series predictions, retaining sequential dependencies using memory cells and gates, making them ideal for predicting groundwater levels over time. The proposed RPCM-LSTM hybrid model leverages the spatial modeling capabilities of meshless methods alongside the temporal forecasting power of LSTM, which captures nonlinear patterns and long-term dependencies in groundwater systems, where the meshless methods are known for their flexibility in handling complex geometries and boundary conditions.

The Multi-Quadric Radial Basis Function (MQ-RBF) is used as the approximating technique in RPCM to derive the shape functions. The Neumann boundaries are handled using the direct approach. The groundwater flow equations are formulated using RPCM for heterogeneous confined aquifer. The RPCM model is developed in MATLAB and is well-validated. The model is applied to a real aquifer in Surat, Gujarat, India. This aquifer has an area of 4.5 km^2 and is highly heterogeneous with 11 transmissivity zones. The aquifer is discretized into 986 nodes, with the nodal arrangement representing the recharge zone in detail. The nodes lying on the boundary are assigned the values as per the Dirichlet or Neumann boundary conditions. The stiffness matrix is formed by looping over the nodes. For every support domain, the values of the shape function, and its first and second derivatives concerning nodes are calculated and incorporated into global stiffness matrices. After the global matrix is created, the head values at all nodes are approximated. This results in the steady state head distribution from the RPCM model. The traditional Finite Difference

Method (FDM) based MODFLOW model, with the same configuration, is developed to compare the results of RPCM.

After computing the steady state head distribution from RPCM and verifying the results with MODFLOW, the RPCM is coupled with LSTM for temporal forecasting to reduce the computational demands while providing accurate groundwater forecasts. Along with the head distribution, various recharge and extraction scenarios and their influence on future groundwater heads are generated to train LSTM networks on the input and output of RPCM to mimic the numerical model simulation. Thus, the temporal simulations by the LSTM model are trained with simulated data from RPCM to capture the temporal dependencies in GWL influenced by recharge and demand changes. The hybrid RPCM-LSTM model is finally used to evaluate the change in groundwater level in the future due to changes in recharge and extraction rates.

The results indicate that the meshless approach provided flexibility with complex boundary conditions and demonstrated high accuracy and adaptability in groundwater flow simulations. The average percentage difference between the groundwater heads estimated by RPCM and MODFLOW is 0.85%, which indicates that RPCM can simulate the flow phenomenon with good accuracy. Thus, RPCM is the best alternative approach to traditional mesh-based methods and has the advantages of computational efficiency, simpler fine-tuning, lower preprocessing, and the ability to handle complex geometries. Using simulated data, the LSTM accurately learned and predicted patterns in groundwater levels, effectively addressing long-term dependencies like changes in recharge rates and demand, thereby successfully mimicking the numerical model. LSTM significantly reduces the computational cost and becomes very adaptable when new information is introduced.

Thus, the hybrid RPCM-LSTM model offers robust solutions for more accurate groundwater level prediction. Through the meshless RPCM simulation, the model achieves flexibility in handling complex geometries and boundaries, while the LSTM network captures essential temporal patterns, providing flexibility and addressing the key challenges in groundwater modeling, such as computational complexity and data scarcity. The obtained results can be used for various groundwater management scenarios and applications such as location of wells, desired pumping, quantity of groundwater that can be extracted etc. Therefore, the hybrid numerical-AI models are valuable tools for decision-makers to balance groundwater use with increasing demand and mitigate the risks of over-extraction and resource depletion.

Keywords: *Meshless method, LSTM, groundwater level predictions, spatial-temporal prediction, groundwater flow*

SIMULATING GROUNDWATER LEVELS AND POLLUTION IN PUNE, INDIA

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Groundwater is perhaps the most useful resource in nature. From agricultural to industrial to residential, the use of groundwater is infinite. But its sources are not. Over 50% of urban water usage is dependent on groundwater. Most of the groundwater comes from rainwater absorption with seepage from rivers and canals contributing a little. However, with urbanization, rainwater absorption is on the decline. Moreover, groundwater resources are being contaminated day after day. Many studies discuss the implications of groundwater pollution on public health. Polluted groundwater has been known to cause a severe decline in immunity levels in children. Contaminated groundwater is a major source of cholera, typhoid, hepatitis, and other similar waterborne diseases. Consumption of groundwater having heavy metals and industrial waste water can cause cancer and neurological disorders. Polluted groundwater can also loss agriculture and aquatic life. The purpose of this study is to find out different factors affecting groundwater levels and quality in the Pune district. By analyzing historical rainfall data, industrial waste output, urban population and water usage statistics, we aim to create a simulation model capable of predicting groundwater usage, contamination, and recharge. This model will assist to know the activities would be best for reducing pollution, enriching recharge channels, and evolving optimal strategies for sustainable groundwater management, that safeguards clean and abundant groundwater resources for the region.

We are collecting data from various government approved sources and other relevant publications. Government agencies like the Maharashtra Pollution Control Board and the Central Pollution Control Board stake water pollution levels and measurements timely. These periodic reports are valuable as they support to compile comprehensive data mapping both surface water and groundwater pollution across the region. Agencies like the Indian Meteorological Department collect and document rainfall statistics every day. This data is crucial for constructing rainfall patterns. Understanding these patterns will be influential in assessing groundwater recharge rates, which are critical for maintaining sustainable water resources. The Groundwater Surveys and Development Agency conducts regular groundwater level surveys. This data can be used to map past and existing groundwater levels. Analysis of this data will allow us a better understanding of the activities taking place as recharge rates of groundwater and the level of pollution within the groundwater. This all collected data will also help to the development of an LSTM-based model predicting the future availability of groundwater and groundwater pollution over time. This work will present a thorough understanding of patterns and trends of water quality and availability. This will contribute making decisions toward water management and environmental protection. All the data collected will be treated and then merged. Preprocessed data will be fed to the LSTM model. The LSTM model is chosen to incorporate both current and previous data giving more accurate results. Since we are working with natural phenomena, previous data plays a vital role in forecasting other related factors (i.e. we will need Y_{t-1} and X_t both). This makes the LSTM model a significant choice due to its integration of the internal current data point (X_t) and the historic one (Y_{t-1}), which has been strong in delivering estimated accuracy compared to others.

Upon training, LSTM will be subjected to multiple scenarios. This will help us simulate different usage, recharge, and pollution conditions in order to find out how we can boost groundwater sources, reduce groundwater pollution, and promote sustainable usage of groundwater. We will also be using other GRU-based architectures to confirm and cross check our findings. This will help strengthen the validity of the LSTM architecture for groundwater simulation tasks. The output of this study would be a model capable of simulating groundwater usage, recharge, and pollution levels against various input conditions. This study would also help us determine the most optimal usage conditions for ensuring sustainability in groundwater levels in Pune district. This work is aimed at identifying the various factors governing both the levels and quality of groundwater in the Pune district. This can be achieved by analyzing historical rainfall data, industrial waste output, and statistics on the urban population and their utilization of water. This paper will try to obtain a simulation model that may predict the dynamics of the region's groundwater resources. Such a model is essential to understanding the complexity involved with the several factors that affect the groundwater resources and their quality. We will also implement some more complex modeling techniques, including Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) architectures. These are relevant methods for this study as they emphasize the importance of sample data in accurate prediction. We will thus be able to validate the importance of our research by examining how different influences affect groundwater resources over time. This way, it will not only add to the existing knowledge but will also help formulate appropriate sustainable groundwater management strategies for the Pune district.

Keywords: *Groundwater, LSTM, GRU, simulation, sustainability*

QUANTITATIVE INSIGHTS AND GROUNDWATER FLOW MODELING IN OPEN-PIT MINES

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Agriculture, industry, domestic purposes and other sectors are dependent on groundwater resources due to the limitations in availability of surface water resources especially in semi-arid and arid regions. The limited groundwater resources are severely affected by open-pit mining operations in many ways which includes inflow into mine pits, depletion in groundwater level, change in regional hydrogeology etc. We have conducted a quantitative analysis study and applied a groundwater flow modelling approach in an open-pit mine in Chittorgarh, Rajasthan, having geology characterized by limestone, granite, gneiss and weathered shale. We have monitored groundwater levels at 15 locations in our study site within 10 km buffer zone surrounding the mine. Both pre- and post-monsoon levels within the buffer zone were measured for understanding the seasonal variations in groundwater level. Electrical Resistivity Tomography (ERT) method was applied in addition to understand the subsurface strata of the region. We conducted infiltration tests in five sites in the study area for determination of hydraulic conductivity. A spatial heterogeneity referring to the variation of hydraulic conductivity within the range of 7.41 to 21.33 cm/day was found as the result of the tests. We also conducted pumping tests and recovery tests for computations of two more parameters, i.e., transmissivity and storativity, for understanding the aquifer's capacity to transmit and store water respectively. The value of transmissivity came out was 142.63 m^2/day and storativity was found 0.000905. We used an advanced groundwater modelling software, Visual MODFLOW Flex, to integrate Geographic Information Systems (GIS) data for enhanced visualization and management. Geological, hydrological, topographical parameters and the groundwater dynamics under transient conditions were simulated holistically by the conceptual model. Recharge from precipitation, interactions with rivers & drains and few more boundary conditions were defined based on the observed data and hydrological characteristics of the region. We used rainfall intensity, infiltration capacity and land use patterns for calculation of the recharge rates. We divided our study area into grids assigning specific hydrogeological properties, e.g., hydraulic conductivity, porosity and storage coefficient to each cell. Estimation of seepage into the mine pit and simulation of the groundwater flow patterns were the primary objectives of our research. Partial Differential Equations (PDE) representing groundwater flow is used by this model, solved using the finite difference approach. Model evaluation, i.e., calibration is done using observed groundwater levels from the field data during pre- and post-monsoon periods. The temporal variations in groundwater levels were accounted for the model using the transient state approach. We used analytical methods for estimation of seepage in addition to numerical modelling. Different analytical equations, provided by renowned scientists and researchers, were used to get initial seepage flow. Though these assumptions offer a simplified approach to seepage estimation, they often fail to capture the complexities of heterogeneous aquifers and dynamic groundwater systems. To overcome these limitations, numerical models account for site-specific data, variations in geology for better understanding of groundwater flow dynamics and seepage. Our results came up with the demonstration of significant groundwater inflow towards the mine-pit for development of the strategies for sustainable dewatering. For better understanding of groundwater behaviour, the integration of geophysical data, ground observations as well as advanced modelling techniques become important. Minimization of environmental impacts and maximization of economic benefits, i.e., ensuring the economic feasibility of mining are the objective functions. Future research will focus on improvement of model by calibrating it with hydraulic conductivity and storage related parameter and validation of the model will be done from the field data. The results of this study will help us in many ways, firstly it will provide a detailed understanding of groundwater flow dynamics and seepage pattern in mining region. It will help us in developing a sustainable mine dewatering plan, ensuring that groundwater extraction is optimised to minimize the environmental impacts. The study will also help in developing regional water management strategies by providing relation between mining activities and groundwater resources. The methodology adopted in this research will not only address short term changes but also help us analysing long term changes. By using techniques like Self organising Maps this study can be enhanced and used for long term monitoring. We will also focus on the application of emerging technologies, e.g., artificial intelligence (AI) and Remote Sensing (RS) for management of groundwater resources in regions where mining takes place. The multidisciplinary approach for management of groundwater resources and its significance is the focus of the research. The primary result from simulation of Visual MODFLOW Flex shows that the flow of groundwater converges towards the mine-pit due to hydraulic gradient. The impacts of mining activities are lightened using velocity distribution maps. The initial results show a difference between the estimated seepage inflow from two different analytical equations used for seepage estimation, having higher value for the second one. The results from Visual MODFLOW Flex estimate seepage value which matches the result of the first analytical equation. These discrepancies refer to the limitations of the analytical equations.

Keywords: *Groundwater flow, seepage estimation, open-pit mining, hydrogeology, numerical modeling, mine dewatering plan*

FLUORIDE CONTAMINATION AND ASSOCIATE HEALTH RISK ACROSS THE STATE OF MAHARASHTRA, INDIA

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This study aims to examine fluoride contamination in groundwater across Maharashtra state and its associated health hazards. To conduct this study, we have collected 1,278 groundwater samples data from CGWB water quality data base. The results indicate that fluoride concentrations ranging from 0 to 4.93 mg/L, with an average of 0.59 mg/L (±0.56). The data indicate significant regional variability, with inland districts exhibiting higher fluoride levels and corresponding health risk values compared to coastal districts demonstrating lower contamination and risk. Mostly the eastern region of Maharashtra has fluoride concentration exceed the maximum (1.5 $mg.L^{-1}$) permissible limit indicating the high vulnerability of dental and skeletal fluorosis. However, the coastal district of state have concentration less that lower permissible limit (0.5 $mg.L^{-1}$) in groundwater depicts the high vulnerability towards health issues causes due to deficiency of fluoride. Our findings underscore the importance of identifying and addressing the sources of fluoride in these regions and implementing effective public health strategies to minimize exposure. Additionally, the study highlights the need for ongoing monitoring of groundwater quality and the development of policies aimed at managing fluoride levels in affected areas. By providing insights into the spatial distribution of fluoride contamination, this research serves as a crucial step toward safeguarding public health in the Maharashtra state and informs future initiatives to combat environmental contaminants. The results emphasize the critical need for comprehensive risk assessments and community education regarding the implications of fluoride exposure.

Keywords: *Groundwater, contamination. Fluoride, Health risk, Maharashtra*

ASSESSMENT AND FORECASTING OF GROUNDWATER TRENDS IN THE BUNDELKHAND REGION: IMPLICATIONS FOR WATER SCARCITY AND RESOURCE MANAGEMENT

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The Bundelkhand region, known for its susceptibility to drought and water scarcity, has been facing a persistent decline in groundwater levels due to over-extraction, limited rainfall, and ineffective water management practices. This study was conducted to analyze groundwater level trends in Bundelkhand, predict future changes, and identify critical areas vulnerable to severe water shortages. These insights aim to assist policymakers, environmentalists, and engineers in designing effective water resource management and conservation strategies for sustainable water availability in the region.

The study involved time-series analysis of groundwater levels collected from over 40 observation wells across Bundelkhand. These wells include both confined and unconfined aquifers, providing a comprehensive view of groundwater distribution and variations within the region. Data analysis was performed using the Mann-Kendall test to detect monotonic trends, Sen's slope estimator to quantify the rate of change in water levels, and the Exponential Smoothing Method (ESM) to forecast groundwater levels for the year 2030. In addition to statistical analyses, spatial analysis software was employed to create isobath maps, offering a visual representation of groundwater levels and helping to identify areas at greater risk of depletion.

Results of the Mann-Kendall and Sen's slope analyses revealed significant groundwater level trends in 23 observation wells during the pre-monsoon season and in 14 wells during the post-monsoon season. Among piezometric wells, which measure water pressure in confined aquifers, significant trends were observed in 12 wells during the pre-monsoon season and 9 wells post-monsoon. The observed groundwater level changes in unconfined aquifers showed a consistent trend, ranging from a decline of -0.541 m per year to an increase of 0.395 m per year during the pre-monsoon period, while post-monsoon levels fluctuated from -0.385 to 0.239 m per year. Similarly, confined aquifers displayed a range of changes in piezometric levels, with variations from -0.341 to 0.870 m per year in the pre-monsoon season and -0.401 to 1.148 m per year in the post-monsoon season. Spatial analysis through isobath mapping provided further insights into the geographical distribution of groundwater levels, highlighting areas of severe decline. Maps generated for both confined and unconfined aquifers identified significant spatial variability in water levels across the region. Areas with the greatest declines in groundwater levels were primarily in Mahoba, Banda, and Jhansi, where water scarcity has been particularly severe in recent years. These areas, identified as "hotspots," are at a heightened risk of water shortage, which could impact local agriculture, industry, and community water supply, if not managed effectively. The Exponential Smoothing Method (ESM) was utilized to predict short-term groundwater level changes for the year 2030. The forecasted scenarios indicate a critical drop in the water table during the pre-monsoon period in several locations across Bundelkhand. Projections suggest a potential reduction in water levels by as much as 11 m in Mahoba and 8.2 m in Banda pre-monsoon. Post-monsoon declines are projected to reach up to 7.9 m in Mahoba and 8.7 m in

Chhatarpur. Additionally, in confined aquifers, a drastic decline in piezometric levels is anticipated, with a maximum drop of 22.15 m predicted in Jhansi. These forecasts emphasize the urgency for immediate intervention and the adoption of sustainable groundwater management practices to prevent further depletion and ensure water security for the region. Given these findings, the study proposes several mitigation strategies tailored to Bundelkhand's hydrological and socio-economic context. One key recommendation is to strengthen water recharge initiatives, particularly in high-risk areas identified through isobath mapping. Implementation of artificial recharge structures, such as check dams, percolation ponds, and rainwater harvesting systems, could help enhance groundwater replenishment during the monsoon season and alleviate stress on water resources. Another critical strategy involves regulating groundwater extraction rates, especially for agricultural purposes, which constitute a major portion of water usage in Bundelkhand. Adoption of efficient irrigation techniques, such as drip irrigation, could significantly reduce water usage and limit further groundwater depletion. The study also emphasizes the importance of community engagement and awareness programs to foster a culture of water conservation within local populations. Education campaigns can help inform residents of sustainable water usage practices and the benefits of rainwater harvesting at household and community levels. Additionally, integrating traditional water management practices, which have historically been effective in arid regions, with modern techniques could provide more resilient solutions to water scarcity in Bundelkhand. Finally, this research underscores the need for continuous groundwater monitoring and policy support to address the ongoing water crisis in Bundelkhand. Regular monitoring of groundwater levels, with data-driven analysis and forecasting, is essential for effective water management. Policymakers are encouraged to utilize findings from this study to implement region-specific regulations that safeguard groundwater resources. By adopting a comprehensive approach that combines scientific analysis, spatial mapping, and local involvement, sustainable groundwater management in Bundelkhand is achievable, providing a blueprint for other water-stressed regions across India.

In conclusion, the groundwater depletion trends and forecasts for Bundelkhand underscore the severity of the water crisis in the region. This study offers valuable insights into groundwater behaviour, potential scarcity zones, and actionable strategies for sustainable water management. With these findings, water resource engineers, environmentalists, and policymakers can better understand the extent of groundwater depletion in Bundelkhand and work toward long-term solutions that secure water availability for future generations.

Keywords: *Groundwater, time Series data, Mann-Kendall's test, Sen's slope estimator, exponential smoothing method.*

Theme 7

ADVANCED TECHNIQUES FOR GROUNDWATER EXPLORATION AND ASSESSMENT

INTERPRETATION AND INTERPOLATION OF ELECTRICAL RESISTIVITY DATA USING INVERSE PLOT METHOD: CASE STUDY OF GROUND WATER EXPLORATION IN HARD ROCK AREAS OF RAJASTHAN, INDIA

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Geophysical exploration techniques play a vital role in probing and understanding the nature of the subsurface rock strata, especially in groundwater and subsurface strata conditions. There is demand of the time to have inputs of cost-effective easy access technology for explorations in finding groundwater sources for industrial, irrigation and domestic supply, which is to fulfill the day today needs of the society. The geophysical techniques like electrical resistivity scanning find its wide application in ground water exploration irrespective of several ambiguities. It has proven its cost effectiveness in terms of production optimization. Resistivity meter model SSR MP ATS microprocessor-based instrument is used for data collection, inbuilt capacity to store 100 scan data with average depth 250 m. It is compatible with PC, where RES software installed. Data transferred possible only by establishing connection between instrument and PC. Beauty of the instrument is there one cannot manipulate or change the data obtained and saved. These data directly uploaded in the software for further analysis and simulation. Interpolation and interpretation done by review of geology of the area and experience, as well as feedback of earlier drilled bore wells at suggested sites. Multi-metal antenna also used for contact tracing of saturated and unsaturated strata in the area of interest and tracing the underground water flow channel.

The interpretation involves processing of data, where parameters obtained about depth-wise strata layer thickness and inference drawn for the subsurface rock formations, leads to find out the water saturation status, using geological background knowledge with the preliminary reconnaissance using geologic observation tools. Electrode spacing decreased or increased depending upon values of variables of ascending and descending depths slice of the litho log obtained directly in the display of the instrument. For finding layers, the quantitative approach of inversion technique, elaborates relationship of measured with the actual appropriation. This is carried out using combination of techniques with inverse plot and the microprocessor based electrical resistivity measurement instrument and simulation with 2D software. The emphases on applied aspects are dealt with the resource identification, quantification of the subsurface deposits by CPQ indexing. The Schlumberger configuration considered for field operation. The field equation directly to get the resistivity and thickness of the subsurface layers from the field data is considered as “Inverse slope method” for the study. This methodology has proved to be suitable for varied geological set up, field areas scanning and found practical utility in locating potential bore wells, which is mainly, based on major six variables, amongst Rho, Strip and R play its immense role.

The field operations carried out in most of the cases, where failure bore wells drilled are present. We collected subsurface data, interpretation done using software and interpolated to find out the groundwater bearing strata in terms of its saturation potential and availability are compiled in this study. Typical groundwater scarcity area of Jawai Dam surroundings area in

Pali districts of Rajasthan, in western India, is famous for its wild life shelter and it is a unique tourist's destination to visit leopard residing in the well jointed open joints/ sheets of granite hills formed millions of years ago by lava, which is truly speaking is home/ shelter house to leopards, sloth bears, wolves, chinkara, and crocodiles. It is also nature's beauty to see many migratory birds during winter. To solve the potable water requirement of the local and tourists during summers, geophysical scanning was carried out and successful bore wells located. Tehsil Mavli in Udaipur belongs the annual average rainfall in 604 mm, with an average of 30 rainy days per year is groundwater scarcity zone, surface water bodies almost vanished, all open wells are dry in majority, except few. The area categorized as groundwater dark zone, even than water availability problem solved viz. located sites and potential bore well drilled.

Similarly, success arrived in several groundwater scarcity areas of Nathdwara area district Rajsamand, Badgaon and Girwa area district Udaipur, Gulabpura area Bhilwara, Padanga in Naguar. Ranabeda, nadol area Pali, Nenva area Bundi, and Aditya Cement Works Sawa-Shambhupura Chittorgarh, etc. Groundwater flow direction, venation mapping, subsurface layered profiling of strata, obtained as a final success and systematics, where inventory has been prepared, which elaborates the potentially proven controls of groundwater localizations i.e., Intrusive contacts with the host, concealed open joints, quartz veins contacts with the country rock, rift and graben, interlayered sheets, weathered horizon, micro lineament, etc. Objectively, it is realized to popularize less expensive techniques to avoid dry bore well and help society in finding potential bore well/open well for getting groundwater to fulfill their demands. Focus has been laid on selected area for varied lithological set up so that this could clearly become understandable to all. Present study deals with the 95% accuracy in exploring the subsurface and it has proven the application of geophysical electrical scanning of several areas of hard rocks, and their quantitative and qualitative assessment resulted in potential yield bore wells. The success stories of finding groundwater in acute dry areas, to meet out irrigation, industrial water supply and domestic water supply encourage us to recommend this cheap and easily available technique. In this technique, the problem of longitudinal conductance never arises and sandwiched saturated groundwater strata easily identified, by basic field curve plotted directly.

Keywords: *Geo-electrical resistivity, hard rock, inverse plot, groundwater, Rho, strip, groundwater scarcity, controls of groundwater localization, flow direction*

GRACE SATELLITE DATA AND OBSERVED WELL LEVELS REVEAL THE RELATION BETWEEN SPECIFIC YIELD AND GROUNDWATER DEPTH

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The specific yield (S_y) is defined as the ratio of the volume of water that saturated rock or soil yields by gravity to the total volume of the rock or soil. It serves as a crucial indicator of the amount of water stored and available in unconfined aquifers. The S_y values are influenced by several key factors such as grain size, shape, initial depth of the water table upon saturation, and rate of water table changes. In land surface models (LSMs), S_y plays a critical role in simulating groundwater dynamics. However, most of the LSMs assume a constant S_y value for the calculations. For instance, the CLM and Noah-MP models commonly uses S_y value of 0.2; VIC and MATSIRO-GW models utilize empirical S_y values of 0.15 or 0.08, respectively. Using a single fixed S_y value can oversimplify groundwater recharge estimations and lead to highly uncertain groundwater estimates. Therefore, there is a need to characterize the spatial and temporal variations in S_y values and investigate the underlying reasons. This knowledge will enhance model performance, thereby improving predictions of groundwater and water availability across diverse hydrological settings at regional and global scale. Various field methods such as pumping and slug tests are used to estimate S_y, but these tests assume steady-state conditions and may overlook complex aquifer heterogeneity. Additionally, they are costly and are not repeated often. Laboratory experiments provide detailed insights into porosity and permeability, essential for S_y calculations, yet they may not fully replicate field conditions. Geophysical methods such as electrical resistivity imaging (ERI) and ground penetrating radar (GPR) offer valuable spatial information on subsurface properties related to S_y but are indirect and require calibration with ground truth data. All these methods collectively provide a comprehensive toolbox for estimating S_y, yet they require careful consideration of aquifer heterogeneity, spatial and temporal variability and uncertainties in data collection and interpretation. Hence, novel methods to estimate S_y are needed.

The Gravity Recovery and Climate Experiment (GRACE) satellite data along with available well data is used to estimate $S_{y.}$ Typically, S_y are used to scale well data to equivalent water height (EWH) and compare with estimates from GRACE data. However, the problem would be posed in an inverse sense and estimate S_y from observations. This study used the monthly GRACE and GRACE-FO Level 3 mascon solutions (JPL RL06.1_v03). The monthly soil moisture data was obtained from the Climate Change Service (C3S) volumetric surface soil moisture (C3SVSSM) COMBINED produce v202212. The Central Groundwater Board (CGWB) provides the groundwater levels (GWLs), which are accessible for four months in a year (January, March, August and November). The S_y is defined as the ratio of change in groundwater storage anomalies (GWSA) to the GWL changes for a given mascon. The change is defined with respect to minimum and maximum values observed each year. The S_y calculated is represented as 'observation based S_y'. The GWSA were obtained from GRACE Total Water Storage Anomalies (TWSA), which is a combination of all forms of water storages such as surface water, soil moisture and groundwater, etc. Thus, to isolate GWSA, soil moisture storage anomalies (SMSA) are removed from TWSA. Next, as GWLs are available for four months (January, March, August, November) in a year. Our analysis is limited to only these four months. Further, uncertainty analysis was carried out using error propagation formulae.

Over the entire country, the yearly observation-based S_y values were calculated at the mascon scale (about 3°x3°). For 20 mascons out of 52, S_y values were not calculated due to lack of GWL data. For most of the mascons, the observation-based S_y values match well with the reference S_y. However, our method marginally overestimates S_y values compared to the reference for few mascons (from 40 to 52). The uncertainty assessment was performed through error propagation and the values are within the range when compared to the reference uncertainty. Out of 32, the uncertainty of three mascons (41, 45, 48) are exceeding the reference uncertainty. Further, we studied the variation of S_y with average GWL. Existing literature reports an inverse relationship between S_y and GWL. Similar behavior was observed in most of the mascons. For instance, in mascons 24, S_y decreased with increase in GWLs (m below ground level) and vice versa. However, for a few mascons (22, 26, 33, 34, 41) the inverse relationship between S_y and GWL did not hold good. It is evident from the scatter plot that S_y is decreasing with increasing GWL. A general pattern is hard to extract from the data as the scatter is large and averaging is needed. Thus, to obtain empirical relation between both quantities dynamic size data binning was performed to obtain representative points for a range of groundwater level values. Then, an exponential function was fitted using regression to establish a mathematical relationship between S_y and average GWLs.

In the present study, we estimate S_y using GRACE TWSA and GWLs for whole India. The observation based S_y values performed well when compared with reference S_y in most of the mascons. The S_y values varied through time, and this motivated us to look into factors driving changes in S_y values. We have found that groundwater level has an inverse relation to S_y, in other words, the deeper the groundwater level, the smaller the S_y. The inverse relationship between S_y and GWLs is formalised into an empirical equation derived using available data from GRACE satellites and CGWB dug well data. GRACE satellite data can be employed along with well data for estimating S_y at various spatial and temporal scales. The proposed method can be applicable across diverse hydrological settings at regional and global scale.

Keywords: *Specific yield, GRACE, total water storage anomalies, mascon, groundwater levels, aquifer*

DEDUCING GROUNDWATER POTENTIAL ZONES IN THE WAINGANGA RIVER BASIN, CENTRAL INDIA USING AHP AND GEOSPATIAL TECHNIQUES

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Groundwater plays a crucial role as a resource for humans, meeting the needs of households, agriculture, industry, etc. Due to its hidden nature, preliminary exploration and identifying the groundwater potential are crucial for effective management and development. Availability of groundwater and its quality are affected by many natural and anthropogenic factors like changes in land use, varied climatic condition, geological and geomorphological conditions and over-exploitation of groundwater. Over-exploitation of groundwater without a thorough understanding of its potential can lead to significant water shortages and resource depletion. To effectively assess groundwater resources, mapping groundwater potential zones (GWPZs) is vital. The latest innovations in remote sensing (RS) and GIS, now provides rapid and precise solutions for determining GWPZs. The objective of this study was to develop a map of GWPZs for the Wainganga River basin in Central India (area ~51,384 km²) using a combination of remote sensing (RS), Analytical Hierarchical Process (AHP), multi-criteria decision-making (MCDM), and GIS techniques and to validate the results using well-specific yields and groundwater level fluctuations.

This study models GWPZs using RS, GIS, and AHP techniques. Nine layers such as geology, geomorphology, LULC, soil, drainage density, lineament density, slope, rainfall, and TWI were converted to raster format, resampled to 30×30 m and reclassified. A weighted overlay approach was used in ArcGIS 10.7 to evaluate the groundwater potential index (GWPI), with weights and ranks assigned based on literature and expert input. Sensitivity analysis was carried out by omitting individual layers to assess their impact on the GWPZs. The data sets used in this study includes SRTM-DEM from USGS (30×30 m), LULC from ESRI Sentinel - 2 (10×10 m), rainfall data from IMD (0.25°×0.25°), soil map from FAO (1:5,000,000), geology and geomorphology from the Bhukosh portal (1:50K), lineaments (1:250,000), and slope, drainage, and TWI derived from DEM (30×30 m). Groundwater level data was sourced from the Indian Water Resources Information System.

The demarcation of GWPZs was done through the application of AHP and GIS techniques. The GWPI values varied from 2.79 to 7.53, dividing the basin into five zones: very poor (8.28%), poor (21.63%), moderate (30.21%), good (28.21%), and very good (11.67%). Occurrence of very high potentiality in the southwest parts of the area was majorly attributed to the geology, high lineament density, and LULC. In the central part, the lithology played a vital role as this area covered by alluvium and sandstones. Also, geomorphologically, it was covered by alluvial plain. The very poor to poor zones occurred in the central eastern part, which resulted due to presence of highly dissected plateaus with higher degree of slope and complex geology. Validation of the potential map against the in-situ groundwater level fluctuations and well-specific yields has revealed a strong correlation (R=0.93). It was observed that exclusion of slope resulted in maximum increase in area of very poor potential

zone by 21.77 % and while omission of LULC showed reduction in very poor zone by 9.08 %. In the poor zone, maximum decrease of 7.11 % showed by exclusion of LULC layer. In good potential area, maximum decrease of 9.77 % resulted due to exclusion of slope layer. In very good zone, the maximum area reduction was of 24.77 and 24.51 % after removing of slope and drainage density respectively. While geology (16.20 %), geomorphology (9.78 %), and LULC (12.01 %) have shown significant increase in the area of very good potential zones. The GWPZs are classified into five categories: very good, good, moderate, poor, and very poor. The southern region of the basin shows higher potential, with good and very good zones, while the northern and eastern regions are marked by poor and very poor potential zones. The deduced potential map was validated by comparing it with groundwater level fluctuations and well-specific yields, showing a high degree of correlation. Zones with good and very good potential are identified as the most favourable for groundwater exploration, while poor and very poor zones are the least favourable. Sensitivity analysis reveals significant changes in the very good potential zones when individual thematic layers are omitted. In complex geological setting of the Wainganga River basin, these identified GWPZs are crucial for understanding recharge capacity and optimal groundwater resource utilization.

Keywords: *Groundwater, remote sensing, GIS, AHP, exploration, sustainability, Wainganga River basin, India*

FIELD EXPERIMENT FOR SUSTAINABLE GROUNDWATER MANAGEMENT: EVALUATING DISCHARGE MEASUREMENT METHODS AND AQUIFER CHARACTERISTICS IN ALLUVIAL AQUIFERS OF NORTH-WESTERN INDIA

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In hydrogeological studies, understanding aquifer characteristics and the behaviour of groundwater flow is essential for sustainable groundwater management. One of the fundamental aspects of this process involves accurately measuring the discharge rate of exploratory pumping wells, as it provides critical data on aquifer parameters such as Transmissivity (T) (m^2/day), Hydraulic conductivity (K) (m/day), and Storativity (S). Variability in discharge measurements can lead to different interpretations of aquifer properties, impacting the assessment and planning of groundwater resources. Field experiments comparing different discharge measurement methods can offer valuable insights into the reliability and precision of each method, as well as their influence on the derived aquifer parameters. This study evaluates the accuracy and precision of four discharge measurement methods namely V-notch Weir, Orifice Flow Measurement (Manometric Head), Volumetric, and Ultrasonic Flow Meter during pumping tests conducted via an 8-inch diameter exploratory well in the alluvial aquifer of Northwestern India. Two pump configurations (a high-capacity vertical turbine (VT) pump and a lower-capacity submersible pump) were used to test each method under varying discharge conditions. The primary objective was to identify the most reliable discharge measurement method by determining the accuracy and precision of each method and to provide insights about how different pumping configurations influence the estimation of T. The experiment involved conducting step-drawdown tests at three incremental discharge rates for each pump configuration. This testing approach allowed for the assessment of different discharge measurement methods under varying pumping conditions. The methodology consisted of three main components viz., discharge measurement method, pumping configuration and data analysis.

Discharge measurements were carried out using four distinct methods over one-hour intervals at three step-drawdown levels. The V-notch weir method involved recording the water height passing through a 90° V-notch plate to calculate discharge based on the height-discharge relationship. The orifice flow method was used for manometric head measurements across a circular orifice with standard equations to determine flow. The volumetric method collected water in a known-volume container and measured the time to fill it, providing a direct volume-per-time discharge. Lastly, a non-intrusive ultrasonic flow meter measured flow velocity in a closed conduit to calculate discharge. Two pumping configurations were employed to explore the impact of pump capacity on discharge measurements and aquifer parameter estimation. A vertical turbine pump, with high capacity, imposed significant stress on the aquifer, enabling greater discharge measurements and substantial drawdown. In contrast, a low-capacity submersible pump produced smaller drawdowns, which could lead to an overestimation of T due to higher discharge-to-drawdown ratios and reduced stress on the aquifer.

Data analysis involved both qualitative and quantitative approaches to evaluate the precision and accuracy of discharge measurement methods. Qualitative analysis such as box-and-whisker plots was used to visually assess data spread, favouring methods with points clustered near the overall mean for accuracy. Quantitative analysis included constructing accuracy vs. precision graphs, where mean square error (MSE) quantified accuracy and standard deviation represented precision. Methods exhibiting high accuracy with moderate-to-high precision were deemed reliable for discharge measurement. Following the identification of the most reliable discharge measurement method, aquifer performance tests were conducted using both pump configurations to estimate aquifer transmissivity. Discharge measurements were taken with the selected reliable method, allowing for a comparison of transmissivity values from each pump setup. This comparison helped determine which pump setup yielded transmissivity values most closely aligned with field observations, providing insights into the impact of pumping configuration on aquifer parameter estimation. The comparative analysis of discharge measurement methods across both pump configurations, provided insights into the precision, accuracy and reliability of each method.

The performance of discharge measurement methods revealed that certain techniques consistently outperformed others when applied under their specific operational assumptions. Among these, the 90° V-notch Weir method exhibited the highest accuracy and moderate-to-high precision across both vertical turbine (VT) and submersible pump setups. Its data showed minimal variability and aligned closely with expected flow rates, establishing it as the most reliable method in this study. A comparative ranking of reliability placed the methods as V-notch > volumetric > ultrasonic flow meter (UFM) > manometric head. Significant variability in T estimates was observed between the VT and submersible pump configurations. The VT pump, with its higher discharge capacity and induced drawdown, produced transmissivity values that closely matched field observations, demonstrating its effectiveness for accurately estimating aquifer parameters under stressed conditions. Conversely, the submersible pump, with its lower discharge rate and reduced drawdown, tended to overestimate transmissivity. This overestimation was likely due to the reduced stress on the aquifer, resulting in higher T values that did not accurately represent true aquifer conditions. These results underscore the importance of selecting appropriate discharge measurement methods and pump configurations for accurate aquifer parameter assessment. This field experiment highlights the critical role of selecting appropriate discharge measurement methods and pumping configurations for accurate aquifer transmissivity estimation. Among the methods tested, the V-notch Weir proved most reliable due to its high accuracy and moderate-to-high precision, making it well-suited for transmissivity assessment aligned with specific discharge-to-drawdown dynamics. The VT pump configuration, capable of inducing higher aquifer stress, yielded transmissivity values closely matching field observations, while the submersible pump tended to overestimate transmissivity due to its lower discharge and limited drawdown. These findings highlight the importance of discharge measurement method and pump dating configuration selection in achieving accurate aquifer characterization, offering valuable guidance for sustainable groundwater management.

Keywords: *Transmissivity, discharge measurement, pumping configuration, aquifer pumping test, precision & accuracy, alluvial aquifer*

ELECTRICAL RESISTIVITY AND VLF-EM METHODS FOR GROUNDWATER MAPPING IN DROUGHT-PRONE BASALTIC TERRAINS OF NORTH MAHARASHTRA, INDIA

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The primary objective of this study is to identify groundwater occurrences in the drought-affected basaltic terrain in North Maharashtra, using an integrated geophysical approach. Water resources in the region exhibit significant temporal and spatial variability. Although the state does not face an overall water shortage, certain locations remain chronically water-stressed due to regional water demands increasing at more than twice the rate of population growth over the past three years. Village administration plays a pivotal role in ensuring sustainable and safe drinking water through the implementation of piped water supply systems for households. Persistent water scarcity restricts access to safe drinking water and hampers basic hygiene practices in homes, schools, and healthcare facilities, exacerbating socio-economic challenges in these regions.

The study area, Rajapur Village, is situated in Yeola sub-division of Nashik District, Maharashtra. The district's climate is generally pleasant, characterized by dryness throughout the year except during the southwest monsoon season. The winter season extends from December to mid-February, followed by the summer season lasting until May. The district experiences significant variability in annual rainfall, ranging from approximately 500 mm to 3400 mm. Analysis of negative departures from normal annual rainfall indicates that about 75% of the district, located east of the Western Ghats including Sinnar, Niphad, Surgana, Kalvan, Satana, Chandwad, Yeola talukas, and parts of Dindori, Peint, and Malegaon sub-divisions can be classified as drought-prone. The average annual rainfall during 2002–2011 ranged from 476.7 mm in Devali to 3508 mm in Igatpuri. In Rajapur, water scarcity is a persistent challenge. The Village administration supplies water once every 15 days through tankers, which are increasingly costly as daily demand grows even in less populous communities. Villagers must transport water approximately 3 km daily from the government headquarters using bicycles, motorbikes, and carts. To alleviate the shortage, the Village administration excavated a new open well, 60 ft deep, located downstream of the Wadpati percolation tank, about 3 km from Govthan. Despite these efforts, the new source often fails to provide water reliably, with interruptions occurring at least once every two days. This underscores the need for a sustainable and comprehensive solution to address water scarcity in the region.

Geophysical investigations were conducted in the vicinity of a drinking water source well, with a depth of 20 m. The primary objective of the survey was to delineate fractures, joints, and groundwater-bearing zones near the source well using Very Low Frequency (VLF) electromagnetic and Vertical Electrical Sounding (VES) resistivity methods. Six VLF profiles (2010E, 2020E, 2030E, 2040E, 2050E, and 2060E) were acquired, each extending 300 m in length with measurements recorded at 10 m intervals. The VLF data were processed and interpreted using RAMAG software. Multi pseudo-depth sections revealed two sets of medium to good conductive geological bodies (depicted in yellow, light pink, and dark pink shades), which were interconnected. Profiles four, five, and six indicated feeble current

densities exceeding 20%, corroborated by VES data. The VES data, interpreted using IPI2WIN software, employed a three-layer resistivity model (ρ1, ρ2, ρ3) to match measured curves with theoretical master curves as described by Orellana and Mooney (1966). Three VES surveys were conducted with electrode separations (AB/2) ranging from 100 to 120 m. Among these, groundwater potential zones were identified at two VES locations. The qualitative analysis categorized geo-electric layer patterns into AA curves ($\rho1 < \rho2 < \rho3 < \rho4$) and HA curves ($\rho1 > \rho2 < \rho3 < \rho4$).

The VES data revealed five to six geo-electric layers with resistivity values ranging from 13.50 Ω-m to 82.20 Ω-m, averaging 40.75 Ω-m. The primary aquifer was identified within the fourth to sixth layers, comprising weathered, vesicular, fractured, or jointed zeolitic basalt. The saturated potential zone depth ranged from 4.23 to 34.01 m (average 19.12 m), with a thickness of 3.32 to 29.78 m (average 16.55 m). The conductive anomalous zones corresponded to fractured lineaments-oriented northeast-southwest. A significant fracture, located 38 m southeast of the source well, was determined to have a width of approximately 38 m. The multi pseudo-depth section indicated that the source well was constructed on a high-resistivity geological body (negative anomaly), interpreted as a groundwater barrier, likely an underground compact rock structure. Notably, a fracture was located 30–40 m east of the well, highlighting a shallow groundwater potential zone in this region. Based on the findings, the Bore Blast Technique (BBT) was employed to enhance connectivity between the southeastern fracture zone and the source well. A total of 20 boreholes, each 20–30 m deep, were drilled in three parallel lines and simultaneously blasted. Following the blast, muddy water with bubbles emerged from the well, accompanied by a significant rise in the water level. This intervention successfully reduced the project’s expenditure by minimizing the number of required boreholes. Within 24 hrs, the source well was replenished with water, enabling the Village administration to lift water, fill overhead tanks, and supply it to villagers daily. This reduced reliance on costly water tankers, ensuring that the community did not face drinking water shortages even during the summer. The integrated geophysical approach provided a comprehensive understanding of surface and subsurface structures and groundwater potential in the study area. The outcomes facilitated sustainable water resource development, significantly benefiting the local community.

Keywords: *Geophysical investigations, groundwater exploration, pseudo-depth sections, electrical resistivity, bore blast technique*

GROUNDWATER POTENTIAL ZONES USING AHP TECHNIQUE FOR THIRUVANANTHAPURAM DISTRICT, KERALA, INDIA

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Groundwater represents an essential natural resource that plays a crucial role in sustaining human health, fostering economic development, and maintaining ecological diversity. This study undertakes a detailed assessment of groundwater potential zones specifically located in the Thiruvananthapuram district of Kerala, employing advanced methodologies including the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS). By integrating these powerful tools, the study aims to effectively evaluate and map the status of groundwater resources, which are paramount for sustaining local populations and ecosystems. The AHP methodology, recognized for its structured approach to decision-making, was applied here to prioritize various factors that influence groundwater availability. In this analysis, thirteen thematic layers have been meticulously chosen and integrated, each reflecting critical aspects of the environment that impact groundwater recharge potential. The layers include lithology, which assesses different rock formations and their capacities for water retention; geomorphology, which examines the effects of landscape features on hydrological pathways; and lineament density, which explores the occurrence of fractures and faults that facilitate the movement of groundwater. Furthermore, drainage density was analyzed to understand the distribution patterns of surface water, which can significantly influence groundwater replenishment. In addition to these, slope characteristics were scrutinized to appreciate how the angles of terrain can affect both infiltration rates and the efficiency of runoff. The study also considers surface curvature and roughness, which provide vital insights into the dynamics of water flow across landscapes. The integration of land use/land cover (LULC) is particularly critical, revealing how human activities impact recharge processes in various regions. Soil characteristics were evaluated to determine their capacities for water retention and permeability, which directly affect groundwater availability. The study utilizes the topographic position index (TPI) to assess the positioning of the landscape in relation to potential recharge areas. The topographic wetness index (TWI) was employed to predict zones where water tends to accumulate, influencing both surface and groundwater systems. Furthermore, the normalized difference water index (NDWI) was calculated to assess the extent and health of water bodies within the region, while rainfall data is integrated to characterize regional precipitation patterns, which are vital for understanding groundwater replenishment. The application of AHP in this study facilitates a thorough and systematic approach to weight assignment based on expert judgment, ensuring a detailed evaluation of how each factor contributes to groundwater potential. The integration of GIS enhances this analysis by enabling detailed spatial mapping and visualization across Thiruvananthapuram district, revealing profound variations in groundwater potential influenced by geographic and environmental factors. For instance, areas characterized by active fluvial deposits have been identified as having very high recharge potential, particularly when these deposits are found in conjunction with lower drainage density and enhanced lineament density that allows for efficient groundwater movement. Conversely, regions that feature gentle slopes and rich forest coverage display increased capacities for groundwater recharge, serving as natural buffers and facilitators for sustainable water flow.

In stark contrast, urbanized areas exhibit a significant decline in groundwater potential due to extensive land use modifications, prompting concerns over resource management. Based on these assessments, groundwater potential zones have been classified into five comprehensive categories: very low (indicating unfavorable conditions for recharge), low (showing limited but recoverable potential), moderate (supporting localized recharge efforts), high (demonstrating good potential for active recharge), and very high (representing optimal conditions for substantial recharge). The results obtained from this detailed evaluation underscore a critical finding, groundwater systems are particularly vulnerable to climate variability, which necessitates the adoption of adaptive management strategies tailored to the specific conditions of the region. High-potential areas generally contain optimal combinations of geological, hydrological, and topographical characteristics, while zones with reduced potential are often linked to urbanization trends and adverse natural conditions. This disparity emphasizes the pressing need for sustainable groundwater management practices, particularly protective measures in high-potential zones, along with rehabilitation strategies aimed at areas with diminished groundwater resources. The insights derived from this comprehensive study offer significant implications for local and regional water resource management strategies. The effectiveness of GIS-based analysis in assessing groundwater potential zones is demonstrated vividly through this research, showcasing how a multi-layered approach can reveal the intricate interactions that affect groundwater recharge and availability. Moreover, the study emphasizes the importance of tackling over-exploitation risks and adapting to the challenges posed by climate change, thereby contributing considerably to informed and evidence-based decision-making aimed at sustainable water management practices in Thiruvananthapuram. Additionally, the adaptability of the methodology utilized in this study provides a robust framework that can be replicated for similar assessments in varied geographical contexts, thereby broadening the relevance of the findings across different regions. Considering escalating climate variability and pressures from human exploitation, there is an increasing necessity for careful planning and the implementation of effective conservation measures to ensure the long-term availability and quality of this indispensable resource for generations to come. Ultimately, this study serves to establish a foundational understanding for developing and executing effective groundwater management strategies within the Thiruvananthapuram district. It highlights the critical balance that must be maintained between resource utilization and conservation efforts. By providing actionable recommendations and insights, the study aims not only to inform local stakeholders but also to contribute to broader discussions concerning sustainable resource management amidst ongoing environmental challenges. This collective approach is essential for recognizing, preserving, and enhancing groundwater resources as integral components of the health and sustainability of both human communities and natural ecosystems alike.

Keywords: *Groundwater potential, AHP, GIS, water resource management*

ASSESSMENT OF DYNAMIC AND STATIC GROUND WATER RESOURCES THROUGH AQUIFER MAPPING IN SIDDHARTNAGAR DISTRICT, UTTAR PRADESH, INDIA

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Ground water, the most preferred common pool resource is under increasing stress due indiscriminate abstraction for agricultural, industrial, and domestic usage. The unregulated exploitation of ground water resources often results in environmental, social and economic stress. Ground water extraction exceeding the natural recharge, results in depletion of ground water levels, predominantly in shallow aquifers. Over-extraction from shallow alluvium aquifers has resulted in declining water levels, and as consequent, the deeper aquifers are being exploited in many areas. The impact of the stress imposed on the shallow aquifer may also be felt in the deeper aquifer depending upon the nature of hydraulic connection between the aquifers. Rapid urbanization, population growth, and agricultural and industrial demands have led to excessive groundwater extraction in India, particularly in Uttar Pradesh, which accounts for nearly 20% of the country's groundwater use. There is, thus, a need to study the nature of inter-aquifer interaction and to assess the actual quantum of ground water resources available in different aquifers for holistic management of ground water resources. Scientific estimation of the groundwater resources depends upon the disposition of the aquifers and its hydraulic properties. With the objective of enhancing groundwater resource management, Central Ground Water Board under Ministry of Jal Shakti, Government of India has launched the National Aquifer Mapping and Management (NAQUIM) program to map the Country’s aquifers in 1:50,000 scale with basic aim to delineate existing aquifer systems, assess their potential and characterise individual aquifers properties in quantitative and qualitative terms. The output of NAQUIM studies, i.e., the aquifer geometry of the multilayered alluvium aquifers and its hydraulic properties has been utilized for Siddharthnagar District of Uttar Pradesh for estimation of the dynamic and static in storage ground water resources down to depth 300 m.

As part of NAQUIM studies, extensive hydrogeological data collection was carried out in the study area, including 62 Vertical Electrical Soundings (VES), construction of 12 aquifer-specific exploratory and observation wells, water level and piezometric head measurements of various aquifers, 12 pumping tests, and sampling of water quality specific to each aquifer. A multilayered three-tiered aquifer system upto depth 300 m has been established using the VES data, lithological log and geophysical log of the exploratory wells. The aquifer system has been characterized by unconfined (Aquifer-IA) aquifers at shallow depths followed by semiconfined (Aquifer-IB) to confined aquifers (Aquifer-II&III) separated by impermeable clay layers at greater depths. Long duration pumping test of 1000 minutes each has been conducted in 12 exploratory wells and aquifer parameters like Transmissivity (T) and

Storativity (S) have been estimated using mathematical models from Jacob 1946, Theis 1935, and Agarwal 1980. Piezometric head of deeper aquifers and water level of lower aquifers were recorded at regular intervals at these locations. Ultimately, the Dynamic (DGWR) and Static Ground Water Resources (SGWR) of the multilayered three-tiered aquifer system upto depth 300 m has been estimated using the aquifer geometry, hydraulic properties of the aquifers and piezometric head of the aquifers in accordance with the methodology prescribed by the Ground Water Resource Estimation Committee (GEC-2015).

The value of the DGWR of Aquifer I has been considered from National Compilation on Dynamic Ground Water Resources of India, 2022 report and the SGWR upto the depth of 50 m using equation [($SGWR_{upto\ 50m}$= (50-D_{PRE}) × A × Sy × Aquifer %), Where, D_{PRE}= Depth to water level in Pre-monsoon, A= Area of aquifer, Sy= Specific yield of the aquifer and Aquifer%= ratio of cumulative thickness of granular zones and total aquifer thickness]. For estimating SGWR below 50 m depth down to the bottom of Aquifer I, block-wise average Storativity value has been utilized. The SGWR of Aquifer I below 50 m depth has been assessed using equation [($SGWR_{below50m}$=(D_{AqI}-50)×A×S), Where, D_{AqI}= Depth to bottom of Aquifer I, S= Storativity of the aquifer]. For estimation of SGWR of confined aquifers i.e., Aquifer II and Aquifer III, average piezometric head and depth up to top of the confined aquifer has been considered. This has been calculated by using the equation [($SGWR_{Aquifer\ II\ \&\ III}$= A × S × Δh = SA($h_{PRE}$-$h_0$)), where, A= Areal extent of confined aquifer, h_{PRE}= Piezometric head, h_0= depth up to top of the confined aquifer].

Total ground water resources down to depth of 300 m has been estimated as 5.16 billion meter^3 (bcm), of which 0.87 bcm (17%) is DGWR and 4.29 bcm (83%) is SGWR. The distribution of the total resource in three aquifers are 4.92 bcm (95%), 0.21 bcm (4%) and 0.03 bcm (1%), respectively. Groundwater resource assessment down to 300 m reveals that about 95% of resources are in unconfined to semi-confined aquifers, with only 5% in deeper confined aquifers. Unconfined aquifers, which are easier to recharge and sustain, are predominantly utilized for various purposes. Confined aquifers, though under high pressure, contain less water due to reduced porosity at greater depths. For sustainable management, extraction from deeper aquifers should be limited to essential drinking water needs only and the cumulative ground water extraction from all the aquifers should not exceed the annual replenishment in shallow aquifer.

Keywords: *Ground water resource, aquifer mapping, NAQUIM*

MONITORING GROUNDWATER FLUCTUATIONS IN AGROCLIMATIC ZONES OF INDIA USING GRACE SATELLITE DATA AND PRECIPITATION CORRELATION ANALYSIS

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Groundwater is a vital resource for India, serving as the primary source of water for irrigation, domestic use, and industry. This dependency on groundwater is critical in the dry months of the year. However, rapid industrialization, urbanization, and intensification of agriculture have led to alarming groundwater depletion rates, particularly in regions of northern India. Understanding the fluctuations in groundwater storage and its controlling factors is essential for sustainable management of water resources and for crafting informed groundwater policies. This study aims to monitor groundwater fluctuations across the country by analyzing trends in Terrestrial Water Storage Anomalies (TWSA) over 14 distinct agroclimatic zones of India using data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. By combining GRACE data with satellite-based precipitation data from the Global Precipitation Measurement (GPM) mission, this study evaluates both the climatic and anthropogenic factors influencing groundwater storage across these zones. The findings offer valuable insights into how groundwater levels are affected by precipitation patterns as well as human activities, providing a foundation for formulating region-specific groundwater management strategies.

This study focuses on the analysis of monthly TWSA data derived from GRACE for the period from 2002 to 2023 across 14 agroclimatic zones of India. TWSA data is a critical measure of changes in terrestrial water storage, encompassing variations in surface water, soil moisture, and groundwater levels. The study area includes diverse agroclimatic zones, including the Trans-Gangetic Plain, Lower Gangetic Plain, Western Himalayan Region and Central Plateau. This zoning is essential for understanding region-specific patterns and enabling tailored management practices. Monthly TWSA values were calculated for each agroclimatic zone, and the trend analysis was conducted using the Mann-Kendall (MK) test, for identifying monotonic trends in environmental data series. The MK test yields the z-score, a standardized statistic that indicates the direction and strength of the trend: positive z-values suggest an increasing trend, whereas negative values indicate a declining trend. In addition to GRACE TWSA data, satellite-based monthly precipitation data from the GPM mission was also obtained for each zone. Correlation analysis was performed between precipitation & TWSA values to identify the influence of rainfall on TWS. A one-month lag was considered in the correlation analysis to account for the delayed effect of precipitation on groundwater recharge processes. This approach helped to distinguish zones where groundwater fluctuations are influenced more by climatic variables from those where human activities are the predominant factor. In this study, GRACE data was not processed to isolate the groundwater storage component. Instead, we directly correlated monthly GRACE TWSA values with rainfall data, enabling us to identify areas where TWSA is in decline but shows a poor correlation with rainfall. This approach suggests that declining trends in GRACE data in these regions are predominantly driven by groundwater depletion, as other variables within TWS typically exhibit strong monthly correlations with rainfall.

The analysis of TWSA trends reveals significant variability in TWS patterns, highlighting both climatic and anthropogenic influences. The test analysis shows a noticeable declining trend in eight out of the 14 zones, predominantly in northern India. Among these, the Trans-Gangetic Plain zone, which spans Punjab, Haryana, Delhi, and parts of Rajasthan, displays the most substantial storage depletion, with a z-score of up to -19, signifying a strongly negative trend. The total water storage decline in this region is particularly alarming, with a cumulative loss of 5213 cm and a maximum annual loss of 73.89 cm in TWS. This extensive depletion is indicative of any continuous climatic extremes or severe over-extraction, likely driven by intensive irrigation practices and high water demands from expanding urban and industrial sectors. Conversely, zones without significant declines in TWSA generally correspond to regions where groundwater storage is more closely associated with rainfall patterns. Correlation analysis between monthly TWSA and GPM precipitation data supports this observation, with R^2 values reaching up to 0.7 in zones where TWSA shows no decline. This positive correlation, particularly with a one-month lag, suggests that in these zones, precipitation is a primary contributor to groundwater recharge and variability. In zones with declining trends, however, the correlation between TWSA and precipitation is markedly lower, indicating that rainfall alone does not account for TWS fluctuations. These results imply that in areas with weak TWSA precipitation correlations, anthropogenic activities such as unsustainable groundwater extraction for irrigation and industrial use are likely the primary drivers of groundwater depletion. For instance, the Trans-Gangetic Plain region exhibits poor correlation between TWSA and precipitation data, reflecting the region's heavy dependence on groundwater for agricultural production and indicating a diminished role of natural recharge processes in replenishing groundwater storage.

This study highlights the significant role of remote sensing in monitoring groundwater fluctuations in India. The findings underscore the potential of GRACE data for tracking trends in TWS and differentiating between climate-induced and anthropogenic factors influencing groundwater levels. By correlating GRACE-based TWSA with satellite-derived precipitation data, this study offers a nuanced understanding of the spatial and temporal variations in groundwater storage. The results indicate a critical need for region-specific groundwater management strategies. In zones where groundwater storage is closely tied to rainfall, water conservation and recharge-enhancement techniques aligned with seasonal precipitation patterns could be effective. In contrast, in areas with severe depletion and weak precipitation correlation, stricter regulations on groundwater use and adoption of sustainable irrigation practices are essential to mitigate further decline. Specifically, the Trans-Gangetic Plain and other northern regions with declining trends require urgent intervention to balance agricultural productivity with sustainable water use practices. The socio-economic implications of these findings are substantial, as groundwater scarcity in highly populated and agriculturally intensive regions could impact food security and economic stability. The outcome of this serves as a critical step towards understanding the complex interplay between climate, human activity, and groundwater trends, offering valuable insights for policy formulation and conservation efforts. By informing both policymakers and stakeholders, this study supports efforts to ensure the long-term sustainability of groundwater resources, contributing to India's water security in the face of mounting environmental and anthropogenic pressures.

Keywords: *Groundwater storage, GRACE, GPM, MK test, remote sensing*

GEOPHYSICAL RESISTIVITY SURVEY (VES) FOR SELECTION OF ARTIFICIAL RECHARGE OF APPROPRIATE ARTIFICIAL RECHARGE FOR AUGMENTATION OF GROUND WATER RESOURCES IN PAITHANKHEDA VILLAGE, MAHARASHTRA, INDIA

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Geophysical exploration techniques play a vital role in probing and understanding the nature of the subsurface rock strata. Groundwater in hard rock like Deccan basalts of Maharashtra, occurs mainly in weathered, fractures, faults, and joints. The electrical resistivity method is the most suitable method among all other geophysical methods for the prospecting of groundwater resources. The main reason is the notable contrast between the resistivity of the water-saturated formation and the formation vadose zone of the area. The electrical resistivity methods, using the instrument named ABEM Tetrameter–SAS 300 and Aquameter CRM 20 (4 W), a microprocessor-based instrument used for data collection by which Aquameter's intelligent microprocessor technology employs ingenious methods for extracting subsurface information. It is a popular instrument, because of its single-button operation, deep penetration, and accurate and reliable results, even in adverse field conditions. The instrument has a facility to measure self-potential (SP) which is useful in mineral prospecting and environmental studies. It also has an inbuilt capacity to store more than 100 scans with an average depth of up to 300 m. The method for investigation is vertical electrical sounding (VES) by Schlumberger configuration. At different parts of the study area, soundings at different lithological layers beneath the ground were probed to understand the thickness and surface geological formation by checking with apparent resistivity of each litho-layer and its capacity to bear water capacity of a particular rock. Appropriate no of soundings is done at the project location for getting litho-logical characteristics variation with depth. The obtained readings in the field are plotted in the b-logarithmic graph sheet and the geoelectric field curve was interpreted and correlated with standard two layer’s master curves by partial curve matching techniques to ascertain the water-bearing strata beneath the earth. The same was also cross-checked with the computer software IPI2WIN and Computer Software IX1D and the geological condition of the selected Project area. In the present study, the data generated while conducting electrical resistivity surveys through Vertical Electrical Sounding (VES) in Paithan Kheda village in Maharashtra State were analyzed at 22 sites in different locations along with geological and hydro-geological information. The objectives were to understand the nature and extent of the aquifer, to find out the location and thickness of unsaturated zones, and to evaluate the extent of appropriate artificial recharge structures at suitable locations across the village. Interpretation of the top-sounding curves indicates the presence of three to four subsurface geo-electric layers across the study area. The topsoil layer has a range of resistivity values of 2 to 30 ohm-m and lithology comprises of clay with kankar, and lateritic sand. This is followed by the weather and jointed basalt layers with resistivity values of 100 ohm-m. The 300 ohm-m could be identified below the depth of 45 m. At some places, doleritic dykes were also observed with resistivity values > 300 ohm-m. The VES data when correlated with the available lithology data indicates a prominent water-bearing zone between 30 and 45 m below ground level (mbgl). The underlying hard and compact basalt has very little possibility of groundwater occurrence. The top unsaturated and unconfined granular zone up to a depth of 30 m could therefore be easily recharged artificially through rainwater harvesting measures thereby augmenting the groundwater resources of the existing aquifers. Site-specific artificial recharge measures from counter bonding, gully plugs, check dams, and percolation tanks. Recharge shafts and subsurface dekes have been identified across the village for effective recharge of the aquifer especially in its northeastern and southern block regions. Considering the deteriorating groundwater situation, these initiatives would be significant in catering to the needs of future generations. It is the most common, time-saving, and easy-to-operate method for groundwater exploration.

Keywords: *Rainwater harvesting, artificial recharge, VES, lithology, morar shales, Schlumberger configuration*

IDENTIFYING GROUNDWATER POTENTIAL ZONES IN DELHI NCR USING INTEGRATED REMOTE SENSING, GIS AND AHP APPROACHES

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The Delhi and nearby NCR regions have been facing the problem of groundwater scarcity which could be due to an increase in population, global warming that leads to a rise in temperature, and urbanization. To meet the rising demands, we need the groundwater. Climate changes like long dry periods and irregular rainfall have given us even more challenges to look out for better management of the groundwater. To address the issue regarding groundwater scarcity, we first need to identify the groundwater potential zones in NCR and nearby regions. Especially in the regions like NCR where the resources are very limited, we must use very accurate and systemic methods to ensure water availability in the future. To identify the groundwater potential zones, we have used a combination of tools like remote sensing (RS), GIS and the analytic hierarchy process (AHP) to analyse various factors affecting groundwater. For analysis, we have included geological features, land use, slope, drainage density, soil type, and fractures in the ground (lineaments). The study area was chosen based on a mix of urban, semi-urban, and rural areas. The thematic layers have been used that represent the factors that influence groundwater availability. The factors include lithology, slope, drainage network density, soil texture, land use/land cover, and lineament density. The thematic layers were converted into raster format for spatial analysis using GIS. We have used high-resolution datasets for lineament density and lithology to enhance the precision and granularity of the hydrological parameter representation. Using AHP, the weights were assigned to each layer based on their relative impact on the availability of groundwater. We have used a pairwise comparison matrix to quantify the relationships between layers and normalized the weights to ensure reliability and consistency. This organized weighting process helped in identifying the most critical factors that influence groundwater recharge and extraction. Furthermore, the thematic layers were overlaid using the weighted sum approach in the GIS to generate the GWPZ map. Study areas were categorized into four zones: based on good, moderate, poor, and very poor, based on the suitability of groundwater recharge and extraction activities of the map. For validation of the GWPZ map, we have used the observational well data collected across the study area. The strong correlation between the delineated zones and observed groundwater levels confirms the robustness of the adopted methodology. The findings indicated that a significant portion of the study area falls within good and moderate GWPZs. This underscores the effectiveness of the integrated RS-GIS-AHP approach that helps in the accurate identification of zones with high groundwater potential. This study emphasizes the importance of leveraging advanced datasets and innovative methodologies in groundwater studies. The permeability as a weighted factor was incorporated to address spatial variability in subsurface hydraulic conductivity, further improving the delineation of suitable areas for groundwater recharge. Also, the integration of lineament density data offered valuable insights into subsurface water flow pathways, that enhanced the precision of the GWPZ map. The spatial analysis based on GIS has ensured that the thematic layers were effectively combined and has facilitated data-

driven decision-making for sustainable groundwater management. The results of this study hold significant implications for regions facing high water demand and resource constraints. The framework for GWPZ mapping has provided a replicable model that policymakers, urban planners, and resource managers can use to prioritize areas for conservation and recharge initiatives. This study also shows the importance of high-resolution datasets and sophisticated weighting methodologies to improve the accuracy and predictive capability of GWPZ maps. The developed methodology has enhanced the reliability of GWPZ assessments, offering important and actionable insights for sustainable development. The findings ensure long-term water resource management in urban and semi-urban settings, particularly in rapidly developing regions like NCR that rely highly on the refined spatial representation of hydrological parameters. By addressing key challenges associated with groundwater scarcity, the findings give insights into ensuring water security and supporting the broader goals of sustainable urban growth. In conclusion, this study introduces an innovative and comprehensive methodology for delineating the GWPZs in NCR and surrounding areas. The usage of advanced datasets along with traditional factors, enables a more detailed and nuanced knowledge of groundwater dynamics. The generated GWPZ maps are a valuable tool for handling groundwater scarcity to promote sustainable growth and development. This adaptable methodology can be extended to similar regions worldwide, which offers a significant contribution to groundwater management and spatial hydrology. This study serves as a typical example for the importance of embracing cutting-edge technologies and interdisciplinary approaches to addressing critical water resource challenges in a rapidly evolving global environment.

Keywords: *Groundwater Potential Zones, GIS, AHP, lithology, lineament density, LULC*

INTEGRATING REMOTE SENSING, GIS AND MACHINE LEARNING TECHNIQUES FOR ASSESSING GROUNDWATER AVAILABILITY

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Groundwater is a critical resource for meeting freshwater demands in a region. In recent years, its significance has grown considerably due to increasing threat of climate change to global water supplies, especially for arid and semi-arid regions where water is already in scarce and groundwater level is at a decreasing trend. Globally, agriculture is the largest consumer of groundwater, followed by domestic use and the industrial sector. Groundwater offers a distinct advantage over surface water as it can be accessed on demand. The growing water demand driven by population growth is often addressed by increased exploitation of groundwater resources. Urbanization has elevated this challenge by reducing groundwater recharge through enhanced surface runoff, increased evaporation, and the expansion of impervious surfaces, leading to decreased infiltration. This study is aimed to assess the groundwater availability for the National Capital Territory (NCT) of Delhi. Currently, the city is facing significant challenges regarding its water resources, with limited availability of surface water for drinking and extensive dependence on groundwater to meet industrial, agricultural, and domestic demands. The large-scale extraction of groundwater has disrupted the balance between supply and demand, raising critical concerns about both the quantity and quality of the groundwater. Overexploitation and pollution of groundwater are among the pressing issues, and Delhi has been classified as an overexploited region in terms of groundwater availability. To ensure the sustainable management and utilization of groundwater resources, it is essential to comprehensively evaluate the hydrogeological conditions, along with the driving forces, demand, current scenario, impacts, and responses affecting the groundwater.

The commonly employed methods for investigating groundwater availability include hydrogeological and geophysical testing at the field level, which offer detailed insights into the subsurface hydrogeological characteristics but are often expensive and time-intensive. To address these limitations, the objective of this study is to present an integrated approach combining remote sensing (RS), GIS and machine learning (ML) to assess groundwater availability and identify critical zones that warrant greater attention for effective groundwater resource management in a region. For assessing the groundwater availability of a specific region, acquiring accurate inventory data also remains a challenge due to the dependence of groundwater yield on multiple factors. Thus, in the present study, hydrological and physiographical factors that influence groundwater availability predominantly were analyzed and used as input to the developed ML model. These factors include pervious and impervious surface characteristics, geomorphological characteristics, soil characteristics, and seasonal rainfall patterns of the region. The geomorphology map was obtained from the Geological Survey of India and digitized using ArcGIS. Soil maps were obtained from the National Bureau of Soil Survey and Land Use Planning and converted into digital format. India Meteorological Department (IMD) gridded rainfall dataset was used to obtain the rainfall pattern. Surface water bodies were delineated from high-resolution satellite data of Landsat 9, and LULC maps were created using supervised classification with a maximum likelihood classifier. Images were geometrically rectified to a common projection (Universal

Transverse Mercator and datum WGS84) and resampled using the nearest-neighbour algorithm in ERDAS Imagine software. The classification accuracy was assessed through a confusion matrix comparing classified pixels with reference data. The proposed methodology utilizes random forest (RF), an ensemble decision tree-based supervised machine learning model, to assess groundwater availability. Groundwater depth and pumping datasets were used for training (70%) and validation (30%) of the supervised-based learning. The model uses a collection of independent individual classification and regression tree (CART) classifiers. RF model was chosen due to its robustness and efficiency in remote sensing applications. It uses the Bootstrap aggregation algorithm for creating multiple models from a single training dataset by estimating the statistical quantities from the samples, such as mean, standard deviation, etc., and the final response is estimated based on all the involved outputs from the decision trees. The accuracy of the developed model was analyzed through the receiver operating characteristic (ROC) curve analysis. It is the area under the ROC curve (AUC) that estimates the overall model accuracy and is widely used to analyze the performance of machine learning models. ROC-AUC value ranges from ranges from 0 (poor) to 1 (good), and 0.5 signifies randomness. Further, a sensitivity analysis was carried out to identify the critical factors that influence groundwater resources significantly and assess the impact of variable uncertainties in the final output. The present study utilizes the Geemap module of the cloud-based computing platform Google Earth Engine in Python for the RF model development and performance analysis to assess groundwater availability in the study area. The thematic maps and spatial analysis of various input parameters and the final output have been carried out using ArcGIS 10.5 geospatial tool.

The study reveals that about 10% of the study area exhibits poor groundwater availability and 13% excellent groundwater availability. The area under the ROC curve for RF also indicates good predictive accuracy of the model. The availability of groundwater is observed across all the geological formations in the Delhi region, with its occurrence primarily influenced by hydrogeomorphic units such as the rocky ridges, pediments, alluvial uplands, and floodplains. The alluvial floodplain of the Yamuna River is found as the most proficient zone for subsurface freshwater resources in the region. Significant groundwater level depressions are observed in the southeastern part of Delhi, enclosed on three sides by the Delhi Ridge. Similar depressions are also observed in the southwest district on both sides of the Najafgarh drain. These depressions strongly influence the dynamics of groundwater flow in the region. The study reveals that the rapid population growth, urbanization, and the transformation of pervious to impervious surfaces have significantly impacted groundwater availability in the region. The developed methodology in the present study is scalable, and the findings would be useful for sustainable groundwater management, basin management strategies, agricultural planning, and managing groundwater resources under climate change.

Keywords: *Groundwater, GIS, remote sensing, machine learning, random forest*

NATIONAL AQUIFER MAPPING AND MANAGEMENT (NAQUIM) PROGRAMME: A PAN INDIA INITIATIVE TO MAP AND MANAGE AQUIFERS

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Groundwater is found within aquifers, which are geological formations capable of storing and transmitting water, typically composed of porous or fractured rocks, or loose materials. In India, groundwater has become a critical resource, fulfilling a significant portion of the nation's requirements for drinking water and irrigation; specifically, it accounts for 80% of the drinking water in rural areas, 50% in urban settings, and two-thirds of the water used for irrigation purposes. The focus has shifted from merely developing groundwater resources to effectively managing them. A fundamental aspect of groundwater management involves aquifer mapping, which serves as the foundational step in the design, planning, and execution of management strategies. This process is essential due to the intricate nature of groundwater systems and the varied conditions influenced by factors such as hydrogeology, social dynamics, economic considerations, and ecological impacts. By implementing aquifer mapping, there is potential for enhanced governance and improved management frameworks for groundwater resources. Aquifer mapping in various hydrogeological settings will provide an accurate and thorough micro-level picture of ground water in India, allowing for the development and execution of effective ground water management plans at the right scale for this shared resource. As a result, many areas of rural India as well as urban India will experience increased irrigation facilities, drinking water security, and sustainable water resource development. Additionally, it will lead to improved groundwater management in places that are susceptible. The Central Ground Water Board is implementing the National Project on Aquifer Management (NAQUIM) under the "Ground Water Management and Regulation" scheme during the XII plan period in order to address the current and upcoming challenges facing the nation's ground water sector. The major objectives are (i) delineation of aquifer disposition in 3-dimension along with their characterization on 1:50,000 scale in identified priority areas; (ii) quantification of ground water availability and assessment of its quality to formulate Aquifer Management Plans, and (iii) facilitating sustainable management of ground water resources at appropriate scales through participatory approach with active involvement of stake holders. Out of 32.8 lakh km^2 of the total geographical area of the country, nearly 25 lakh km^2 of mappable area was identified and has been covered under the NAQUIM program up to 2023. The methodology includes compilation, generation, and integration of existing and new data, thematic map preparation, and formulation of a Management Plan with pinpointing the demonstrative artificial recharge structures. The NAQUIM outputs include information about the lateral and vertical extents of aquifers, groundwater levels, groundwater quality, and status of groundwater resources, along with management plans that include supply- and demand-side interventions. NAQUIM reports are being disseminated to policymakers, state governments, and other stakeholders and are being used to mitigate groundwater issues, with special emphasis on drinking water and groundwater regulation to ensure the sustainability of India's groundwater resources. Based on the ideas of participatory groundwater management, NAQUIM produced a toolkit for groundwater management. Additionally, the management plans are valuable resource for developing appropriate climate change adaptation plans.

Keywords: *Groundwater, aquifer, NAQUIM, artificial recharge, supply and demand side interventions, source sustainability*

GEOSPATIAL ANALYSIS FOR GROUNDWATER RESOURCE ASSESSMENT: A CASE STUDY OF KIRTI NAGAR BLOCK, TEHRI GARHWAL, UTTARAKHAND, INDIA

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Groundwater is a vital resource for sustaining livelihoods, particularly in mountainous regions such as Uttarakhand, where surface water availability is both seasonal and limited. The state heavily relies on natural springs and groundwater resources to meet the water demands of its population. However, increasing water demand, coupled with climatic variations and the challenging topography of the region, has made sustainable water resource management a pressing concern. The Kirti Nagar block in Tehri Garhwal, Uttarakhand, exemplifies these challenges due to its rugged terrain, variable rainfall, and limited surface water sources. This study addresses these challenges by focusing on the delineation of groundwater potential zones (GWPZs) in the Kirti Nagar block using geospatial techniques and validating these zones through the spatial distribution of natural springs. Springs are an essential source of water in this region, making their preservation and sustainable management critical for the local communities. A systematic and Integrated approach was adopted to delineate GWPZs, leveraging advanced geospatial tools such as remote sensing, GIS and Analytical Hierarchy Process (AHP). The methodology involved generating multiple thematic layers, including slope, lithology, land use/land cover (LULC), soil type, rainfall, drainage density, and lineament density. These layers were derived using satellite imagery, field surveys, and secondary datasets. The AHP method was employed to assign weights to each parameter based on its relative importance to groundwater recharge, determined through expert opinion and pairwise comparisons. This multi-criterion decision-making technique is well-suited for groundwater studies as it enables the integration of diverse factors influencing recharge potential. The weighted overlay analysis in GIS was then applied to integrate the thematic layers and generate a comprehensive groundwater potential map.

The generated map classified the Kirti Nagar block into five distinct categories of groundwater potential: very high, high, moderate, low, and very low. Validation was a critical step in this process, conducted by overlaying the spatial distribution of natural springs on the generated GWPZ map. Field validation and hydrogeological observations further substantiated the reliability of the findings. The analysis identified areas with flat to gentle slopes, high lineament density, and favorable lithological conditions as having higher groundwater potential. Conversely, regions characterized by steep slopes and rocky terrain exhibited significantly lower potential. In the northern part of the Kirti Nagar block, characterized by alluvial deposits and dense vegetation, groundwater potential was found to be very high to high. These areas are favorable for groundwater recharge due to their flat terrain and permeable lithology, which enhance infiltration. In contrast, the southern and western regions, dominated by steep slopes and rocky formations, exhibited low to very low groundwater potential. The steep slopes in these areas promote surface runoff rather than infiltration, thereby limiting groundwater recharge. The validation process indicated a strong correlation between the high-potential zones delineated on the map and the actual locations of

natural springs in the region. This correlation reinforces the accuracy and reliability of the adopted methodology. Springs were predominantly located in areas classified as very high to high potential zones, suggesting that the factors influencing groundwater recharge, such as lineament density and favorable lithology, also govern spring distribution. Drainage density emerged as a critical factor influencing groundwater potential in the study area. Areas with lower drainage density demonstrated higher groundwater recharge potential, as reduced surface drainage encourages water infiltration into the subsurface. Similarly, lineaments, which are fractures or faults in the rock, were found to play a significant role in groundwater movement. These features act as conduits, facilitating the flow and storage of groundwater. The inclusion of rainfall data provided valuable insights into the spatial variability of recharge potential across the study area. Regions with higher rainfall exhibited greater recharge potential, aligning well with field observations and hydrogeological conditions. This study highlights the efficacy of geospatial techniques in delineating groundwater potential zones in mountainous regions with complex hydrogeological settings. The integration of AHP and GIS ensures a reliable and cost-effective approach for groundwater exploration. By combining scientific methods with local knowledge, the study offers practical solutions to address water scarcity challenges in the Kirti Nagar block.

The findings provide valuable insights for policymakers, planners, and local authorities to develop sustainable groundwater management strategies. The identification of high-potential zones can guide targeted groundwater exploration and the implementation of recharge structures such as check dams and percolation ponds. Additionally, conserving natural springs, which are intrinsically linked to groundwater systems, is essential for maintaining the water security of local communities. This study also emphasizes the importance of adopting a holistic approach to water resource management, considering both surface and subsurface water systems. By integrating multiple criteria and leveraging advanced geospatial tools, the methodology ensures a comprehensive understanding of the factors influencing groundwater potential. The results demonstrate that areas with flat terrain, dense vegetation, and permeable lithology are most suitable for groundwater recharge, whereas steep and rocky regions are less favorable. Moreover, the study underscores the role of lineaments and drainage density in influencing groundwater movement and storage. These insights can inform the design of site-specific interventions to enhance groundwater recharge in low-potential areas. For instance, constructing recharge pits along lineaments or reducing surface runoff in steep terrains can improve water infiltration. The Integration of rainfall data adds another dimension to understanding groundwater dynamics in the region. By correlating rainfall patterns with recharge potential, the study provides a basis for predicting the impact of climate variability on groundwater resources. This is particularly relevant for Uttarakhand, where monsoon rains are critical for replenishing water sources. In conclusion, this study demonstrates the potential of geospatial techniques in addressing the challenges of groundwater resource management in mountainous regions like the Kirti Nagar block. The delineation of GWPZs provides a scientific basis for sustainable water management and the conservation of natural springs. By combining modern technology with traditional knowledge, this approach offers a pathway to ensure water security for communities in Uttarakhand. The findings can serve as a model for similar studies in other mountainous regions, contributing to the broader goal of sustainable water resource management in the face of increasing demand and climate change.

Keywords: *Groundwater, geospatial techniques, springs, sustainable water management*

ESTIMATION OF AQUIFER HYDRAULIC CHARACTERISTICS USING DAR-ZARROUK PARAMETERS: A CASE STUDY OF LOHAGHAT BLOCK, CHAMPAWAT DISTRICT, UTTARAKHAND, INDIA

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Groundwater is a critical source of potable water for domestic, industrial, and agricultural uses. However, it is increasingly under threat due to over-exploitation driven by urbanization, industrial activities, and agricultural demands. This degradation has had severe, long-term impacts on both human populations and ecosystems. The Vertical Electrical Sounding (VES) is a widely used geophysical method based on measuring the potential difference between one pair of electrodes while transmitting direct current through other pair and offer valuable insights into the depth, thickness, and lateral extent of aquifer systems in the piedmont zone. For this study, resistivity soundings were conducted using the Schlumberger electrode configuration with a maximum current electrode separation (AB/2) of 470 m. The apparent resistivity values derived from the formula were plotted on a bi-logarithmic graph against the half-current electrode separation. From these plots, qualitative deductions were made regarding the resistivity of the top layer, the depth of each layer, and the signature of the curves. Initial quantitative interpretations were conducted using the partial curve matching technique, wherein the field curves were matched segment by segment with appropriate master and auxiliary curves. These methods are crucial for identifying groundwater potential zones and managing water resources effectively. While traditional hydraulic characterization involves pumping tests to determine parameters such as hydraulic conductivity, transmissivity, porosity, and specific yield, geo-electric parameters can provide alternative estimates in the absence of pumping test data. The Schlumberger array is particularly effective for subsurface investigations due to its high signal-to-noise ratio, good resolution of horizontal layers, and sensitivity to depth. This study aimed to characterize the geo-electrical properties of shallow aquifers and estimate their hydraulic parameters using surface geophysics, and calculate their protective capacity in Lohaghat block of Champawat district, Uttarakhand.

The Lohaghat block, located in the Kumaon Division of the Champawat district and covers about 216 km² area. The climate is relatively temperate and humid compared to adjacent regions. The diurnal temperature range is significant, with the hottest months being May and June, though temperatures are generally not excessively comfortable and heavily relies on groundwater for drinking and agricultural purposes. Groundwater in this area primarily originates from localized aquifers within favorable geo-hydrological conditions such as river valleys and fractured rock formations. Physiographic factors, including gently sloping areas and broad valleys, also influence groundwater emergence. The study area exhibits a complex geological framework characterized by a diverse array of rock types, influenced by intermittent tectonic disturbances associated with various orogenic cycles. The aquifer behavior in this region is complex, influenced by alluvial sediments from surrounding mountain ranges and the Doon Gravels along the Sarda River. Despite this complexity, delineating aquifers remains challenging due to the reliance on surface features rather than

subsurface characteristics. Effective groundwater management necessitates thoroughly understanding the area's geological, geomorphological, and hydrological conditions.

The interpretation of the Vertical Electrical Sounding (VES) data was conducted using IX1Dv3.1 software, employing a layered resistivity model ($\rho 1$, $\rho 2$, $\rho 3$) to match measured curves with a set of theoretically calculated master curves, as described by Orellana and Mooney (1966). This study conducted twenty VES with electrode separations (AB/2) varying between 100 and 470 m, and out of 20 VES locations, the groundwater potential zones occur in 12 VES locations in the study area. Qualitative assessment identified four primary geo-electric layer patterns: HK curves ($\rho 1 > \rho 2 < \rho 3 > \rho 4$) and KH curves ($\rho 1 < \rho 2 > \rho 3 < \rho 4$). The VES data revealed seven to eight geo- electric layers, with resistivity ranging from 13.24 Ω-m to 170.59 Ω-m, and an average resistivity of 83.66 Ω-m. The principal aquifer was located within the fourth to seventh geo- electric layers, consisting of weathered or fractured phyllites, granite, quartzite, and sand. The aquifer depth varied from 17.24 to 91.15 m with an average value of 53.88 m and its thickness ranged from 14.59 to 69.56 m (average 28.17 m) Hydraulic characteristics derived from the geo- electric data indicated a porosity range of 33.31% to 56.14% with an average of 45.40%, protective capacities from 0.12 to 1.9 mhos with an average value of 0.55 mhos, and transverse resistance between 344.03 and 8272.25 Ωm^2 with an average of 2476.63 Ωm. Whereas, Transmissivity values ranged from 67.61 to 902.54 m^2/day with an average value of 268.77 m^2/day, transverse resistivities from 4.72 Ω-m to 208.53 Ω-m with an average value of 61.21 Ω-m, longitudinal resistivities from 37.11 Ω-m to 521.63 Ω-m with an average value of 165.25 Ω-m, and anisotropy values from 0.27 to 1.35 with an average value of 0.64. Hydraulic conductivity varied between 3.20 and 34.72 m/day with an average of 10.45 m/day. These parameters were used to estimate hydraulic conductivity and transmissivity. Dar-Zarrouk parameters including aquifer thickness, resistivity, hydraulic conductivity, transmissivity, longitudinal conductance, transverse resistance, and anisotropy were utilized to assess groundwater potential, classifying the area into moderate and good productivity zones. This study demonstrates the efficacy of surface geophysical methods in estimating aquifer hydraulic characteristics where pumping test data are not available.

Keywords: *Electrical method, Dar-Zarrouk parameters, Hydraulic parameters, Longitudinal resistivity, Transverse resistivity, Anisotropy*

MAPPING AQUIFER POTENTIAL: A HYDROGEOLOGICAL INVESTIGATION OF THE LUNI RIVER BASIN, RAJASTHAN, INDIA

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The Luni River Basin in Rajasthan, India, faces critical groundwater challenges due to over-extraction, limited recharge, and climatic variability. This study investigates key aquifer parameters transmissivity and storativity revealing significant spatial variations influenced by geological heterogeneity. The hydrogeological investigation of the Basin underscores the significant impact of geological heterogeneity and human activities on groundwater dynamics. This study identified wide spatial variations in aquifer properties, emphasizing the need for region-specific management strategies. By combining field investigations and historical data, the research provides a robust framework for understanding aquifer behavior in arid and semi-arid regions. The Luni River Basin, encompassing the arid and semi-arid regions of Rajasthan, India, is crucial for sustaining agricultural livelihoods and local ecosystems. Assessing aquifer parameters like transmissivity, storativity, and hydraulic conductivity is crucial for understanding groundwater dynamics in the Luni Basin. However, a notable gap in comprehensive studies evaluating these parameters leads to a limited understanding of the basin's hydrogeological dynamics. This research aims to accurately characterize aquifer parameters by conducting comprehensive pumping tests, facilitating better water resource management. However, unsustainable groundwater extraction practices, coupled with limited recharge rates and climatic variability, have led to declining groundwater levels and quality. This poses significant challenges for water resource management and sustainability in the region. Existing research in the Luni River Basin has primarily focused on groundwater assessment, hydrogeological mapping, and water quality analysis. However, there is a gap in comprehensive spatio-temporal analyses that examine long-term trends and variations in groundwater levels across different spatial scales within the basin. There is a need to investigate spatial variations in groundwater levels across different hydrogeological units, land use types, and administrative boundaries within the Luni River Basin. With climate variability exacerbating the issue, understanding the hydrogeological dynamics of the basin is critical for sustainable water management. This study aims to estimate key aquifer parameters-transmissivity, storativity, and hydraulic conductivity-through comprehensive field investigations and laboratory experiments. The outcomes will facilitate the development of better water resource management strategies tailored to the basin's unique geological and climatic conditions. The Luni River Basin originates near Ajmer, Rajasthan, and flows through seven districts, covering a stretch of 495 km before terminating in the Rann of Kutch, Gujarat. Characterized by extreme climatic conditions, the region experiences annual rainfall averaging 464 mm (2000–2022 IMD data). The basin's geology includes diverse formations like alluvial plains, dunes, and sedimentary rocks, impacting groundwater availability and movement. Groundwater extraction supports agriculture, but overuse, coupled with low recharge rates, has intensified water scarcity. To achieve the study objectives, a multi-phased methodology was adopted: Geological data was analysed to select pumping test locations across diverse hydro-geological settings. Constant-rate and step-drawdown methods were employed to determine aquifer properties for the time-drawdown data obtained from the CGWB. Using Jacob's straight-line, curve fitting method and Theis's recovery methods, data was analysed to estimate transmissivity, storativity, and hydraulic conductivity. Two exploratory wells will be drilled in confined and unconfined aquifers, and sediment samples will be collected for lithological profiling and laboratory experiments. The data from field tests and historical trends were synthesized to identify patterns and drivers of groundwater fluctuations. The study from the data collected revealed significant spatial variations in aquifer properties across the Luni River Basin, attributed to geological heterogeneity and land use practices. Transmissivity values showed a wide range, from as low as 4.42 m^2/day (Amritpura, Ajmer) to 792.11 m^2/day (Gangasara, Barmer). High transmissivity values in areas like Barmer indicate more permeable aquifers, likely due to quaternary deposits. Low values in regions like Ajmer suggest restricted groundwater movement, possibly influenced by compacted sedimentary formations. Storativity values ranged from 3.81×10^{-4} to 1.02×10^{-3}, with variations linked to aquifer confinement levels and geological settings. Observation wells in confined aquifers exhibited lower storativity, indicating limited storage potential. Specific capacity was highest in exploratory wells at Balotra and Barmer, confirming the presence of productive aquifers in these regions. Quaternary formations displayed better aquifer properties, such as high transmissivity and storativity, supporting enhanced groundwater extraction. Jurassic and Palaeocene formations had limited permeability, reducing groundwater potential. The hydro-geological investigation in the Luni River Basin highlights the critical role of geological heterogeneity and human activities in shaping groundwater dynamics. The study's findings emphasize the need for region-specific groundwater management strategies, including recharge enhancement and regulation of extraction practices. High-transmissivity regions can be targeted for managed aquifer recharge (MAR) initiatives. Low-transmissivity areas require controlled groundwater extraction and alternative water sources to prevent aquifer depletion. By integrating field, lab, and historical data, this research offers a comprehensive framework for understanding aquifer behavior in arid and semi-arid regions, providing a valuable basis for policy formulation and sustainable water resource management in the Luni River Basin.

Keywords: *Luni river basin, pumping test, transmissivity, storativity, geology*

SATELLITE-BASED APPROACH TO ESTIMATE THE GROUNDWATER STORAGE CHANGES AND LAND DEFORMATION FOR JODHPUR CITY

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The Sentinel-1 satellite provides high-resolution radar data for precise land deformation monitoring using InSAR, detecting subtle ground movements such as subsidence. Launched on 3 April 2014, this polar-orbiting satellite operates in a sun-synchronous orbit and offers frequent revisits, ensuring regular and accurate surface displacement measurements and giving high temporal resolution images. InSAR techniques analyse phase differences between SAR images captured at different times to detect changes in the Earth's surface. DInSAR, an advanced form of InSAR, is particularly effective for monitoring land subsidence, environmental changes, and geohazards. It processes sequential interferograms to estimate cumulative displacement over time and is well-suited for tracking surface deformation in stable regions. On the other hand, the GRACE satellite monitors changes in total water storage (TWS) across large regions, capturing variations in groundwater mass by measuring subtle shifts in Earth's gravity field. GRACE's data helps identify groundwater depletion or accumulation over time, providing valuable insights into long-term groundwater trends and anomalies on a regional scale.

The present study focuses on Jodhpur in western Rajasthan, India. This region is characterized by its arid climate conditions and unique geomorphology that comprises dunes, rocky outcrops and alluvial plains that make it significant reliance on groundwater resources. The study combines Sentinel-1's DInSAR technique with GRACE data to analyse surface deformation caused by groundwater extraction. The study used 30 Single Look Complex (SLC) images from 1 January 2017 to 31 December 2024, processed with the Sentinel Application Platform (SNAP) software. SLC data, retaining phase information and amplitude, are indispensable for interferometry. The DInSAR technique successfully detected subsidence and uplift in the region with surface deformation. Key methodologies of DInSAR include pre-processing, which is (a) orbit file correction, which is updated precise orbit information that improves geolocation accuracy. (b) Coregistration: Aligning master and slave images at the sub-pixel level using Enhanced Spectral Diversity (ESD) ensures phase consistency. (c) Interferogram Generation: Subtraction of flat-earth and topographic phases to produce differential interferograms. Post-Processing: (a) Debursting: Seamline removal creates a continuous interferogram. (b) Phase Filtering: Goldstein filtering enhances fringe visibility and reduces noise. (c) Phase Unwrapping: Ambiguities are resolved in interferogram using SNAPHU (Statistical-Cost Network Flow Algorithm for Phase Unwrapping). (d) Geocoding: The unwrapped phase is georeferenced using SRTM 1 arcsec DEM for spatial accuracy. (e) Validation: Ground-truth data from GPS measurements and groundwater level studies are used for accuracy assessment.

The preliminary results from the present study, compared GRACE'S TWS data with DInSAR surface deformation. TWS data indicate distinct seasonal and long-term annual trends in water storage variations. The results reveal changes in hydrological dynamics in Northern and Central part of Jodhpur. For example, during pre-monsoon of year 2023 in northern Jodhpur, average TWS was recorded at -201.73 mm, showing water storage depletion, possibly due to high groundwater extraction during summer. The post-monsoon period partially recovered, with an average TWS of -156.72 mm. The overall year in northern Jodhpur showed a marginal decline in water storage, with a net change of -2.73 mm from January to December. On the other side, Central Jodhpur displayed comparatively better hydrological condition throughout the year, with an average TWS of -133.02 mm and a significant recovery in post-monsoon with an average TWS of -62.49 mm; overall +77.11 net change from January to December, highlighting effective monsoon recharge. The Sentinel 1 SAR study shows that the subsidence of 10-20 mm per in the areas of sandy and sediment-filled zones that may be due to intensive groundwater pumping. However, Jodhpur's rocky basement may limit subsidence in some areas. On the other hand, upliftment is negligible (<5 mm/year), mainly in areas of low groundwater extraction, rates make upliftment relatively rare. The reasonable consistency of both Sentinel 1 SAR data and GRACE'S TWS is observed. The in-situ groundwater level data provided by Central Ground Water Board's (CGWB) having good seasonal correlation with GRACE data. The joint inversion of Sentinel 1 higher resolution data with GRACE data may enhance hydrological monitoring that can allow more accurate and detailed analysing the spatial and temporal fluctuations of water storage patterns across the region. Groundwater level (GWL) data is point-based data of well observation that will supplement the regional trends observed in Sentinel 1 and GRACE, allowing for a more complete examination of groundwater dynamics. Integrating these InSAR and GWL measurements will provide great insight into groundwater sustainability and sufficient detailed information about land deformation.

This analysis underscores the applicability of DInSAR techniques in land deformation studies for urban and arid regions. The availability of Sentinel-1 SAR data and SNAP software presents a strong avenue through which trends may be detected and analysed. However, for future studies, advanced techniques such as StaMPS PSI (Persistent Scatterer Interferometry) and SBAS (Small Baseline Subsets) should be employed to analyse long-term deformation trends with better resolution. Expanding the study area to include the entire Luni River Basin and analysing Sentinel-1 could provide a comprehensive understanding of regional deformation trends and improve monitoring surface deformation linked to groundwater depletion. Additionally, the effects of anthropogenic activities such as industrial expansion and urbanization can be quantified more precisely. In conclusion, Sentinel 1 high-resolution SAR data and Grace's TWS data with groundwater level change data give a valuable approach to land deformation analysis. The study also shows the challenges in combining SAR and TWS data, but it can be overcome by extending the dataset's timeframe of Sentinel 1 and interpolation for TWS data. This study outcome will serve as a baseline for assessing subsidence in urban and agricultural zones, aiding better infrastructure planning and management.

Keywords: *SAR, InSAR, DInSAR, GRACE, ground water storage, land deformation*

GEOPHYSICAL INVESTIGATIONS TO QUANTIFY FRESHWATER STORAGE FOR CONJUNCTIVE WATER RESOURCE MANAGEMENT IN IGNP

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The Indira Gandhi Nahar Pariyojana (IGNP), an important irrigation project in northwestern India, was established to transform arid lands into productive agricultural areas. While the project has achieved significant success in enhancing agricultural output and livelihood opportunities, it has also led to unintended challenges. Issues such as waterlogging, soil salinity, and uneven groundwater distribution have emerged over time, resulting from excessive seepage, inefficient water use, and the region's complex hydrogeology. Waterlogging, particularly in the upper commands, and salinity in the middle and lower commands have undermined agricultural productivity, posing a significant challenge for sustainable water resource management. Addressing these issues necessitates an integrated approach that combines the use of surface water and groundwater, especially by leveraging the freshwater pockets of saline aquifers. This study employed a combination of geophysical and hydrochemical methods to identify and quantify freshwater storage zones in the IGNP command area. Electrical Resistivity Tomography (ERT) was used to delineate subsurface resistivity variations, which help distinguish between freshwater and saline water zones. Freshwater exhibits higher resistivity due to its lower ionic concentration compared to saline water. The ERT survey, conducted at 10 strategic locations involved a Schlumberger electrode configuration with spacing optimized for capturing resistivity profiles up to a depth of 50 m. These locations were chosen based on their hydrogeological importance and their relevance to water resource management.

The ERT findings provided valuable insights into the spatial distribution of freshwater and saline zones across the IGNP area. Results revealed that in the upper commands, including Sardarpura and Masitawali, the shallow zones of high resistivity indicate freshwater accumulation. These zones, often shallower than 20 m, are likely being recharged by canal seepage and rainfall. The lower density of fresh water leads to its retention in the top layers, creating these freshwater pockets. In the middle commands, encompassing areas like Suratgarh and Zorawarpura, the resistivity profiles were dominated by low-resistivity zones, reflecting extensive saline aquifers. However, intermittent localized freshwater pockets were observed at various locations. The lower commands exhibited a mix of resistivity patterns, with some areas showing moderate resistivity values that may correspond to brackish or slightly saline water. To complement the geophysical analysis, water samples were collected from different locations for water quality assessment. The samples were analyzed for parameters such as pH, electrical conductivity (EC), trace metal concentrations, and isotopic composition (δD and $\delta^{18}O$). These hydrochemical parameters provided additional context for interpreting the ERT results and evaluating water suitability for agricultural and domestic purposes. The pH values of the samples ranged from 8.08 to 9.49, indicating slightly alkaline conditions typical of the region. Electrical conductivity values, a direct indicator of salinity, varied significantly across the study area, with values ranging from 750 µS/cm in freshwater zones to over 20 mS/cm in highly saline aquifers. These findings aligned well with the

resistivity patterns observed in the ERT profiles, further corroborating the delineation of freshwater and saline zones.

The trace metal analysis revealed varying concentrations of elements such as arsenic (As), iron (Fe), and manganese (Mn). While arsenic and iron concentrations were generally within permissible limits for irrigation in freshwater zones, elevated levels were detected in some saline areas, emphasizing the need for cautious groundwater use. The isotopic analysis of δD and $\delta^{18}O$ provided critical insights into the recharge mechanisms of the aquifers. The isotopic signatures indicated that groundwater in the upper commands is primarily recharged by canal seepage and rainfall, with minimal evaporation effects. In contrast, the middle commands exhibited isotopic enrichment, consistent with evaporative processes and limited recharge. This distinction highlights the dynamic interaction between surface water and groundwater in the IGNP region and underscores the importance of localized management strategies. The integration of ERT results with hydrochemical data highlights the heterogeneous nature of aquifers in the IGNP area. The identified freshwater zones, particularly in the upper commands, offer significant potential for sustainable groundwater extraction to supplement irrigation and domestic water needs. These zones can support conjunctive water use strategies, wherein surface water and groundwater are managed together to optimize resource availability and minimize adverse impacts such as salinity intrusion. Conversely, the predominance of saline aquifers in the middle commands calls for alternative approaches, such as the use of saline-tolerant crops, aquaculture, or controlled drainage systems, to mitigate the challenges of salinity while utilizing available water resources effectively.

The findings of this study demonstrate the value of combining geophysical and hydrochemical methods to characterize groundwater systems in regions facing complex water resource challenges. By delineating freshwater storage zones and understanding the hydrogeological processes governing groundwater quality, this research provides a foundation for sustainable water resource management in the IGNP command area. The potential for leveraging freshwater pockets within saline aquifers underscores the importance of targeted interventions to enhance water use efficiency and ensure long-term agricultural sustainability.

Keywords: *IGNP, groundwater, conjunctive management, ERT, salinity*

GEOSPATIAL DELINEATION OF GROUNDWATER POTENTIAL ZONES: A MULTI-CRITERIA APPROACH FOR PROBLEMATIC DISTRICTS OF BUNDELKHAND AND KYMORE PLATEAU, INDIA

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The water demand is increasing rapidly with the growing population, urbanization, and industrialization in the whole world. Among the resources of water, groundwater is considerably a highly reliable source of fresh water. Because of various factors like pollution, over-extraction, and climate variability, both the quality and quantity of groundwater supplies are under severe threat. Also, it has become a difficult task to identify and delineate the groundwater potential zones precisely for sustainable water resource management. Madhya Pradesh being one of the important states in India from the point of view of water availability and forest cover, is selected for research. Because of the state's diverse hydrogeological qualities, the groundwater potential in Madhya Pradesh varies noticeably from one location to another. Chhatarpur district (8672 km^2) from Bundelkhand region, Katni (5058 km^2), Panna (7092 km^2), Rewa (6303 km^2), and Satna (7491 km^2) from Kymore Plateau region was selected for the study. The total area is about 34,616 km^2 approximately with elevation ranging from 200 m to 600 m above mean sea level. The soil profile of the study area comprises mainly alluvial and red sandy soil. The average infiltration rate ranges from 2.5 to 5 cm/hr. The land use land cover (LULC) analysis reveals that 25% of the area includes urban and barren land, 30% of the area is forested whereas 45% of the total area is under agriculture. The region lies within the Tons and Ken River basin. It receives around 800-1200 mm annual average rainfall out of which only 10-15% contributes to the recharge of groundwater due to high evaporation rates exceeding 60% of the precipitation. Also, the study area faces a reduction in recharge potential by up to 20% and an increment in surface runoff and sediment load by 15%-20% due to extensive mining activities and extraction of groundwater for irrigation in the area of Panna and Satna districts. In this study, Analytical Hierarchical Process (AHP), Geographic Information System (GIS), and Remote Sensing is used to create Groundwater Potential Zones (GWPZ). The remotely sensed data including elevation, slope, drainage density, geology, rainfall, soil texture, topography, modified normalized difference water index, normalized difference vegetation index, and land use/cover were used to generate thematic layers in the GIS environment. Drainage density was evaluated to assess capability for surface runoff by using SRTM DEM, supported by the geological and soil texture data that aids in establishing subsurface storage and infiltration potential acquired by FAO. Rainfall data were added to incorporate estimations of recharging taken from IMD, while RS indices such as Modified Normalized Difference Water Index and NDVI were utilized to show water presence and vegetation cover, respectively. LULC analysis was done to determine the anthropogenic impacts and natural land use influences on the dynamics of groundwater produced from the Landsat dataset. This integration of multi-criteria elements with GIS and remote sensing techniques will ensure a robust analysis of the groundwater potential zones.

The AHP method was used to assign the weightage and ranking to each affecting element. The thematic layers are then overlayed over each other, Groundwater Potential Index (GWPI)

was calculated by summation of products of the attribute class and its thematic layer weight. This groundwater potential index was subjected to various values that define the classification of different Groundwater Potential Zones. The superimposed maps were categorized into five distinct classes of groundwater potential zones (GPZs): “very low”, “low”, “moderate”, “high”, and “very high” GWPZs. The class title is self-explanatory as “Very High” shows the maximum chances of availability of groundwater in the area whereas “Very Low” shows the least. The classification was done by integrating the main controlling factors including elevation, slope, drainage density, geology, rainfall, soil texture, topography, MNDWI, NDVI, LU/LC, and proximity to water bodies. The generated zonation map showed 12.54% area falling under the high GPZ, which represents the areas of highest recharge and higher availability of groundwater. Conversely, 60.54% of it was in the moderate GPZ, which shows areas characterized by balanced patterns of recharge and extraction. The low GPZ occupied 16.52%, representing zones with limited availability due to adverse geological or hydrological conditions, while the extremely low GPZ accounted for 10.40%, representing critically water-scarce regions. The zonation mapping was validated on the basis of yield data over observed boreholes developed in the study area itself to ensure its accuracy. This validation showed that 78.25% of the bore wells manifested yield as per the projected GPZ classification and confirmed that the model was appropriate. In general, the average yield ranges from 4 to 12 litres per second for the high and moderately classified zones, and that for the low and extremely low yield zones fall below 3 lps in most cases. The results have marked the strength of the methodology in delineating groundwater potential zones and emphasizing its potential to guide effectively groundwater exploration and management strategies. The results are very helpful in not only gaining the groundwater status but also in the management of sources, planning policies, and acknowledging the recharge possibilities in the problematic area in special reference to attaining sustainable development goals. Overall, this research provides a technique to delineate groundwater potentiality, which will be very helpful for managing groundwater resources.

Keywords: *AHP, GIS, groundwater, potential zones, remote sensing*

QUANTIFICATION AND GEOSPATIAL MAPPING OF DUG WELLS IN DISAPPEARING DRY TROPICAL WATERSHEDS

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Since the inception of human civilization, Hand-dug wells have provided water for drinking, bathing and cleaning, irrigation, livelihood, industries. In light of recent global and regional data compilations and analyses, the paramount question is why the shallow and deeper dug well density (DwD) is increasing despite depleting groundwater levels, seasonal and interannual water table fluctuations, high construction and operational costs, stringent regulatory measures, extreme changes in LULC and rainfall, etc. We answered this fundamental question by carrying out the dug well inventory in the "Critically Endangered" 4th order Banki watershed (518.35 km^2) and its sixteen sub-watersheds (varied from 8.43-160.61 km^2) situated in the lower Ganga River basin and supporting livelihoods and ecosystem services to $\geq$ 0.4 million people residing in the 197 villages of seven administrative blocks. We quantified and analyzed the dug well frequency (DwF), dug well density (DwD), and dug well abundance (DwA) in the well-defined 1 km x 1 km grided watershed and sub-watershed boundaries. The DwF is the number of grids in which a dug well occurs, expressed as a percentage of the total number of grids examined. The DwF indicates the probability of finding the grid(s) with dug well(s), which does not involve counting or measuring the dug well in each grid. Additionally, it provides a probabilistic approach to dug well distribution, allowing for efficient spatial analysis and clear comparisons across sixteen sub-watersheds. The DwD and DwA refer to the number of dug well(s) per unit area, but the DwA is always equal to or greater than the DwD because the DwA considers only those grids in which dug wells are recorded and counted. These intrinsic quantitative parameters were finally evaluated by developing GIS techniques and statistical relationships with agriculture areas, population density, number of households, and drainage order of the Banki watershed and its sixteen sub-watersheds. The overall DwF was 75.97 % in the Banki watershed and varied from 1.18 to 31.20 % in its sixteen sub-watersheds. The DwF was higher in the larger sub-watersheds than in the smaller sub-watersheds and showed a lack of uniformity in the distribution of dug wells. Low DwF indicates that the dug wells in the sub-watersheds are either irregularly distributed or rare in particular grids. The high DwF exhibited by the large sub-watersheds denotes their significant groundwater development owing to the long history of settlements and agricultural practices. The DwD in 591 grids varied from 0 to 52 km^{-2}. However, 142 grids covering 103.76 km^2 showed zero DwD. The DwD were grouped into five classes: 0-10, 11-20, 21-30, 31-40, and > 41. The mean DwD in the Banki watershed (9.32 km^{-2}) is higher than the global (0.7 km^{-2}) and national average (2.51 km^{-2}). The mean DwD varied from 0.05 to 3.11 km^{-2} and was higher in the large sub-watersheds than the small sub-watersheds. The DwD increased with the sub-watershed and agricultural areas and the expansion of settlements (number of households and population density). The DwD further showed an increase with a decrease in the drainage density (Dd), indicating disappearing ephemeral and perennial small streams in the sixteen sub-watersheds pose irreversible tipping points, and local people are overcoming spatiotemporal challenges of water availability by constructing dug wells at different depths in the entire Banki watershed. Introducing DwA in the quantitative assessment deals with increasing footprints of intensive groundwater exploration on the aquifer vulnerability. Unlike the DwD, the DwA varied from 2.67 to 19.14 km^{-2}. It was higher in the small sub-watersheds than the large sub-watersheds, indicating that the former have well-developed dug well networks. The low DwD and high DwA in small sub-watersheds are responsible for the dynamic groundwater development and shifting toward the aquifer-centric ecosystem services in the disappearing dry tropical sub-watersheds. Moreover, the quantitative assessment of the dug wells offered robust methods of ground truth verification of the increasing poor groundwater potential zones (GWPZ) in the Banki watersheds and its sixteen sub-watersheds. To overcome this pressing global water crisis at the microscale, we must rejuvenate the drainage density in the small watersheds and sub-watersheds. Linking DwF, DwD, and DwA with Dd offers a holistic, empirical, and novel approach to (1) channel the surface runoff and stormwater, (2) offset the difference between DwD and DwA, (3) augment the recharge of the aquifers, (4) buffer the impact of groundwater over-pumping on river-aquifer interactions, (5) slow or reverse the rapid and accelerating groundwater declines without compromising drinking, domestic and agricultural water supply, and (6) effectively implement the groundwater policies and schemes as well as regulatory measures. Our new method of dug well quantification is flexible, scalable, and useful in groundwater management and decision-making without exhaustive secondary data collection. Additionally, our study is the first attempt to quantify hydro-sociology (dug well frequency, density, and abundance) at the local, regional, or global scale. This could become possible when we developed watershed and sub-watershed models of dug well inventory. The irreversible diversions of small watersheds and sub-watersheds in large river basins increased groundwater dependency. The watershed model of quantifying dug wells simplified the intricate relationship between rivers and aquifers and invariably addressed the limitations of random dug well sampling in regional and global data analysis. Therefore, the watershed model of dug well assessment reflects the external state of aquifer systems. As seen in our study, stream shrinkage and loss of landscape connectivity can affect groundwater recharge, highlighting the need for immediate attention to aquifer conservation.

Keywords: *Dug well inventory, GIS, river-aquifer interactions, aquifer conservation, aquifer-centric ecosystem*

ASSESSMENT OF HYDROLOGICAL CHARACTERISTICS OF THE KAMENG RIVER BASIN BASED ON MORPHOMETRIC PARAMETERS USING GEOSPATIAL TECHNOLOGY

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Morphometry is defined as the scientific measurement of the Earth's surface configuration, including the sizes and shapes of various landforms. It is utilised to assess the hydrological and interpret the geologic conditions and morphometric characteristics of various aspects of a catchment, including linear, surface, and relief aspects. Also, drainage morphometry provides a quantitative description of basin geometry better to understand a drainage basin's geological and geomorphic history. This analysis provides valuable insights into the hydrological behaviour of the rocks present within the river basin or watershed. This morphometry is an exploratory tool to obtain quantitative measurements that provide information about certain aspects of a region, including tectonic activity, flood dynamics, surface runoff, and soil erosion and also emphasizes that the geomorphological characteristics of a catchment area significantly influence runoff intensity, which is particularly sensitive to the basin's features. In morphometric studies, drainage basins are typically regarded as distinct physical units. In this study, an investigation was conducted into the characteristics and hydrological behaviour of the Kameng River basin to promote sustainable river resource management. The primary focus on quantitative methods aims to comprehensively identify the area's relief features.

The Kameng River basin, a tributary of Brahmaputra River originates in Tawang district from the glacial lake below snow-capped Gori Chen Mountain on the India-Tibet border. River is situated between the latitudes 26°37'38" and 27°57'33" North and the longitudes 91°58'2" and 93°22'32" East, encompassing an area of approximately 10,786 km^2. The river meanders through the foothills of the Himalayas for approximately 265 km through the Assam and Arunachal Pradesh in India. Many residents depend on fishing and various water-based activities, making it an important source of income for the surrounding communities. This stunning location, which combines a rich heritage, adventure, and natural beauty, holds significant cultural importance. The river flows through the Kameng Valley in Arunachal Pradesh, passing through dense forests, valleys and hills. Kameng River joins the Brahmaputra River at Tezpur, near east Kolia Bhomora Setu bridge in Assam. The Kameng River is the border between East Kameng and West Kameng districts and separates the Sessa and Eaglenest wildlife sanctuaries to the west from the Pakke Tiger Reserve to the east. Near Bhalukpong in Arunachal Pradesh, the river enters the alluvial plains. It initially flows east-southeast, flanked by two boulder ridges, before making a sharp turn to the south and continuing along a relatively straight path until it joins the Brahmaputra River. Image-interpretation techniques were employed to classify the drainage information of the study area. The drainage maps were developed utilizing ALOS PALSAR DEM data at a resolution of 12.5 m. Several parameters were taken into consideration in this study namely 1) Linear Aspects of the Basin: This category includes stream order, stream number, bifurcation ratio, stream length, stream length ratio, and the length of overland flow. 2) Areal Aspects of the Basin: Key factors in this category encompass basin area, perimeter, drainage density, stream frequency, basin shape, form factor, elongation ratio, circulatory ratio, and drainage texture. 3) Relief Aspects of the Basin: To evaluate the relief characteristics, the analysis included ruggedness, relative relief, relief ratio, gradient ratio, dissection index, and hypsometric. The analysis was conducted within the ArcGIS environment, which facilitated the processing and visualization of these parameters effectively. This study examines the dynamics of morphometric analysis through geospatial technology.

The Kameng River basin demonstrates a diverse drainage pattern that includes dendritic, sub-dendritic, trellis, and rectangular configurations. Additionally, the analysis indicates a notable degree of elongation within the basin. These morphometric characteristics are crucial for understanding the region's hydrological behavior and landscape dynamics, contributing valuable insights for environmental assessment and management efforts. This indicates a robust conformity between the slope factors and the drainage system, strongly influenced by tectonic activity. The analysis of the hypsometric integral and dissection values reveals that the landscape is predominantly in the early youth stage of the erosion cycle. This finding offers a valuable opportunity to deepen our understanding of the natural processes involved in shaping the environment. At this stage, the landscape is marked by sharp relief features, youthful topography, and minimal soil development, highlighting the active role of erosive forces. Recognizing these characteristics can enhance our exploration of how this developmental phase influences ongoing geological and ecological dynamics. A well-established relationship exists between slope angle and drainage structure. The basin's lithological characteristics can be effectively understood by examining texture and drainage density. The geometric layout of the basin enhances our ability to analyse flood dynamics, playing a crucial role in shaping Stream Energy and erosion patterns. This understanding can lead to more effective management strategies for flood risks and sediment control. The unique shape of the basin plays a crucial role in understanding flood dynamics, shaping the flow of streams, and impacting erosion patterns. This configuration not only reveals the secrets of how water moves and behaves during floods but also highlights the powerful forces at work in shaping our landscapes. As a result, these morphological attributes increase flood velocities, enhancing the river's ability to erode and transport sediment. The river is anticipated to be vital in transporting sediment downstream, contributing to current and future geomorphological processes. The river is set to continuously transport sediment downstream, shaping the landscape throughout both the present and future geological eras. This dynamic flow sculpts the earth and tells the story of our ever-changing environment.

Keywords: *Kameng River basin, morphometric parameters, DEM, GIS*

INTEGRATED GEOHYDROLOGICAL, GEOSPATIAL, AND GEOPHYSICAL APPROACHES FOR SUSTAINABLE GROUNDWATER MANAGEMENT IN THE BUNDELKHAND CRATONIC REGION, INDIA

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Groundwater management in semi-arid and arid regions, particularly in hard rock settings, requires innovative and integrative approaches due to the inherent complexity of the geological environment. The Bundelkhand Cratonic region, characterized by limited groundwater availability and challenging hydrogeological conditions, demands precise tools to identify, monitor, and manage water resources effectively. In response to these challenges, this study employed a suite of nine thematic layers lineament density, drainage density, slope, water level, geomorphology, geology, land use/land cover (LULC), rainfall, and soil developed within the ArcGIS environment. These thematic layers were systematically ranked according to their influence on groundwater emergence and mapped using the Analytic Hierarchy Process (AHP) technique, producing a groundwater potential map categorized into very low, low, moderate, good, and very good zones. This integrated geospatial, geohydrological, and geophysical methods approach offers a promising solution for sustainable groundwater management, particularly in data-scarce regions like the Bundelkhand Craton. This study explores an integrated approach for groundwater management in arid hardrock regions, combining Geospatial techniques**,** Electrical Resistivity Tomography (ERT), and Geohydrological methods for sustainable management of groundwater. This research focuses on the comprehensive analysis of hydrological factors controlling the semi-arid and arid regions by developing an integrated approach for effective management in the Jhansi region of the Bundelkhnad cratonic region.

The combination of GIS-based multi-criteria decision analysis (MCDA) through the AHP and geophysical Electrical Resistivity Tomography (ERT) gradient surveys measuremnts is a potential way for groundwater mapping in hard rock regions. Numerous factors, directly and indirectly, affect the behavior of Cratonic aquifers. So, the methodology involves the selection and analysis of thematic layers controlling the cratonic emergence based on the literature survey and advice of hydrological experts such as lineament density, slope, geology, geomorphology, drainage density, water level, rainfall, soil, and LULC. The geology and geomorphological layers were downloaded from the Bhukosh portal. The Digital Elevation Model (DEM) downloaded from USGS SRTM data with a resolution of 30 m was used to create lineament density, drainage density, and slope map. The LULC map was created by training the Sentinal II satellite image samples in a GIS environment using the Random Forest algorithm in ArcGIS software. All the thematic layers were analyzed in a GIS environment with the same resolution. A pairwise comparison matrix was created by allocating weights to various parameters using the AHP methodology. Following the allocation of weights to each parameter and its sub-parameters based on their significance in hard rock hydrology, a potential map is generated by superimposing and integrating all layers on a pixel basis using a weighted overlay approach inside the ArcGIS environment. This methodology is validated with field-based data, including well locations and ERT pseudo-sections, ensuring robustness and reliability. The study used location data of 7 borehole discharge data collected from the field to validate groundwater potential maps. The relationship between the different thematic layers and the groundwater potential values presents the relative importance of different hydrologic layers in controlling the hard rock aquifers. A hydrogeological field survey was also conducted to assess the geological conditions that lead to the formation of groundwater pathways channeling toward the flow.

The research region is categorized into five distinct groundwater potential zones: very high (8.24%), high (37.63%), moderate (33.62%), low (17.34%), and very low (3.17%). Approximately 80% of the research region is classified within the "moderate" to "very high" potential zones. The 2D ERT gradient survey measurements conducted at eight sites underscore the significance of shallow preferential and saturated zones in the region. A very good correlation between the groundwater potential zones and the ERT, as well as finding well-yield data, yields validation of approximately ~71.5 accuracy of the above findings. The findings also highlight the strong correlation between geological structures like fractures, faults, etc., identified by geospatial, hydrogeological survey, and geoelectrical resistivity methods.

This study demonstrates the effectiveness of combining GIS, geophysical, and geohydrological techniques to generate accurate and comprehensive groundwater potential maps. The use of ERT further enhances this integrated approach, especially in areas with limited data, providing critical insights into groundwater distribution in the arid Bundelkhand Cratonic region. These findings not only advance the understanding of groundwater resources but also offer valuable information for residents and policymakers to devise sustainable management strategies. Looking forward, future research should aim to refine modeling techniques, incorporate additional data, and leverage advanced technologies to address ongoing challenges in groundwater management. Interdisciplinary collaboration and stakeholder engagement will be essential in developing adaptive strategies and informing policies for sustainable groundwater use. This integrated approach offers valuable potential not only for the Bundelkhand Craton but also for other arid regions worldwide, where sustainable groundwater management is crucial for socio-economic development and environmental conservation. Furthermore, fostering interdisciplinary collaboration and stakeholder engagement will play a pivotal role in developing adaptive management strategies and informing policy frameworks for sustainable groundwater use. By embracing these advancements and approaches, future studies can further refine our understanding and management of groundwater resources, ensuring resilience and sustainability in water-stressed environments globally. This integrated approach holds promise not only for the Bundelkhand Craton but also for similar arid regions worldwide, where effective groundwater management is essential for socio-economic development and environmental conservation.

Keywords: *Cratonic region, groundwater potential zone, GIS, AHP, Electrical Resistivity Tomography, sustainable groundwater management*

DEMARCATION AND ASSESSMENT OF INLAND SALINITY/GROUNDWATER QUALITY IN PARTS OF WESTERN DHARWAD CARTON FROM TRANSIENT ELECTROMAGNETIC SOUNDINGS

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Lithology, rock water interaction, and unexploited groundwater over a period of time genesis for the accumulation of salts in groundwater in the subsurface which leads to groundwater quality degradation/Inland salinity. The present study area (Navalgund Taluk, Dharwad district, Karnataka State, India) of 693 km^2 in Western Dharwad craton is an example of an inland salinity problem. Delineation of electrical subsurface resistivity distribution, depth extent of salinity, and identification of freshwater pockets in study area are objective of present research study. A geophysical method, the Transient electromagnetic technique (TEM), has been widely used to find low resistivity zones since it is sensitive to highly conductive zones.

Dharwad craton comprises a predominant suite of TTG (Tonalite-Trondhjemite-Granodiorite) gneisses collectively referred to as peninsular gneisses. The second category of rocks within the Dharwad craton comprises greenstones or schist belts characterized by sedimentary associations. The study area is situated in western Dharwad craton, Karnataka state. It is dominated more or less by Granites and Granitic Gneisses. Schists, Greywackes and Sericite Schists are observed as thin patches in the northeastern part of the study area. High-grade metamorphism is observed in the southern part, while low-grade metamorphism is observed in the northern part. The climate classified as sub-tropical temperate. Normal annual rainfall for the period 1991 to 2020 is 588 mm. The study area forms a more or less vast plain at an average elevation of 564 m.s.l. It comes under the drainage of the Malaprabha river, which is in turn a tributary of the mighty Krishna River. In the southwestern part, Ferruginous cherts and Banded Haematite Quartz bands occur alongside Argillites and Greywackes. The lithology in the study area is indicative of poor groundwater repositories and Granitic Gneiss is the main water-bearing formation. Groundwater occurs within the weathered and fractured Granitic Gneiss under water table and semi-confined conditions. The bore wells were drilled from a minimum depth of 53 mbgl to a maximum of 200 mbgl. The depth of the weathered zone ranges from 5 mbgl to 20 mbgl.

TEM Soundings were conducted with a maximum 40x40m square single-turn Coincident loop, where the transmitter and receiving coils were laid parallel to each other, with an offset distance of 5m. TEMPLOT software is used for data reduction and interpretation of TEM-sounding data. Acquired data. i.e. voltage versus time transformed into conductivity versus depth based on the SPIKER algorithm. A total of 153 TEM (Transient Electromagnetic) soundings were carried out to delineate the depth extent of inland salinity and freshwater pockets in the study area. 40 good quality soundings out of 153 were extracted for depicting 1D, 2D, and 3D distribution of subsurface electrical resistivity.

Pseudosections from TEM data in the study area revealed the presence of subsurface low resistivity zones affected by inland salinity. Resistivity values after pre-processing and

processing of TEM data, have been used to identify the depth extent of salinity in the subsurface. Resistivity values in the subsurface are in the range of 2-30 Ω.m and there are exceptional values also present in some locations in the study area. Based on resistivity values, water bearing formations in this area is divided into three zones. 1. Saline zone: <10 Ω.m, 2. brackish zone: 10-20 Ω.m and 3. Freshwater zone: >20 Ω.m. Due to a limited transmitter loop (40*40m size) and instrumental constraints, the depth of investigation is restricted to shallow depths in the range of tens to hundreds of meters. From the acquired data, it is clearly possible to map the salinity extent in depth. At most locations depth of investigation is restricted to saline zone only. It is depicted that the saline zone extends from 5 m to 110 m depth. In the central part of the study area, the depth of salinity is in the range of 75-110m whereas east and western part salinity is observed in the depth range of 50-75m.

The geophysical study has clearly deciphered the extent of inland salinity in aquifers I and II. In the major part of the study area, both the aquifers are affected by salinity in the depth range of 50-140m. Few freshwater pockets have been identified. Additionally, to know the resistivity regime of the aquifers, the Dar-Zarrouk parameter, longitudinal conductance (S), is also performed along with the spatial variation of resistivity from Vertical Electrical Sounding (VES) data. The high resistivity values and low S values, at these locations, are in correspondence with low EC values of groundwater samples of exploratory and key wells. However, investigation of contaminated land and groundwater can be linked to detective solving a mystery. To adequately define the relations between the subsurface resistivity measured by TEM and the change in water quality in depth, additional borehole geophysical data are needed for more detailed qualitative interpretation.

Keywords: *Inland salinity, transient electromagnetic sounding, Navalgund, saline zone, brackish zone*

LITHOLOGICAL MODELING AND DELINEATION OF GROUNDWATER POTENTIAL ZONES FOR GROUNDWATER RESOURCE MANAGEMENT FOR JORHAT AND MAJULI DISTRICTS, ASSAM, INDIA

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Groundwater, although is a replenishable source of water, has emerging concerns as its quality is degraded day by day and its quantity is also getting decreased. Groundwater is often considered a safer source of drinking water compared to surface water, as it is typically less vulnerable to contamination. However, geogenic sources can contaminate groundwater as it passes through various rocks, soils, and minerals. In the context of Assam, although the quantity of groundwater is not a big issue, its quality is in alarming situation as it is contaminated with some deadly contaminants like Arsenic and fluoride. The contamination of arsenic in Assam is coming in a big way and it can cause public health hazards and natural misfortune. Till now, the source of these contaminants is believed to be geogenic as the geomorphology and lithology favour the dissolution of the elements. A detailed investigation of the source of these contaminants is essential to protect the aquifers and mitigate further contamination. Although the groundwater of Assam is in a better place than any other state in case of groundwater availability, with increasing population and urbanization, the probability of depletion of groundwater level increases as extraction increases to fulfil the water demand. Therefore, sustainable measures should be taken as necessary steps to prevent the resource. The present study aims to investigate the arsenic contamination in groundwater and examines the role of clay layers in influencing its distribution within the Majuli and Jorhat districts of Assam, India. The subsurface lithology has been classified into four units viz., clay, silt, fine sand and coarse sand. The significance of clay disposition and thickness in the distribution of Arsenic and other contaminants has been analysed. Additionally, this study identifies groundwater potential zones to support sustainable groundwater management. These zones are classified into six categories: very poor, poor, moderate, good, very good, and excellent. The primary data used for this study were lithological data and aquifer depth. These data were collected from the field during drilling through a dedicated mobile application that was developed to collect lithological data. The data were verified and digitized through Rockworks.20 for the 2D and 3D interpretation of the aquifer characteristics and the preparation of the fence diagram to know the aquifer disposition. The secondary data for groundwater quality were collected from literature. The thematic maps were prepared using secondary data from Bhukosh, Alos Palsar, and Google Earth Engine. The maps were prepared using ArcGIS 10.8 software, and overlay analysis was done using the Analytical Hierarchy Process (AHP).

Groundwater is contaminated in both the two districts with arsenic according to studies conducted by many researchers. Arsenic contamination occurs in shallow aquifers (above 25m) of the Majuli district, decreasing with increasing depth. The local inhabitants were also affected as arsenic was found in their hair, nails and urine. Likewise, the Titabor area in Jorhat district is also highly contaminated with arsenic in shallow aquifers. The present study indicates that a significant clay cap exists between shallow and deeper aquifers in this region, playing a dual role. It acts as a barrier to prevent arsenic contamination in deeper aquifers

while facilitating arsenic concentration in the overlying shallow aquifers. High arsenic load in shallow aquifers may be attributed to the presence of a clay layer underlying the aquifer which potentially may act as a barrier for the underlying aquifer. The clay layer may promote the process of reductive dissolution during organic carbon drawn from the clay layer. There is a clay layer of thickness ranging from 2 m to 46 m which acts as a confining layer between the two aquifers. The expanding nature of clay may also result in the dissemination of arsenic from the pores of the overlying aquifer. The extensive geochemical and hydrogeological study could reveal the provenance of arsenic in the area.

Analysis of the he groundwater potential zones in the area indicates that the highest area is covered by very good potential zone followed by good, excellent, poor, moderate and very poor potential zone. The excellent potential zones are present in the Majuli district. For the sustainable management of the groundwater resource, excellent and very good potential zones can be selected as suitable sites which will be ideal for the implementation of artificial recharge projects. The findings of this research provide valuable insights for planners and policymakers, enabling more informed decisions regarding sustainable groundwater management. The groundwater potential zone was delineated such that the groundwater management plan could be properly planned.

Keywords: *Arsenic contamination, clay capping, groundwater potential zone, lithology, sustainable groundwater management*

AN EXCEL BASED PROGRAMMING APPROACH TO ANALYZE PUMPING TEST DATA FROM LARGE DIAMETER WELL BY PAPADOPULOS-COOPER (1967) METHOD USING DRAWDOWN AND RECOVERY PHASE DATA

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Papadopulos - Cooper (1967) method is popularly used to analyse the pumping test data from large diameter wells. Although method considers confined aquifer in its assumption, but can be applicable for leaky or un-confined aquifer tapped in large diameter shallow dug wells. Here, a small resultant storage coefficient (S) indicates that the aquifer is essentially confined, while a large value indicates that it is leaky or un-confined. The method uses an analytical type-curve fitting approach, which involves the preparation of type curves on logarithmic paper for a family of F ($u_{w,}$ α), versus $1/u_w$ for different values of 'α' as given in tables presented by Papadopulos and Cooper (1967). The method considers only drawdown phase data for estimation of the aquifer parameters, whereas the drawdown phase data of large diameter wells in hard rock areas usually shows negligible aquifer response indicating that most of the water is pumped from the well storage. Therefore, the recovery phase data is equally important and need to be considered while estimating the aquifer parameters from large diameter well pumping tests. Secondly the method requires long duration pumping test data to get close match, as the form of type curves differs only very slightly when 'α'differs by an order of magnitude. Hence, an error is caused in estimating storativity (S) by this approach, as large diameter wells in hard rock areas cannot sustain long duration pumping due to low permeability of aquifers.

Many researchers have suggested the numerical approach to analyse the pumping and recovery phase data from pumping tests on large diameter wells in hard rock areas. However, an EXCEL based tool is not available for analysis. Hence efforts are made to analyse the large diameter wells pumping test data of drawdown and recovery phases in EXCEL spreadsheet domain by applying the same general flow equation, for drawdown '$\mathbf{s_w}$ 'in a large diameter well. The approximation of Well Function for large diameter well 'F ($u_{w,}$ α)', as developed by Sushil K Singh (2007) is used to get different set of values of F ($u_{w,}$ α) for a given set of 'u_w' and 'α'. An EXCEL spreadsheet is developed for a set of time domain data including time since pumping started (drawdown phase) and time since pump stopped (Recovery or residual drawdown phase) as maintained during field observations. 'Q', r_w and $r_{c,}$ are kept constant and an arbitrary value of 'S' and 'T' are considered initially, to get the corresponding values of 'u_w' and 'α' for each time set. These values of 'u_w' and 'α' are, then used for calculating the value of F($u_{w,}$ α) using approximation formulae. Then, by putting input values drawdown and residual drawdown (s_w) is estimated for each time value. Thus, for each value of time period as maintained in the field observations, 's_w' is calculated based on the input data and a spreadsheet of time and drawdown is developed. Field curve (graph), for time since pump started versus drawdown and residual drawdown is plotted in the same spreadsheet and for the same time set, modelled values of drawdown and residual drawdown are also plotted on the same graph. An EXCEL based programming is adopted to match the modelled drawdown and residual drawdown graph with the observed one, by changing 'T' and 'S' values till the close match is obtained for both the pumping test phases. When the

closed match is obtained between two graphs, the input values of ‘T’ and ‘S’ are considered to be the representative transmissivity (T) and storativity (S) values for the given set aquifer condition.

Drawdown and Recovery phase data from short duration pumping tests conducted on fifty-Seven (57) large diameter wells in hard rock and soft rock areas of Nagpur Region, Maharashtra, including Basalt, Granite and Rhyolite, Granite Gneisses, Schists, Fractured Limestone, Sandstone, Shale and Alluvium aquifers were analyzed by this approach. Of these fifty-seven (57) tests, three (3) are from Alluvium aquifer, fifteen (15) from Basalt aquifer, two (2) from Gondwana Sandstone, five (5) from Penganga Shale and Limestone, four (4) from Granites and Rhyolites, and twenty-eight (28) from Granite Gneisses and Schists. For Alluvium aquifer ‘T’ ranges from 62 to 131 m^2/day and ‘S’ from 0.056 to 0.070, for Basalt aquifer, ‘T’ ranges from 18 to 82 m^2/day and ‘S’ from 0.0083 to 0.021, for sandstone ‘T’ ranges from 17 to 91m^2/day and ‘S’ from 0.001 to 0.01, for shale and limestone aquifers ‘T’ ranges from 24 to 31 m^2/day and ‘S’ from 0.017 to 0.022, for Granites and Rhyolites ‘T’ ranges from 18 to 45 m^2/day and ‘S’ from 0.001 to 0.0227, for metamorphic rocks (Gneisses and Schists) ‘T’ ranges from 14 to 34 m^2/day and ‘S’ from 0.006 to 0.011. The ‘S’ values in the range of 0.001 to 0.009 indicate leaky aquifer condition and values in 0.01 to 0.07 range indicate un-confined aquifer conditions (i.e. S=Sy (Specific Yield). The aquifer parameters (T and Sy), as estimated by the presented approach find best resemblance with local hydrogeological setting and are in close range with the values of ‘Sy’ as recommended by GEC-2015 (National Groundwater Estimation Committee) norms. Thus, the approach as discussed is found to be very useful in analysing the pumping test data from large diameter wells in hard rock areas.

Keywords: *Aquifer, large diameter well, pumping test, drawdown and recovery phases, well function, transmissivity, storativity, specific yield*

DEVELOPMENT OF WEB-BASED BASEFLOW SEPARATION ANALYSIS TOOL

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Baseflow separation is a critical process for understanding groundwater contributions to streamflow and spring flow, essential for water resource management and hydrological studies. However, existing methods for baseflow separation are often fragmented across multiple platforms and programming languages, making it difficult for researchers to efficiently analyze datasets. This study introduces a unified web-based tool for baseflow separation that consolidates three established base flow separation methods into a single, user-friendly interface, integrating a Python Flask-based backend and a React-based frontend, enabling hydrologists to easily analyze and visualize hydrological data. The web-based tool developed in a virtual Python environment within VS Code. This analysis tool uses a Python Flask backend with scientific libraries such as Pandas and NumPy for processing hydrological data. Presently, three common baseflow separation methods incorporated are Eckhardt (2005): A recursive digital filter for separating base flow from total flow; Chapman and Maxwell (1996): A modified version of Lyne and Hollick for greater flexibility; and Lyne and Hollick (1979): A linear filter to decompose streamflow into base and quick flow components. The frontend, built with React, enables users to upload hydrological datasets in Excel format, apply the baseflow separation methods and configure analysis parameters, extract periods of recession, delivering comprehensive outputs such as MRC graphs and visualize results through interactive charts, and exhaustive downloadable reports in PDF format, summarizing key statistics and results. The tool also allows users to identify recession periods which provides insight into streamflow dynamics. The results visualized through interactive charts and Master Recession Curve (MRC) graphs plays crucial role in analysing the streamflow recession behaviour over time. The tool was tested on multiple datasets, yielding reliable base flow separation results. Visualizations generated using the Lyne and Hollick, Chapman and Maxwell, and Eckhardt methods were consistent with traditional manual methods. The MRC graphs effectively illustrated streamflow recession patterns, providing insights into the groundwater-surface water interaction. Users were able to adjust analysis parameters, tailoring the tool to specific datasets and hydrological conditions. The PDF reports contained detailed outputs, including base flow indices and recession rates, making it easy for users to share and document their findings. In conclusion it may stated that the developed web-based baseflow separation tool successfully integrates multiple separation methods into a single platform, simplifying the process of analyzing hydrological data. By providing easy-to-use interactive features and generating visualizations, the tool enhances the efficiency of base flow analysis. It is a valuable resource for researchers and water resource managers, offering comprehensive outputs for informed decision-making. Future improvements could include the integration of real-time data or advanced predictive models to further enhance its capabilities in hydrological research and water resource management.

Keywords: *Base Flow Separation, Streamflow, Water Resource, Master Recession Curve*

ANALYSIS OF GROUNDWATER LEVELS AND AQUIFER PARAMETERS IN THE YAMUNA RIVER BASIN FOR SUSTAINABLE GROUNDWATER MANAGEMENT

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Water is vital for ecosystems, socio-economic development, and human survival, with groundwater serving as the primary freshwater source. However, excessive extraction driven by population growth, agriculture, and industrial needs has led to severe depletion and contamination. Globally, agriculture accounts for 42% of groundwater use, followed by households (36%) and industries (27%). In India, 90% of the rural and 30% of the urban population rely on groundwater, with Uttar Pradesh, an agriculturally dominant state, heavily dependent on it for irrigation. Yamuna river basin, which supports both surface and groundwater irrigation, nearly 81% of farmers depend solely on groundwater. The Yamuna River basin in Uttar Pradesh, faces major stress due to extensive agricultural practices and unplanned groundwater abstraction, further aggravating public health and economic concerns. Sustainable management is urgently needed. The study focuses on the Yamuna River Basin in Uttar Pradesh, covering 24 districts, and is divided into three zone. Zone-1 (Saharanpur to Firozabad), zone-2 (Mainpuri to Lalitpur) and zone-3 (Kanpur Nagar to Prayagraj). Each zone presents distinct hydrological challenges, making this zonal classification essential for understanding groundwater dynamics in the region. Uttar Pradesh experiences a subtropical climate with hot summers, a monsoon season from June to September, and cold winters. The majority of rainfall occurs during the monsoon, influencing groundwater recharge. The combination of climatic factors, agricultural practices, industrial demands, and population growth makes this region critical for understanding groundwater sustainability challenges.

The present study evaluates groundwater resources in Uttar Pradesh using data from 151 monitoring wells across three zones and transmissivity data from 24 districts, obtained from the Central Groundwater Board (CGWB). Spanning 24 years (1996–2019), the dataset includes seasonal records for pre-monsoon and post-monsoon periods, providing insights into groundwater dynamics and trends. The inclusion of transmissivity data helps enhances the understanding of groundwater movement and storage capacity. This study highlights the critical role of the Yamuna River in maintaining groundwater levels (GWL), though it faces challenges related to water quantity due to excessive extraction. The Mann–Kendall and Sen’s slope tests at 95% of confidence level were applied for analysing groundwater level trend.

In Zone-1 during the post-monsoon season, 47.06% of wells revealed no significant changes in water levels, 41.18% showed a decline, and 11.76% exhibited rising groundwater levels. In Zone-2, 64.29% of wells were stable, 26.19% showed a decline, and 9.52% exhibited rising levels, while in Zone-3, 65.33% of wells remained stable, 25.34% showed a decline, and 7.33% exhibited rising levels. Similarly, during the pre-monsoon season, 50.00% of wells in Zone-1 maintained stability, 47.06% revealed a decline, and 2.94% exhibited rising levels. In

Zone-2, 59.52% of wells remained stable, 35.71% showed a decline, and 4.75% exhibited rising levels, while in Zone-3, 64.00% of wells were stable, 30.67% revealed a decline, and 5.33% exhibited rising groundwater levels. The decline in groundwater levels, observed in 41.18%, 26.19%, and 25.34% of wells in Zones 1, 2, and 3 respectively during the post-monsoon season, as well as in 47.06%, 35.71%, and 30.67% during the pre-monsoon season, highlights insufficient recharge or over-abstraction of groundwater. Zone-1 experiences a greater decline in groundwater levels followed by Zone-2, and Zone-3. This indicates that Zone-1 is the most stressed zone, while Zone-3 is the least concerned. The higher stress in Zone-1 can be attributed to its dependence on the Yamuna River, whereas Zone-2 benefits from both the Yamuna and some additional rivers. In contrast, Zone-3 is recharged by the Yamuna as well as the Ganga River during monsoon season, which significantly supports groundwater replenishment. The GWL trends analysis highlight the sustainable groundwater management to mitigate long-term environmental and socio-economic consequences. During the post-monsoon season, the groundwater level in Zone-1 ranges from 0.01 to 17.39 m below ground level (bgl) with an average depth of 6.14 m bgl, followed by Zone-2, where it ranges from 0.10 to 38.20 m bgl with an average depth of 6.63 m bgl, and Zone-3, where it varies from 0.02 to 30.58 m bgl with an average depth of 6.24 m bgl. Similarly, during the pre-monsoon season, the groundwater level in Zone-1 ranges from 0.13 to 17.55 m bgl with an average depth of 7.13 m bgl, followed by Zone-2, where it ranges from 0.37 to 38.60 m bgl with an average depth of 8.14 m bgl, and Zone-3, where it varies from 0.45 to 33.60 m bgl with an average depth of 8.49 m bgl. The varying geological formations, draft and recharge across the zones can be linked to the transmissivity values, which measure an aquifer's ability to transmit water. Zone-1, with a transmissivity range from 25 to 2500 m^2/day, Zones 2 and 3 have higher transmissivity values of 20 to 5755 m^2/day and 1.5 to 6338 m^2/day, respectively, enabling greater water movement and well yield potential. The GWL is bit shallow in zone1 but showing declining trend in more wells in comparison with zone 2 and zone 3. A conjunctive use may be adopted for sustainable management in Yamuna River basin of Uttar Pradesh.

Keywords: *Yamuna, groundwater level, Uttar Pradesh, trend analysis*

Theme 8

AUGMENTATION OF GROUNDWATER RESOURCES

EVALUATING POND RECHARGE PONTENTIAL IN THE RAMGANGA BASIN WITH DATA DRIVEN MODELING APPROCHES

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Managed Aquifer Recharge (MAR) stands out as an environmentally friendly approach. MAR involves the deliberate infiltration of surface water into aquifers to replenish groundwater reserves, and it has shown great potential in mitigating water scarcity. Therefore, the primary objective of the study is to fill the knowledge gap in pond recharge estimation by creating a comprehensive prediction model tailored to the unique hydrological and climatic conditions of the Ramganga Basin. While most ponds in the area are not currently utilized as MAR systems, this study provides a systematic framework for evaluating their suitability for MAR deployment. By combining statistical and machine learning approaches, it is aimed to establish a predictive methodology that can support policymakers and resource managers in implementing efficient groundwater management strategies. To achieve this, study undertook extensive data collection and validation efforts. Data from 7,443 ponds across the RGB were compiled using multiple sources, including field visits, government registers and remote sensing techniques. These datasets provided critical information on pond characteristics, including location, size, and recharge capacity. The field visits were particularly instrumental in validating the data obtained from government records and remote sensing. For example, while government records often provided outdated or incomplete information, the field visits ensured the accuracy and reliability of the dataset by cross-verifying pond locations using GPS applications. Additionally, remote sensing techniques helped to identify and map ponds that were not listed in official records, thus enhancing the comprehensiveness of dataset.

To validate the recharge prediction model, 23 monitoring stations were installed in the Moradabad zone of the Ramganga Basin. These stations were strategically located to collect data on recharge rates, water levels, and other hydrological parameters. This real-time data was critical for training and testing the prediction model, ensuring its accuracy and applicability across diverse conditions within the basin. The collected data also facilitated an in-depth analysis of recharge patterns and their dependence on various parameters. The study identified 10 key parameters influencing pond recharge: slope, topographic wetness index (TWI), normalized difference vegetation index (NDVI), demographic population, aridity index, turbidity index, groundwater level, curve number, infiltration rate, and precipitation. These parameters were selected based on their relevance to hydrological processes and their ability to capture the spatial and temporal variability of recharge dynamics. By integrating these parameters into the prediction model, it aimed to develop a holistic understanding of the factors driving pond recharge and their relative importance in determining recharge potential. The analysis utilized a combination of statistical and machine learning techniques to develop the prediction model. Among the machine learning models tested, the Gradient

Boost model emerged as the most reliable and accurate for identifying high-potential recharge zones within the basin. The model achieved an impressive area under the curve (AUC) score of 0.92, indicating its high discriminative power in distinguishing between areas with varying recharge potentials. Additionally, the model demonstrated strong performance in forecasting recharge rates, achieving a correlation coefficient (R) of 0.83. It also minimized key error metrics such as the root mean square error (RMSE) and mean absolute error (MAE), further validating its robustness. When compared to traditional statistical models, machine learning models consistently outperformed in terms of accuracy, flexibility, and predictive capability. The Gradient Boost model, in particular, excelled in capturing the complex, non-linear relationships between the recharge parameters and the observed recharge rates. This underscores the potential of machine learning techniques to revolutionize groundwater management by providing more precise and actionable insights. Using the validated model, analyses was extended to predict recharge potential across the entire Ramganga Basin. This basin-wide assessment was crucial, as the 23 monitoring stations provided only localized data, which, while valuable, was insufficient for comprehensive basin-scale analysis. By leveraging the model's predictive capability, identified high-potential recharge zones that could be prioritized for MAR implementation. These zones represent areas where targeted interventions, such as pond restoration or construction, could yield significant benefits in terms of groundwater recharge.

The implications of the findings are far-reaching. By promoting the use of ponds as MAR systems, the proposed approach has the potential to enhance groundwater storage, reduce water stress, and improve the resilience of water resources in the Ramganga Basin. Moreover, the model provides a scalable framework that can be adapted to other regions facing similar challenges. The integration of machine learning techniques with traditional hydrological analysis represents a significant advancement in groundwater management, enabling more efficient and data-driven decision-making. The environmental and socio-economic benefits of pond-based MAR systems cannot be overstated. In addition to augmenting groundwater resources, these systems can help mitigate the adverse impacts of climate change, such as droughts and erratic rainfall patterns. They also offer a cost-effective solution for rural water management, particularly in regions with limited access to alternative water sources. By revitalizing traditional water management practices and integrating them with modern technological approaches, our study demonstrates the potential of ponds to play a pivotal role in sustainable water management. In conclusion, this research addresses a critical gap in the field of groundwater management by developing a robust prediction model for pond recharge estimation in the Ramganga Basin. Through extensive data collection, validation, and analysis, we have demonstrated the feasibility and effectiveness of using ponds as MAR systems. The Gradient Boost model, with its superior performance metrics, provides a reliable tool for identifying high-potential recharge zones and forecasting recharge rates. By enabling more efficient groundwater management, this study offers valuable insights for resource managers and policymakers worldwide. The proposed approach not only enhances the understanding of recharge dynamics but also contributes to the development of sustainable solutions for addressing water scarcity and groundwater depletion. As the global water crisis intensifies, the need for innovative and region-specific strategies like ours becomes increasingly urgent, highlighting the importance of continued research and investment in this critical area.

Keyword: *Pond recharge, managed aquifer recharge, machine learning models, recharge*

GROUNDWATER RECHARGE POTENTIAL OF VILLAGE PONDS IN LUDHIANA DISTRICT OF INDIAN PUNJAB, INDIA

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A study was conducted during 2021–22 to estimate the potential groundwater recharge from the village ponds in a Ludhiana district of Punjab. One of the most dependable sources of water to meet the rising demands of diverse consumer sectors worldwide is groundwater. But the resources sustainability has been seriously threatened by the irrational and indiscriminate exploitation of groundwater without much regard for its depletion. The water table is dropping alarmingly fast in the state of Punjab, where more than 90% of the land is irrigated, at a pace of 55 cm/yr in 2017. This ongoing decrease in the water table necessitates the rapid and efficient development of artificial groundwater recharge and use of available surface water sources for the groundwater recharge. Keeping this in view the study was planned to assess groundwater recharge potential of village ponds using geospatial techniques. To achieve the objectives of the study, Sentinel 2 images of Ludhiana district was downloaded for the March 2021. In order to cover whole Ludhiana district, three tiles (imageries) having ID L1C_T43REQ_AO20909, L1C_T43RFQ_AO20866 and L1C_T43REP_AO29746 were downloaded and used for the analysis. The area of interest was extracted after doing all the operations in Arc GIS. Three spectral indices namely normalized difference water index (NDWI), modified normalized difference water index (MNDWI) and normalized difference pond index (NDPI) were used to identify and demarcate the area of village ponds in each village of the district. The efficiency of these indices were compared with the manually digitized area of the village pond for the accuracy assessment. NDWI could identify about 370 village ponds, MNDWI could identify and extract about 1263 village ponds and to further extract the village ponds, NDPI was used and NDPI could extract about 1410 village ponds whereas manually about 1513 village ponds could be demarcated. During the study, ground truthing of some the pond was also done to support the archived results. The number of ponds and area resulted from the manual digitization was considered as the reference to determine the accuracy of the spectral indices. For accuracy assessment, one village pond from each block of Ludhiana district was selected and then extents of areas for all the selected ponds were compared between manual digitization and three indices. A total of 13 representative village ponds from all 13 blocks of the district were selected during ground truthing. The efficiency of area demarcation was calculated on the basis of manually digitized pond area and area identified using the particular spectral index. NDPI was found to be a superior index than NDWI and MNDWI for identifying the number and area of the village pond through comparison of spectral indices. Manual digitization is very time consuming and cumbersome process so NDPI can be used with an overall efficiency of 90-95% in identifying the number of village ponds and overall efficiency of 65-70% in demarcating area of village ponds. Five village ponds were selected from the district and infiltration study was conducted at the bottom of these ponds during the month of April 2022. The soils samples of the pond bottom at different depths viz. 1-25, 25-50, 50-75 and 75-100 cm were collected and

textural analysis was done using hygrometer. After analysing the percentage fractions of sand, silt and clay for different depths by using soil textural triangle, it was found that the upper layer upto 50 cm was having higher clay percentage due to continuous ponding of these ponds and settlement of the finer particles. This leads to formation of partially impervious layer at the pond bottom. The infiltration rate without disturbing the dried pond bottom and after removing the top 50-60 cm of layers of soil was determined using double ring infiltrometer. During the field study, the infiltration rate of the disturbed bottom of village ponds found higher infiltration rate as compared to undisturbed bottom of those ponds. Therefore, to maximize the pond's capability for recharge, the bottom soil layer should be removed so that entry of water into the ground takes place. After improving infiltration rate, about 60% recharge can be enhanced through village ponds over undisturbed pond bottom. This helped to analyse the rate of change of infiltration of the village pond bottom. Further, the water quality from some the village ponds was also assessed. The water quality parameters such as pH, EC, TS, turbidity, BOD, COD, e-coli were analysed. The majority of the village ponds water quality was determined to be within allowable limits for irrigation, while for some of the ponds, it was above permissible values. So the water should be treated before use for irrigation. While estimating the volume of these village ponds, the average depth of 2 m was considered for the volume estimation of the village ponds and using NDPI, the volume of 873.8 ha-m was estimated. Considering the daily infiltration rate from the pond, annually about 301.9 ha-m of water can be recharged after removal the bottom layer. If the bottom layer is kept undisturbed, then the recharge rate of 181.3 ha-m would be achieved in village pond.

Keywords: *Spectral indices, GIS, village pond, recharge potential, spectral indices*

INTEGRATING HYDROGEOLOGY AND GEOSPATIAL TECHNIQUES FOR GROUNDWATER POTENTIAL MAPPING IN THE SIRHIND CANAL TRACT, PUNJAB, INDIA

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Groundwater depletion is a global concern, necessitating concerted efforts for judicious management, enhancement and development. Groundwater, which, has occupied a commanding position in India's food security and agriculture in the modern years, but a rapid decline in the groundwater table of India has resulted in unmanaged extension. The condition is no better in Punjab. Punjab, a north western State in India has also been witnessing an average annual decline of 53 cm/year which is mainly due to high agricultural consumption and an increase in the domestic water requirement. Despite the critical importance of groundwater resources in sustaining various sectors, including agriculture, industry, and domestic needs in Punjab, a limited number of studies have focused on identifying potential groundwater recharge zones. This scarcity of research is particularly concerning given the heavy reliance on groundwater as the primary source of water supply in the region. The present study therefore aims to address this knowledge deficiency by conducting a comprehensive analysis to delineate and prioritize these recharge zones in the Sirhind canal tract which occupies significant areas in the central and south-eastern region of Punjab, India by leveraging geospatial technology and the Rockworks software. A comprehensive set of 13 thematic layers, such as geology, soil, land use/land cover and drainage density, lineament density, geomorphology, annual rainfall, slope, groundwater level, lithology, specific yield, depth of first aquifer and hydraulic conductivity were meticulously prepared and integrated using a multi-criterion decision-making (MCDM) approach. The remote sensing data for the Sirhind canal tract underwent pre-processing and analysis using ArcGIS 10.2 software, while the Rockworks software was used to develop the subsurface lithology and stratigraphy map of the aquifer zone for Sirhind Canal Tract. The weighted overlay analysis was employed to assign ranks to each parameter, with normalized weights determined through the analytic hierarchy process (AHP) technique. The AHP process involved four groups: AHP1, AHP2, AHP3, and Groundwater Recharge Potential Zones (GRPZ). AHP1 involved the thematic layers of land use/land cover, soil, and rainfall. AHP2 encompassed geomorphology, lineament density, geology, drainage density, and slope. AHP3 included the layers of hydraulic conductivity, specific yield, water table, depth of the first aquifer, and lithology. Afterward, the AHP was applied to AHP3, AHP2, and AHP1 in order to define the GRPZ. Pairwise matrices and normalized pairwise matrices were generated for each group, considering their relative impact on groundwater occurrence, insights from relevant literature, and expert evaluations. The subclasses within each thematic layer were also reclassified in the GIS platform to assign weights ranging from 0 to 9, reflecting their perceived impact on groundwater development. The sensitivity of the results to the removal of one or more layers was analyzed using the map removal sensitivity analysis. The groundwater potential zone map for the *Sirhind canal tract* was then created by integrating the thematic layers using the weighted overlay analysis technique within a GIS platform. The resulting groundwater potential zone map was classified into five categories: very low, low, medium, high, and very high zones. The groundwater potential zones were further cross validated with the results of the pumping test data of observation well of the CGWB. The study's outcomes indicated that 5.01% (1269.09 km^2), 15.38% (3896.47 km^2), 16.43% (4163.23 km^2), 31.05% (7867.71 km^2), and 32.13% (8140.17 km^2) of the study area (25336.67 km^2) were classified as very low, low, medium, high, and very high potential recharge zones, respectively. Very high and high groundwater potential zones are confined generally to central parts of the study area i.e. Ludhiana, Jagraon, Malerkotla, Barnala, Sangrur, Mansa, Talwandi Sabo and some portion of Moga, Faridkot, Rampura Phul, Sunam, Samana, Nabha, Patiala, Rajpura, Sirhind, Samrala and Rupnagar. The moderate groundwater potential zones occur generally in the valleys and areas of high drainage density that are Nakodar, Zira, Firozpur, Moga, Faridkot, Muktsar, Bathinda, Talwandi Sabo, Mansa, Sunam, Samana, Rampuraphul, Patiala, Khanna, Samrala, Sirhind, Nabha and Malerkotla. Notably, low potential zones were identified in the foothills of Shivalik and the southwest region, whereas high recharge potential zones were concentrated in the central plains of the study area. The low and very low groundwater potential zones occur in the steep slope, high drainage density. Sensitivity analysis revealed that among all the thematic maps, the identification of potential recharge zones was most influenced by several factors, including groundwater level, depth of the first aquifer, soil characteristics, geomorphology, rainfall patterns, land use and land cover, lineament density, hydraulic conductivity, geology, and specific yield. The validity of the findings was further confirmed through the analysis of yield data obtained from existing observation wells. The results affirmed that areas with higher yield categories (ranging from 16 to 55 l/s) corresponded to excellent groundwater potential zones, whereas regions with lower yields (ranging from 8.1 to 13 l/s) were associated with poor groundwater potential zones. This differentiation underscores the diversity in recharge capabilities across the region.

Keywords: *AHP, groundwater potential, remote sensing, sensitivity analysis, groundwater recharge*

POTENTIAL AND CHALLENGES OF RIVERBANK FILTRATION IN NORTH AND NORTHEAST INDIA

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India has experienced commendable growth in agricultural production and food security since the Green Revolution in the 1960s, however this has also resulted in it becoming the world's largest groundwater (GW) abstracter at an estimated 251 km³ per year, of which 89% is used for irrigation (UN, 2022). With simultaneous increasing urbanization and economic growth, the water demand of the domestic and industrial sectors is also expected to increase rapidly, such that sustainability of water sources is important for achieving future cross-sectoral water security. India leads globally in installed capacity for managing aquifer recharge. While MAR is considered a crucial strategy to address GW over-exploitation in India, a comparatively low portion of drinking water is intentionally produced by the natural water treatment technique of riverbank filtration (RBF, a technique of MAR), especially from the Indus–Ganges–Brahmaputra (IGB) basin alluvial aquifer that taken together, is one of the largest GW reservoirs on Earth. RBF serves as an ecosystem service for human health because it effectively removes contaminants, especially pathogens, other particles and organic micropollutants (OMP). Although in Europe new RBF site developments are rare due to decreasing water demand, there is a renaissance of RBF technology in China, Middle East and North Africa, Vietnam, and other countries. On the other hand, in the north Indian state of Punjab, where agriculture is the mainstay of the economy, the establishment of RBF systems has been recommended as a safe long-term solution for rural water supply. With the aim to further investigate RBF as a conjunctive SW–GW management strategy for drinking water production in the IGB Basin, this study evaluated a few sites for RBF in the states of Uttar Pradesh, Uttarakhand, Punjab and Assam.

Geohydraulic and water quality investigations were conducted on a production well for RBF in Agra waterworks (Jeoni Mandi) by the extremely polluted Yamuna River, at rural water supply schemes (RWS) along polluted stretches of the Sutlej and Ghagger rivers in Punjab and for a few RWS along tributaries of the Brahmaputra River in Assam. Additionally, occasional water quality monitoring was conducted for the existing and well-documented RBF site of Haridwar (Uttarakhand) by the Ganga River to re-evaluate its purification capacity. Water samples were analyzed for ions, heavy metals, dissolved organic carbon (DOC), OMP and bacteriological indicators between October 2021 and March 2024. Information on system-design and capacity was also collected from operators of the water supply schemes.

The main advantage of RBF in Agra is the high attenuation of OMP and that no bacteriological indicators were found in the production well despite high impact of partially to untreated wastewater on the Yamuna River (> 2.4×10^{8} MPN/100 mL) and even with a moderate portion of bank filtrate (>50%) in the abstracted water from the well. High mean attenuation of 70% was observed for DOC and also for sulfamethoxazole (~100%). Other OMP like naproxen, triclosan, diclofenac, atrazine, atenolol and diuron also showed good removal during RBF. The production well abstracts around 70 to 84 m^3/day and supplements the capacity of the conventional waterworks. Tankers are filled directly at the well with the abstracted water. The water is subsequently distributed by the tankers to areas in the city that are not supplied through pipelines from the waterworks. Based on feedback from the waterworks, the consumers appear to be very satisfied with the water quality (based on the consumer's organoleptic assessment of taste, colour and odor) and there is a high acceptance for the well water even if it is supplied by tankers.

In Punjab, 11 OMP were analyzed with concentrations of over 100 ng/l in river water, for example up to 459 ng/l ibuprofen or a maximum of 1,934 ng/l for caffeine. Only five OMP were found in the well water and in lower concentrations of <100 ng/L (ibuprofen, bisphenol A, caffeine, atrazine and carbamazepine). Atrazine and carbamazepine were found in river and well water in even lower concentrations (<50 ng/L) and showed little to no removal as compared to a very good removal for triclosan, chlorpyrifos, naproxen and diuron. Due to the poor elimination of atrazine and carbamazepine during subsurface passage, these compounds indicate a river-aquifer connection and potentially a certain portion of bank filtrate. Fluoride, arsenic and other trace metals (Cd, Co, Cu, Ni, Pb) in well water were below the limits of the Indian Drinking Water Standard. In Assam, OMP were detected at much lower concentrations (<100 ng/L) in river and well water. Fe, Mn and trace metals As, Cd, Cr, Cu, Pb and Zn were within the acceptable limits of the Indian Drinking Water Standard in the production wells in Agra and Guwahati. The hydraulic connection between the river and aquifer is the most essential criteria for RBF and this is necessary to establish for potential new sites in the IGB basin in order to plausibly determine the portions of bank filtrate and GW in the abstracted well water and consequent removal rates of contaminants. This is also beneficial, if RBF is proposed as a strategy to address overexploitation of GW resources, which is an additional motivation of using RBF in China and Vietnam. Unlike in Haridwar, where the alluvial aquifer is in direct connection with the Ganga River as indicated from borehole profiles, such that the RBF wells abstract a high portion of bank filtrate, at some other sites such as in Agra, the river-aquifer connection is challenging due complex subsurface lithology. At such sites, geohydraulic investigations should be supplemented with stable isotope and OMP investigations, such as for carbamazepine that is considered to be chemically and microbially relatively stable. Overall, there is a high potential to include RBF as water management measure in river basin plans in the IGB basin.

Keywords: *Drinking water, conjunctive water management, organic micropollutants, pathogens, river basin plans*

IDENTIFICATION OF FEASIBLE SITES FOR THE CONSTRUCTION OF SUBSURFACE DYKES (SSD) IN THE DROUGHT PRONE AREAS OF PALAKKAD DISTRICT, KERALA: APPLICATION OF GEOPHYSICAL TECHNIQUES

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Subsurface Dykes (SSD) are water conservation structures, is built across a stream or valley to establish an underground reservoir and to recharge groundwater. The best sites for construction of SSD's are those where the soil consists of sand and gravel with rock and an impermeable layer at a few meters depth. In many regions, frequent droughts create critical water shortages. Subsurface dykes (SSDs) can be a game-changer, storing rainwater underground to combat these challenges. A subsurface dyke is a subsurface barrier or hidden check dam that spans a stream or river. It slows down the system's natural subsurface/groundwater flow and reserves water below the surface to satisfy demand when it's needed. A groundwater dam's primary function is to stop the base flow, which also serves to keep the sub-basin's groundwater level stable.

The study identified suitable locations for constructing SSD's in drought-prone areas of Palakkad district, Kerala applying geophysical techniques (ERT & VES) and AHP Analysis. Palakkad is the land of Palmyrahs and Paddy fields. There is considerable change in the land use and cropping pattern in the district for the last five years. The district receives maximum rainfall during the south west monsoon followed by the north east monsoon. The other months receive considerably less rainfall. The annual rainfall varies from 1883 to 3267 mm based on long term normal. The district receives on average 2362 mm of rainfall annually. Major rainfall is received during June to September in the southwest monsoon (71%). The northeast monsoon contributes about 18%. The western part of the district around Pattambi receives the maximum rainfall whereas in the rain shadow area of Chittur in the eastern part receives the minimum rainfall. Due to low income from paddy and coconut, farmers are changing the cropping pattern to cash crops like sugarcane, vegetables and flower cultivation. Over dependence on groundwater for domestic, irrigation and industrial purposes in the district has led to the lowering of water table and water scarcity especially along the eastern parts. In most of the areas especially in the eastern part of the district decline of water levels necessitates deepening of existing dug wells and putting deep bore wells thereby increasing cost of pumping and quality deterioration. To stop further groundwater depletion and contamination and to ensure the long-term sustainability of the state's groundwater resources, scientific management of these resources is essential. The factors viz., geological formations, land elevation, and ground water flow patterns was analyzed to pinpoint the most effective spots. This information will be crucial for water management organizations and local communities to strategically implement SSD's and improve access to groundwater during droughts. The results of the study show the suitability of the sites for the construction of subsurface dyke in drought prone regions of Palakkad district based on the geology, geomorphology, lineaments and depth to the bedrock Chittur, Pattambi and Thrithala blocks.

To identify the places of SSD in this study, the AHP approach in ArcGIS was used. To confirm the location identified as feasible for SSD, geophysical techniques were used - vertical electrical sounding (VES) was conducted using the Aquameter CRM AUTO-C and electrical resistivity tomography (ERT) using ABEM Terrameter LSv2 multi-electrode system. ERT was carried out using two multi-core cables each having 21 electrodes. Spacing between two electrodes is 2.5 m. Spread length for this ERT unit was 100 m. In the present study 2D electrical resistivity tomography carried out applying GRP, Wenner and Scclumberger methods (ABEM Terrameter LSv2) to determine the subsurface lithological profile in the valleys for the feasibility for construction of subsurface dyke.AHP Analysis was employed in the three severely drought prone administrative blocks in the Palakkad district - Chittur, Pattambi, Thrithala Blocks which are coming under critical and semi critical category as per CGWB groundwater resources assessment (2022). Analytical hierarchy process is a structured decision-making process that involves using expert knowledge to determine the rank and weights by constructing an eigenvalue pair wise comparison matrix. This method is best-suited for decision-making in a problem involving several parameters influencing the result. The methodology of the study involved collecting and preparing all the eight thematic layers using ArcGIS software. The geo-referenced maps were assigned weights computed by the analytical hierarchy process. Google spreadsheets were utilized to compute the average and weightage, while Microsoft Word was utilized to create the table and assign ranks.

In Pattambi block the ERT profiles (GRP and Wenner) in the surveyed location showed a saturated surface layer up to 6 meters from 2 meter below ground level. The massive bed rock was identified at 6 meters below ground level. A narrow subsurface valley was clearly indicated by the 2D Inverse models. In the Thrithala block, the surveyed location showed a saturated layer from 1-4 m bgl. The bed rock was found approximately at 6 meters bgl. Various lithological layers in the valley region were clearly identified from the 2D Inverse model. The location surveyed in the Chittur block showed an ideal condition for construction of SSD with depth to bed rock approximately 2-3 mbgl. The study concluded that SSD was suitable for construction in these locations having depth to massive rock was less than 6m bgl. It was possible to store and recharge large volume of groundwater in the upstream watershed areas affected by water scarcity in the summer months in these areas.

Keywords: *Subsurface Dykes (SSD), AHP tools and ERT profiling techniques, critical and semi-critical blocks, Palakkad District, Kerala*

AUGMENTATION OF GROUNDWATER RESOURCES THROUGH TECHNICAL SURVEYS AND COMMUNITY BASED GROUNDWATER MANAGEMENT INITIATIVES TO BRING THE AREA OVER EXPLOTED TO SEMI CRITICAL ZONE IN BULDHANA DISTRICT, MAHARASHTRA, INDIA

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Groundwater availability for drinking water is directly linked to the overall groundwater usage in agriculture. It also depends upon its management by the farmers, industries and urban users. Developmental processes both in rural and urban areas start and end with the availability of water of desired quantity and quality. The demand of freshwater reserves has increased largely during last three decades. Geometric growth of population has led to greater pressure on domestic, industrial water supplies and on producing sufficient food grain, which requires more and more water. Inefficient irrigation practices compound the problem of freshwater availability. The available quantity of fresh water is further reduced due to contamination of water resources caused by the discharge of untreated/partially treated wastewater and industrial effluents as well as excessive use of fertilizers and pesticides for irrigated agriculture. The state of Maharashtra covers 9.37% of India's total geographical area, but shares only 1.43% of the total surface water potential and 3.17% of the total groundwater potential. In Maharashtra, groundwater is the main source of water supply for drinking and domestic uses in rural area. Approximately, 80% of the state drinking water and about 51% of its irrigation needs are met through groundwater resources. Recurring droughts in the state of Maharashtra aggravated the already stressed water resources. Even in the assured rainfall zone, some areas have reached over-exploited stage of groundwater development. In the last few decades, the farmers to have private irrigation sources has led to mushrooming wells/bore wells/tube wells resulting in large declines in groundwater levels. Resulting 73 watersheds are become over exploited, 3 are become critical and 119 water sheds are become semi-critical in the Maharashtra state. Therefore, an immediate attention is taken as far as management of water resources is concerned as Aquifer delineation.

Aquifers are basic units for understanding groundwater and attempting the sustainable management of groundwater resources. Understanding aquifers also includes precisely locating their natural recharge and discharge areas through surface infiltration into shallow, unconfined aquifers. The aquifer based participatory groundwater management project has been implemented in over-exploited mini-watershed of PT-11 (2,3,4,5,6/8) in Jalgaon Jamod tehsil, Buldhana district. Hence, the first step was to construct a disaggregated picture by carefully mapping the aquifers across different hydrogeological settings and understanding their storage and transmission characteristics. Aquifer boundaries are clearly demarcated through groundwater technical surveys of hydro-geological, geo-physical and geo-chemical. The groundwater management with community participation has been attempted through a systematic implementation of supply and demand side interventions formulated with the help of community-based Groundwater Management Action Plan (GWMAP). The supply side interventions envisaged implementation of groundwater recharge structures. Whereas the demand side interventions encompassed various community awareness programs on groundwater conservation, adopting water saving techniques and self-regulatory measures. Substantial part of demand management component has been dovetailed with Agriculture Department and various other government line departments which collectively brought the required demand side management in the project areas.

Water harvesting structures play a major role in groundwater recharge of shallow aquifers. It facilitates augmentation and helps in retaining the water column in wells for longer period of time. The supply side interventions of the GWMAP implemented in the project area comprised of total 537 recharge structures having substantial number of direct groundwater recharge structures such as 273 recharge shafts and trench and 264 gabion bandhara. Operation and maintenance of recharge structures must be done by Groundwater management action plan and village community, preferably through beneficiary groups. A significant positive impact in gross groundwater recharge is seen as it has been increased from 1562.20 Ham in 2014-15 to 2371.70 Ham during 2019-20. An increased net groundwater availability by 809.68 Ham is found to be beneficial in restoring recharge-discharge balance. During year 2014-15, the net groundwater recharge was 1562 Ham and groundwater draft computed was 1614 Ham. The stage of groundwater development which had gone high upto 103% before the project initiation has now been reduced to 76.97 % transforming the aquifer from over-exploited state to safe zone. The aquifer which was groundwater deficient has now retained groundwater balance of 443.91 Ham ascribed to successful implementation of the GWMAP. The stage of groundwater development decreased by 26.03% after the project implementation. Pre and post-monsoon groundwater levels are raised by 2.70 m and 3.28 m, respectively. The saturation has helped in sustaining the groundwater availability round the year. It has helped in bringing the area from over-exploited to semi-critical zone and release the restrictions imposed on groundwater development to a certain extent in the area, hence PT-11 (2,3,4,5,6/8) mini-watershed shows very good performance category. It is evident that the supply side interventions have elevated groundwater recharge and the demand side interventions with the help of community participation like adoption of micro-irrigation practices have gradually decreased groundwater withdrawal.

A positive attitude of farmers developed regarding conservation of groundwater resources for agriculture purpose. Village community is aware and involved in optimized use of groundwater resources. Farmers adopting water saving techniques for irrigation purposes and Micro-irrigated area increased from 0.00 ha to 233.71 ha. The cumulative effect of demand management and raised awareness resulted in increase in cultivable area. After completion of supply and demand side interventions in year 2019-2020, all Twenty-two villages show normalised Groundwater Drought and vegetation cover increase. The project has also shown moderate impact on groundwater quality as about 50% samples have shown excellent to good groundwater quality index, yet, analytes like Nitrogen, show increased concentration.

***Keywords**: Augmentation of groundwater, unconfined aquifer, over-exploited and semi-critical watersheds, groundwater technical surveys, recharge structures, micro-irrigation, groundwater drought*

ARTIFICAL RECHARGE TO GROUNDWATER LEVEL DECLINING AREA USING CANAL WATER OF BHANDARA DISTRICT, MAHARSHTRA, INDIA

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Artificial recharge is the process of adding water directly to the aquifer for replenishing the groundwater levels. Development of groundwater resources for irrigation and rural drinking water supply during last few decades have resulted in declining groundwater levels. Due to erratic and scanty rainfall, these aquifers are not replenished. In Mahabharata State eastern most part area of Pauni and Lakhandur taluka of Bhandara district is drained by Wainganga and Chulband rivers is known as Chauras belt (shape of area is square) lies between latitude 20° 40': 20° 55' and Longitude 79° 35': 79° 55', is famous for perennial paddy cultivation and facing problem of progressive water level decline. The area falls in the Survey of India Toposheets No-55 P 9, 10, 13 and 14, forms part of the Wainganga sub-basin and included in Groundwater surveys and development agency watershed WGC-6 and WG 11 and has an aerial extent of 285.33 sq km is under command of right bank canal of the project. Normal rainfall of taluka Pauni is 1274.4 mm and 30 years rainfall shows highest rainfall 2139.1 mm in year 1994 and lowest rainfall 661.7 mm in year 2004. The entire area of Chauras Belt is covered by 30 m thick alluvium, which consists of silt, medium to coarse grained sand, rounded to sub rounded pebbles and boulders which is main aquifer of the area. The alluvium is underline by older metamorphic rocks. The main crop of area is paddy. The water requirement of paddy is very high about 44.21cubic-meters/day (m^3/d). Over exploitation of the groundwater is roughly through 7149 irrigation dug wells and dug cum bore wells having average depth of 25m to 28m (well depth 18m and in well bore 10m) in the local alluvial belt has resulted in an alarming depletion in both post and pre monsoon water levels and in turn the aquifer is partially saturated even after monsoon season. Over-exploitation of groundwater in this belt has resulted in gradual depletion of water level in the area day by day by 11.75 m (7.5 M to 19.25 M) in last two decades. Wainganga River was the primary source of groundwater recharged to sand and gravel aquifers in the Chauras area. History reveals that after the construction of Gose.kh dam on Wainganga River, this buried channel is hydrologically disconnected from Wainganga River which has stopped groundwater recharge to aquifer of Chauras area which is one of the causes of water level depletion in the area.

To overcome this problem Groundwater surveys and development agency delineate aquifers and buried channel of Waingangariver which is hydrologically disconnected from Wainganga River in Construction wall of Gosi kh major irrigation project, and also calculated the acceptance capacity of aquifer was finding out by conducting slug test in study area. The test plays a vital role in designing a model of artificial recharge. The quantity of water that is accepted per unit time and per unit area of aquifer is calculated by slug test and recommended an innovative artificial recharge model of dug well recharge. To delineate the aquifer periodic motioning of groundwater level through 25 observation wells stations, 7 piezometers with digital water level recorder and 325 irrigation well inventories of groundwater extraction structures were carried out in grid pattern of 65 villages on 1:50,000 scale. For construction of artificial recharge structure demarcate the suitable zone for

artificial recharge to groundwater with area and depth in command area of Gosi Khurd left bank canal. As hungry sandy aquifer is available and surface water available through canal considering this field conditions an innovative model of dug well recharge has been recommended in which the surface water (Canal) is filtered through one filter trench and two filter well and then crystal clear water is recharged through recharge well of depth 16 m with filter media. Groundwater surveys and development agency completed the structure for artificial recharge to groundwater by using surplus surface water available in Gosi kh dam. Overall more than hundred projects of such techniques have been constructed to recharge hungry zone of the aquifer, as the water acceptance rate of the aquifer is very high i.e. 4225 Liters per hour. The major outcomes of the study are construction of artificial recharge structure left bank canal command of Gosi Kh, major irrigation project. Outcomes of this study can be replicated in other areas situated in similar hydrological and hydro-geological set up i.e., area of Tapi Purna alluvium of Maharashtra and other states of India.

***Keywords**: Artificial recharge, alluvium, aquifer, chauras, overexploitation, decline water level. watersheds, groundwater technical surveys, recharge structures, micro-irrigation, groundwater drought*

SUSTAINING GROUNDWATER RESOURCE THROUGH SOCIO-HYDROGEOLOGICAL APPROACH: A COMPREHENSIVE STUDY IN A CLUSTER OF OVEREXPLOITED VILLAGES IN AMRAVATI DISTRICT, MAHARASHTRA

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While Groundwater spurred the Green Revolution that made India a food secure nation, the widespread extraction of groundwater has led to its alarming decline. Being the most dependent source of water for most of India's people providing the bulk of water for farming and domestic use, availability of groundwater is at risk. As mammoth revenue is invested in implementing water conservation practices and most of the area uses traditional irrigation techniques that stress the availability of water. Thus, there is a necessity to study interaction of water and human systems to address these crises. The government of India is undertaking several steps to manage groundwater and it includes the flagship program named as 'Atal Bhujal Yojana' (Atal Jal). The major objective of the scheme is to improve the management of groundwater resources in selected water-stressed areas in identified states through community-led sustainable groundwater management practices. This program will foster community led groundwater management and behavioral change with a fundamental focus on groundwater management. Present study focusses on a cluster of five over exploited villages from Warud taluka (Block) of Amravati district of Maharashtra state. In this area orange cultivation is a prime perennial horticulture crop which requires irrigation cycles throughout the year. Warud and Morshi blocks of the Amravati district are known for the orange cultivation since last so many decades. In the absence of surface water irrigation projects in the area, the crop is mainly groundwater dependent and hence led to the groundwater over-extraction. Well density has already crossed the safe limit, groundwater levels show long term predominant declining trend, shallow or un-confined aquifer is almost dried up, because of which dug wells are replaced by borewells, and depth of bore wells and their failure percentage is increasing day by day. Due to over extraction and aforesaid problems, Central Groundwater Authority had banned the drilling of new borewells in these two blocks during 2005.

In order to address such groundwater issues over a pan India level through community partnership the Atal Bhujal Yojana is launched in 2020. The area under discussion is a part of the scheme area in Amravati district. In accordance with the scheme objective socio-hydro geological approach is adopted, which includes village level awareness of stakeholders especially farmers through meetings and IEC tools, earmarking of groundwater monitoring stations(observation wells) and measurement of groundwater levels and rainfall by the community, field survey with them for geo-tagging the existing water conservation structures and identifying the sites for new ones, surface geological survey and well inventory in presence of them, data collection of existing cropping pattern and irrigation practices as adopted by farmers, water quality testing. Based on all the data and surveyed information water budgeting and water security plans have been prepared and updated through community consultation and discussions. This led to build the confidence among the

community to manage the groundwater resource at the village level. As the confidence built up among the community, volunteers came forward and took the charge of groundwater management, implementation of measures suggested in water security plan as well as motivated the other people for crop water management practices. It will help in building a comprehensive database that incorporates ground water data availability and quality, as well as its demand on the resource base.

This improved the quality of groundwater monitoring network and the assessment and utilization of monitoring data. With the continued collective efforts of volunteers, community and Government machinery, a visible impact can be seen in the field in the form of crop water management practices, increased water balance and arrest in rate of decline in groundwater level. Supply and demand side management is achieved through convergence of ongoing schemes and with the help of public participation. Forty-five percent farmers have been shifted from high water to low water consuming crops. Area under micro irrigation (drip and sprinkler) has been increased by twenty-five percent. Also, area under Broad Bed Furrow (BBF), mulching (plastic and organic), shed-net, poly-house have been increased during last four years through community participation. More importantly behavioral change and increased capacity of the community to handle the resource management is leading towards the sustainability of resource. Volunteers and village people are monitoring the charts of groundwater level, daily rainfall pattern and supervising the execution of water conservation and artificial groundwater recharge measures, being undertaken in the area through incentive and convergence funds. The present study highlights the success of community-led groundwater management that to in the over-exploited area, whereby an aspiration can be taken for sustainable groundwater management. As groundwater resource is at the discretion of the community, a strong community led groundwater management and public governance can only be the solution for sustainable groundwater management. This requires a fundamental handholding between Government machinery, NGOs and the Community.

Keywords: *Sustainable groundwater management, socio-hydrogeological survey, water conservation measures, artificial groundwater recharge, NGOs, IEC, Water security plans*

QUANTIFYING RAINWATER HARVESTING POTENTIAL ACROSS VARIOUS TOPOGRAPHIES: A TEN-SITE STUDY FOR FIVE STATES IN INDIA

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In regions with fluctuating water availability, comprehending rainwater harvesting potential across diverse soil characteristics is critical for sustainable water resource management. This study systematically evaluates the rainwater harvesting (RWH) potential across ten distinct sites in India, spanning the states of Uttar Pradesh, Rajasthan, Maharashtra, Madhya Pradesh, and Telangana. The study aims to quantify rainwater harvesting (RWH) potential, with a focus on how local environmental and anthropogenic factors, such as soil characteristics, rainfall patterns, and land use, influence the effectiveness of rainwater harvesting techniques. Utilizing a comprehensive 30-year dataset of average rainfall, detailed soil analyses, and land use classifications, this study estimates runoff volumes. The rationale behind this approach lies in the significant variability in rainfall patterns and soil characteristics across India. By assessing runoff volumes for both annual and seasonal periods, especially focusing on the monsoon season (June to September), the study highlights how regional differences impact the efficiency of RWH systems.

The gridded rainfall data for the area was obtained from the India Meteorological Department (IMD), Pune. Long series of gridded (0.25^o x 0.25^o) daily rainfall records of 122 years from 1901 to 2022 from the IMD are used in the analyses. In order to ascertain the certainty of rainfall that may occur, the probability analysis of the rainfall data for the period from 1901 to 2022 is also carried out for different probability levels. Lower probability indicates less assurance to the occurrence of rainfall, while higher probability indicates that rainfall has more chance to occur. For doing the analysis, average daily rainfall data has been converted to the average monthly data. The monthly rainfall data has thereafter been analyzed for different probability levels. The rainfall distribution at various probabilities with desired assurance can be used for planning water usages and manage the water resources during low rainfall years. Normal rainfall for the period 1993-2022 (30 years) is used to estimate RWH potential. The annual average normal rainfall for the locations varies as: 0.809 m for Edullapur, Thupakulapalli Medak; 1.139 m for Atkuru-2, Krishna; 0.704 m for Warud, Aurangabad; 0.744 m for Nayakpura, and Nirawali Gwalior; 0.681 m for Sodawash, and Karoda, Alwar; 0.775 m for Teharki, Atmadnagar, and Alipur, Meerut; and 0.930 m for Dudhli Bukhara Aht, Saharanpur. Further, it was found that the percent soil moisture content of the various locations varied from 3.12 % (Medak) to 20.67 % (Dudhli Bukhara Aht, Saharanpur). On the other hand, the bulk density of the various soils ranged between 1.17 g/cm^3 (sodawash, Rajasthan) to 1.72 g/cm^3 (Dudhli, Saharanpur). The soil texture at the various locations varies from silt loam to highly graveled loam.

Key findings from this study revealed estimated annual runoff potential for different station varies from 2,39,578.05 m^3 at Nayakpura, Gwalior to 6,26,446.99 m^3 at Atkuru, Krishna. Site wise the runoff volume was found as: Edullapur, Medak 511666.80 m^3; Thupakulapalli, Medak 461917.80 m^3; Atkuru-2, Krishna 626446.99 m^3; Warud, Aurangabad 395750.34 m^3;

Nayakpura, Gwalior 239578.05 m^3; Nirawali, Gwalior 278233.78 m^3; Sodawash, Alwar 368756.25 m^3; Karoda, Alwar 401544.86 m^3; Teharki, Meerut 310883.63 m^3; Atmadnagar Alipur, Meerut 294369.61 m^3; Dudhli Bukhara Aht, Saharanpur 502432.83 m^3. Similarly, estimated runoff potential for monsoon months (JJAS) for different station varies from 2,09,374.17 m^3 at Nayakpura, Gwalior to 4,31,773.46 m^3 at Atkuru.

The implications of these findings are to emphasize the necessity of site-specific RWH strategies tailored to local soil characteristics, topography, and rainfall distribution. For example, regions with high runoff potential, such as Edullapur, can benefit from enhanced RWH systems, such as larger catchment areas and more efficient water storage infrastructure, to maximize water capture. Moreover, integrating RWH systems into regional water management policies offers significant economic and environmental benefits. In water-stressed regions, RWH systems can alleviate pressure on conventional water sources like wells and rivers, ensuring a more sustainable supply of water for agricultural and domestic use. From an economic standpoint, the initial investment in RWH infrastructure can provide high returns in the form of reduced water scarcity and improved agricultural productivity, especially in arid regions like in Alwar Rajasthan where water scarcity is a major challenge. This research provides a scientific basis for optimizing RWH practices in semi-arid and water-stressed regions. By correlating soil properties, land use patterns, and rainfall data, the study offers actionable insights for policymakers, NGOs, and local communities to enhance water conservation efforts. Furthermore, integrating climate change projections into RWH modeling could help predict future runoff patterns and assist in designing more adaptive systems. In conclusion, the variability in RWH potential across the ten studied sites underscores the importance of localized interventions in water resource management. By aligning RWH techniques with the unique hydrological and geological contexts of each region, stakeholders can achieve sustainable water conservation and support the livelihoods of community's dependent on these critical resources. As RWH continues to gain recognition as a key strategy for sustainable water management, this study sets the stage for more comprehensive approaches that integrate regional differences in rainfall, soil characteristics, and land use into water conservation planning.

Keywords: *Rainwater harvesting, runoff potential, infiltration capacity, Medak, Alwar, Edullapur, Sodawash*

DELINEATING GROUNDWATER LEVEL IMPACT FROM RAINWATER HARVESTING RECHARGE WELLS ACROSS DIVERSE INDIAN GEOGRAPHIES: IMPLICATIONS FOR SUSTAINABLE MANAGEMENT

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Groundwater depletion is an escalating issue in India, driven by increasing water demands, unsustainable extraction practices, and climate variability. The problem is particularly acute in semi-arid and over-exploited regions, where groundwater serves as the primary source of water for agricultural, domestic, and industrial use. This study evaluates the performance of ten rainwater harvesting (RWH) recharge wells distributed across five Indian states—Telangana, Maharashtra, Madhya Pradesh, Rajasthan and Uttar Pradesh—highlighting their role in augmenting groundwater levels and promoting sustainable water management practices. The analysis focuses on site-specific soil properties, groundwater level analysis, and rainfall patterns, which collectively influence the efficiency of recharge wells in replenishing aquifers. The study utilized a robust methodology, incorporating both field and laboratory analyses to capture the diverse hydrological and geological characteristics of the study locations. Soil texture and bulk density analysis were conducted to classify the soils and evaluate their infiltration capacity. Infiltration tests using a double-ring infiltrometer measured the rate at which water percolates through the soil, a critical parameter for estimating recharge efficiency. Rainfall pattern analysis was performed for the monsoon season (June to September, JJAS), as well as on an annual scale, to account for seasonal and inter-annual variability in water availability. Groundwater level analysis spanned three years (2021–2023), with pre- and post-monsoon readings collected to assess the impact of recharge wells on water levels.

Results revealed significant variability in soil infiltration rates across the ten sites, ranging from 1.553 cm/hr at Sodawash village, Alwar, Rajasthan, to 6.809 cm/hr at Nirawali village, Gwalior, Madhya Pradesh. These variations are attributable to differences in soil texture, with sandy soils exhibiting higher infiltration rates compared to clay-rich soils. For example, the sandy loam soil in Nirawali facilitated faster water absorption, enhancing the recharge efficiency of wells in the area. Conversely, the clay-rich soil at Sodawash restricted infiltration, limiting the effectiveness of recharge structures. This underscores the importance of tailoring RWH interventions to local soil characteristics to maximize their impact. Seasonal groundwater level analysis highlighted substantial recharge effects at several locations. For example, groundwater levels in Edullapur village, Medak, Telangana, demonstrated a marked improvement, rising from 17.5–15.1 m below ground level (bgl) during the pre-monsoon season of 2022 to 10.3–7.87 m bgl by the pre-monsoon season of 2023. Similarly, other sites, such as Nirawali, Gwalior, and Jalgaon, Maharashtra, also showed significant gains in groundwater levels following the implementation of recharge wells. These findings illustrate the capacity of recharge wells to mitigate seasonal declines in groundwater levels, particularly in regions with pronounced monsoonal rainfall. The rainfall pattern analysis provided critical insights into the role of monsoonal variability in recharge well performance. The study sites experienced diverse rainfall distributions, ranging from moderate rainfall in Rajasthan to higher precipitation levels in Telangana. Sites with

consistent monsoon rainfall, such as Edullapur and Nirawali, exhibited higher recharge rates, whereas regions with erratic or lower rainfall patterns, such as Sodawash, demonstrated less pronounced effects. This emphasizes the need for integrated water management strategies that consider both recharge infrastructure and supplemental measures, such as soil conservation techniques, to enhance water retention in low-rainfall areas. A detailed cost-benefit analysis of the recharge wells revealed their high efficiency and cost-effectiveness as interventions for groundwater management. Recharge wells, with their relatively low construction and maintenance costs, yielded significant returns on investment in terms of improved water availability, reduced dependency on external water sources, and enhanced agricultural productivity. For instance, in Medak, the availability of groundwater for irrigation increased significantly, reducing the vulnerability of local farmers to water shortages during the dry season. These economic benefits underscore the potential of recharge wells to serve as a scalable solution for water-scarce regions across India. Despite their effectiveness, the study also highlights challenges associated with implementing recharge wells. Site selection, informed by comprehensive hydrological assessments, is critical to ensuring optimal performance. Additionally, the long-term sustainability of recharge wells requires regular maintenance, such as clearing sediment accumulation, which can obstruct infiltration. Policy frameworks must support these efforts by promoting community participation, capacity-building programs, and financial incentives for adopting RWH technologies. The findings from this study have significant implications for groundwater resource management in India. By demonstrating the effectiveness of recharge wells in diverse topographies, the research provides a blueprint for scaling up RWH initiatives to address groundwater depletion at a national level. Integrating recharge wells into broader water management frameworks could play a transformative role in achieving sustainable groundwater resources. Furthermore, this study underscores the importance of continued research and monitoring to refine RWH strategies. Future studies could focus on incorporating advanced hydrological modeling to predict the long-term impacts of recharge wells under different climatic and land-use scenarios. In conclusion, the variability in soil properties, rainfall patterns, and groundwater dynamics across the ten study sites highlights the need for localized RWH interventions tailored to regional conditions. Recharge wells have proven to be highly effective, cost-efficient solutions for mitigating groundwater depletion and supporting sustainable water use in India. By aligning recharge well implementation with comprehensive water resource management plans, stakeholders can address the growing challenges of water scarcity and ensure the long-term availability of this critical resource for future generations.

Keywords: *Rainwater harvesting, soil infiltration rates, groundwater level, recharge wells, recharge efficiency*

GROUNDWATER RECHARGE ZONING AND ARTIFICIAL RECHARGE SITE IDENTIFICATION IN CHOHAL AND DAMSAL COMMAND AREAS, HOSHIARPUR, PUNJAB USING GEOSPATIAL TECHNIQUES

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This study offers a comprehensive geospatial analysis of groundwater recharge potential within the command areas of the Chohal and Damsal reservoirs, situated in the Shivalik foothills of North-West India, specifically in Hoshiarpur district, Punjab. As the demand for groundwater continues to increase, especially in areas with limited water availability, such studies are crucial for informed resource management. This study focuses on identifying potential zones for artificial recharge within these reservoir command areas, which consist of predominantly 3rd- and 4th-order streams and span diverse landscapes. By identifying the areas suitable for groundwater recharge, this research aims to support sustainable water management practices within the Shivalik foothills. The command areas of the Chohal and Damsal reservoirs are characterized by an average elevation of approximately 296 m above sea level. These regions consist of a variety of land uses, including water bodies (the reservoirs), forests, agricultural land, and built-up areas. The presence of these different land uses plays a significant role in influencing the region's groundwater recharge potential, as factors such as land cover, soil type, and slope gradient impact water infiltration rates. The Shivalik foothills, particularly in Punjab, are known for their undulating terrain and periodic monsoon rains, which contribute to both surface runoff and potential recharge of groundwater aquifers. Therefore, managing these resources effectively is essential for local agriculture, biodiversity, and water security. The primary objectives of this study are twofold. First, it seeks to delineate the command areas of the Chohal and Damsal reservoirs. This process involves mapping the catchment and command areas associated with each reservoir, paying special attention to the contributing stream orders and drainage network. Defining these areas provides a clearer understanding of where water naturally accumulates and flows, allowing for a more targeted approach to groundwater recharge. The second objective is to identify suitable zones within these command areas that have high potential for artificial groundwater recharge. Given the increasing stress on groundwater resources, identifying recharge-prone areas enables effective intervention and ensures that recharge efforts are concentrated in the most beneficial areas. Methodologically, this study employs advanced geospatial techniques, which are particularly useful for natural resource management and hydrological studies. Using geographic information system (GIS) tools, the researchers were able to delineate the command areas associated with each reservoir and analyze various geospatial parameters that impact groundwater recharge potential. The GIS-based approach provides a spatially accurate, data-driven analysis, enabling a systematic assessment of recharge potential based on critical factors such as land use, stream order, slope, and topography. These factors were integrated within a geospatial framework to create recharge potential maps that depict suitable areas for groundwater recharge interventions. The study first delineates the command areas of the Chohal and Damsal reservoirs by defining the stream orders and establishing a 500-m stream threshold. Stream order is an essential parameter in hydrology, as it indicates the size and flow capacity of a stream segment, which affects surface runoff and water infiltration. By focusing on 3rd and 4th order streams, the study ensures that the assessment captures areas with significant water flow, which are more likely to contribute to recharge. Additionally, the command area delineation takes into account the natural boundaries of these catchment areas, where surface water from precipitation or runoff accumulates and flows into the reservoirs. Following the delineation of the command areas, the study applies geospatial analysis to assess recharge potential. Data on land use, soil characteristics, stream order, topography, and slope gradient were incorporated to identify the zones within these command areas that are most conducive to groundwater recharge. The use of GIS allows for the integration of multiple datasets and the generation of recharge potential maps, which highlight areas that could be prioritized for artificial recharge projects. For instance, areas with gentle slopes and permeable soils were deemed more favorable for recharge, as they allow water to infiltrate rather than flow away as surface runoff. The results of this analysis highlight a substantial recharge potential within the command areas of both reservoirs. Specifically, the Chohal Dam's command area was found to have 70.6% of its area classified as good or very good for groundwater recharge. This indicates that over two-thirds of the area has favorable conditions for recharge, making it a prime candidate for intervention strategies aimed at increasing groundwater levels. Similarly, the command area of the Damsal Dam exhibits a balanced recharge potential, with 69.6% of the area categorized as good or very good for recharge. These figures underscore the potential for implementing focused groundwater recharge projects within the identified zones, which could help mitigate the effects of water scarcity and groundwater depletion. In terms of practical applications, the study's findings provide valuable insights for water resource managers, policymakers, and local authorities responsible for sustainable water management in the region. The high recharge potential in both command areas suggests that targeted recharge interventions could yield significant benefits. For instance, constructing check dams, percolation tanks, or infiltration wells in these high-potential areas could enhance water percolation into the ground, thereby replenishing local aquifers. Furthermore, integrating these interventions with existing land use practices, such as agroforestry or conservation agriculture, could further support sustainable water resource management and improve agricultural productivity. The study concludes that implementing focused recharge strategies in the identified zones has the potential to significantly enhance groundwater sustainability in the Shivalik foothills. Given the dependency of the local population on groundwater for agricultural and domestic purposes, enhancing recharge is a crucial step towards ensuring long-term water availability. Additionally, the recharge potential maps developed through this study serve as a valuable tool for guiding future groundwater management initiatives, enabling stakeholders to allocate resources and plan interventions more effectively.

Keywords: *Groundwater Recharge, Geospatial Assessment, Dam reservoirs, Command Area, Sustainable Water Management*

ARTIFICIAL RECHARGE OF GROUNDWATER: PROCESSES AND ITS IMPACT IN INDIA

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Groundwater is a replenishable resource, and hence, its availability has often been taken for granted. The limitation of surface water resources and increased agriculture, industry, and domestic use have put the onus on groundwater. Artificial recharge of groundwater is one of the processes to replenish the underground aquifers through accumulating rainwater or using surface water directly or indirectly. However, these recharges are facing significant challenges such as changing rainfall patterns, heterogeneous and complex sub-surface flow, uncertain bio-geophysical processes, and the population is increasing so urbanization reduces the infiltration. For urbanization "progress cannot be stopped; it can only be channelled". Hence to increase the potential of recharge, analysis of methods of artificial recharge is required for particular climatic and geological regions in India. Each type of artificial recharge structure has both upside and downside consequences, which determine whether it will effectively meet the required water resources. In India, there is a varied climate, geology, and topography setup and hence there is a need for various data to understand the artificial recharge system. Artificial recharge is to replenish the groundwater resources through human intervention and rainwater harvesting (RWH) is to collect rainwater for direct use or recharge of groundwater. Managed aquifer recharge (MAR) system is one of the processes to increase the potential of groundwater charge. This paper reviews different methods, their utilization, and their influence on groundwater levels. For a long time, the artificial recharge system has been carried out but as over-exploitation has increased day by day and the resources are finite, there is a need for thorough study. One of the biggest challenges for future investigation is to include advanced MAR systems, machine learning, and GIS for artificial groundwater recharge. Future work should also investigate the role of climate change affecting the recharge system. The primary objective of this paper is to understand the extent and suitability of artificial recharge according to the geological and climatic regions and elaborating on different processes with advantages and disadvantages.

This research methodology involves various techniques of groundwater recharge systems in India. The groundwater level data and other information related to the recharge system are collected from CGWB and state groundwater departments. Due to the decrease in the natural recharge of groundwater, there is a need to increase the potential of artificial recharge by using conventional methods with numerical modeling and managed aquifer recharge systems. There are several methods used for the artificial recharge of groundwater such as percolation tanks, check dams, recharge wells, recharge pits, flooded recharge areas, infiltration galleries, artificial recharge using treated wastewater, and RWH. Several conditions must be considered for artificial recharge to understand its extent and impact like hydrogeological characteristics, water availability, and its quality, environmental and climatic conditions, soil and topography, and understanding of the extent of the aquifer.

The upside and downside of each method are described in the water budget sheet. Feasibility, impact, and challenges are tabulated. Infiltration is one of the best methods to replenish the groundwater that is affected by land use and land cover, soil type and texture, soil moisture content, vegetation, rainfall intensity, temperature, and topography. At some places it is not feasible to construct recharge through infiltration then other structures must be accounted for recharge. Recharge wells can be horizontal or vertical mainly very useful for deep confined aquifers that have restricted natural recharge. Surface spreading methods are one of the best methods to recharge groundwater. Surface water or rainwater has been stored in ponds and basins and percolated to recharge groundwater. This method is widely used and beneficial to conserve the soil, and surface and replenish the groundwater. The induced infiltration method is very useful for coastal regions where fresh water is vulnerable due to saline water intrusion. The geology of the area and lithology are some of the most important parameters to understand which type of structure should be assigned.

This study has conducted a thorough analysis to understand the artificial groundwater recharge system of India. For this purpose, groundwater level data and its fluctuation and groundwater recharge potential index data (wherever present) of different regions of India have been used. Analyzing different data sets from every region of India yields invaluable insight into both artificial recharge and the key factors that influence it. Notably, the outcome of this study indicates the significance of a few fundamental factors in determining the potential recharge system. Explicitly rainfall pattern, geomorphology and lithology, water level, and its fluctuations. Different regions have different specific important factors that influence greatly the recharge system. The contrary importance of other factors is not negligible but according to the different basins. But progressively there is delineation in proper replenishment of groundwater through artificial groundwater recharge indicating a subtle understanding of meteorological and hydrogeological factors at play. Hence this rigorous study not only indicates potential methods for recharge of particular regions but also reduces the chance of failure of structures.

Keywords: *Infiltration, artificial recharge, rainfall patterns, managed aquifer recharge, groundwater recharge potential index*

MAPPING OF VULNERABLE AREA OF DRINKING WATER IN MAHARASHTRA

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Groundwater availability and rainfall impacts vulnerability of drinking water sources to water shortage. This study highlights the key factors for vulnerability of drinking water sources and its security from precipitation, runoff and groundwater prospects of aquifer. The aim of mapping is to build up a common database for various allied departments involved in prediction, planning, estimation and implementation of Drinking Water Scarcity mitigation programme. The Database needs to be brought to minimum common requirements and must be uniform. The main aim is to find out the actual causes for repeated drinking water scarcity in a particular area thereby marking the most scarcity prone areas and least vulnerable areas. This study aims at guiding researchers and water managers in considering the climate-related threats. It highlights how climate change increases the seasonal risks of water supply insecurity in Maharashtra, thereby increasing socioeconomic risks. Groundwater availability for drinking water affects socio-economic status of human being. The precipitation, runoff and groundwater prospectus of aquifer plays an important role in drinking water availability at local scale. Drinking water sources are especially vulnerable and needs to be protected in order to maximise its benefits and minimise drinking water related risks. This study focuses on drinking water vulnerability and its mapping. Different departments of Maharashtra Government are engaged in mitigation of water scarcity by implementing water conservation activities and drinking water scarcity mitigation. Groundwater availability and the factors which impact it, are considered to map the vulnerability areas of drinking water. This helps to provide accurate results for planning and mitigation for drinking water scarcity, so that proper and adequate drinking water may be provided to the end users during the stressed period. Vulnerability of drinking water depends on precipitation, runoff and groundwater prospectus of aquifer. To study the precipitation, rate the Taluka level normal rainfall is considered and rainfall data for last 10 years have been collected and analysed. The available groundwater assessment data of CGWB with taluka and watershed boundaries and static water level data for observation wells have been considered. The slope map of state is classified into different class according to slope percentage to differentiate runoff. Drainage map of state is classified according to the order of drainage to assess the vulnerability of the area for drinking water availability as it directly impacts the runoff and recharge by precipitation. The groundwater prospect map has been used for studying the aquifer characteristics. The total dataset used include rainfall, static water level, groundwater prospect, slope, ordered drainage and groundwater assessment. The thematic map was generated by using the above factors and used for over lay to map the vulnerable areas of drinking water. The areas identified in the thematic map has been classified into four classes i.e., no vulnerable area, mild vulnerable area, moderate vulnerable area and sever vulnerable area. This study is helpful to users who are working on planning and implementation of drinking water scarcity mitigation program.

Keywords: *Vulnerability, groundwater prospects, groundwater assessment, precipitation*

IDENTIFICATION OF CAUSE FOR WATER LEVEL DEPLETION IN COAL MINE AREA OF NAGPUR DISTRICT, INDIA

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The Nagpur district is well known for its coal reserves. Large scale coal mining is carried out in various parts of the district. Coal mines are located in Saoner, Parseoni, Kamptee and Umred talukas. At present, there are 14 (38.90%) underground and 22 (61.1%) open cast mines. The present study is mainly concerned with groundwater depletion in coal mines area (i.e, Bhanegaon and Singhori of Saoner taluka), which falls in Survey of India Topo sheet number 55 O/3. The study area covers around 10249 ha, which includes mining area of 773.46 ha. Buffer zone of 5 km has been taken from centre of Bhanegaon and Singhori mines for the present study covering 21 villages. The exploratory wells are pumped at optimum sustainable yield of 2100 litres per hour (LPH). The wells are pumped continuously. Therefore, main objective of study is to assess the current quantity and quality of groundwater withdrawal from coal mining area in time and space on groundwater regime area of 10429 ha within a buffer of 5 km around the mines. Study also aimed to investigate the changes in the land use pattern and impacts on groundwater due to mining activities in the project area. In addition, the study aimed at recommending the method for artificial recharge to groundwater in affected area by using dewatered mine water during production of coal considering water quality standards and for domestic purpose in vicinity of mines.

Various historical baseline databases like demographic details, rainfall for last 52 years (1971- 2022) were collected from IMD. For static water levels, reconnaissance and detailed surveys in all 21 villages and existing open cast coal mine have been carried out. The well inventories of 123 irrigation wells were carried out to know the present condition of groundwater occurrence. Total 8 tube wells cum piezometers were drilled for knowing the subsurface geology and occurrence of groundwater in the study area. A few traverses for knowing the information regarding surface geology of the study area were taken and a geological map was produced. For assessing dewatering, data for mine was collected from the coal mining company and as well as from CGWB. For land use comparison between the land use pattern in 2008, before inception of mine (2016) and current land use (2022) for the study area was generated using GIS software. The soil type data was collected from various government organizations like WCL, CMPDI, GSI, CGWB, Pollution Control Board, DGM, MRSAC and Local Gram panchayat and in house data of GSDA. Generation of ground water scenario and its uses was done by ground water estimation. Present groundwater usage by all end users was collected and the comparison between the historical and present-day groundwater estimation of study area was performed. Dewatering in the mine for winning ore material is a very common phenomenon and it involves large quantity of pumping of ground water and its discharge into nearby streams. A comprehensive study has been carried out to understand the actual process and its implication over groundwater regime. The draft calculation is performed for 2015-16 and 2022-23 on the basis of water table fluctuation observed during the particular year. The results obtained indicate that in land use in the mining area has increased while agricultural area has decreased in the year 2022 as compared to the land use pattern of years 2008 and 2015 The water table fluctuation of year 2015-16

was 5.2 m and for 2022-23 it was 7 m, respectively. Normal Monsoon recharge for 2015-16 and 2022-23 was 1812.20 ham and 2525.44 ham, respectively. It could be observed that normal recharge to groundwater has increased by 713.24 ham i.e. the increase of 28.24% when compared to 2015-16. Net groundwater availability after removing base flow is found to be 1821.92 ham during 2015-16 and 2530.97 ham during 2022-23, which indicates that there is remarkable increase in groundwater recharge during the current year. The gross groundwater draft (Agricultural + Domestic + Mining) for 2015-16 is 1653.89 ham and for 2022-23 it is 2630.05 ham. The stage of ground water development for study area was 92.12% during 2015-16 and 191.18% during 2022-23. The study area was having groundwater balance of 168.03 ham in 2015-16 and -99.08 ham in 2022-23. Thus, according to GEC 2015 guide lines, the area could be categorized into overexploited category. But, as the study area is a part of five watersheds, therefore, on large scale, it is occurring as safe with respect to groundwater development. Based on above groundwater estimation, it can be concluded that the stage of groundwater extraction prior to inception of mine in 2015 was at 90.78 %, which has shown an exponential growth to 103.91% after 8 years of the start of the coal mining in the year 2023.

Keywords: *Groundwater draft, groundwater withdraw, fluctuation, land use, coal mining, geology, GIS, dewatering*

AN ARTIFICIAL RECHARGE IN THE DECCAN BASALTIC TERRAIN: A CASE STUDY OF THE EXPLOITED DEO MINI-WATERSHED, AMRAVATI DISTRICT, MAHARASHTRA, INDIA

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The utilization of a dug well for artificial recharge is a simple and economical approach. However, inconsistent precipitation and varied hydrogeological conditions result in an unequal distribution of water resources, particularly in hard rock regions. Therefore, an investigation of the Deo mini-watershed was conducted utilizing remote sensing and GIS tools to develop artificial recharge strategies. Field observations suggest that a significant proportion of surplus water is present in certain areas, particularly adjacent to the main channel of the Deo mini-watershed, which can be designated for artificial recharge structures. Artificial recharge of groundwater through dug wells is one of the most effective groundwater recharge techniques for controlling groundwater level depletion, resource augmentation, and well sustainability, in addition to groundwater problem mitigation. To recharge existing dug wells with rain, run-off from agricultural fields are diverted towards was in order to enhance the groundwater levels in the affected areas. The Artificial Recharge of groundwater, using Dug wells recharge techniques will be useful to control over-exploitation of groundwater resources, as well as to ensure sustainable water resource management and assured irrigation facilities in the affected areas. It helps to reduce surface runoff, increase water availability for irrigation, the industrial and residential sectors, improve drainage, revive springs, and improve groundwater. Artificial recharge groundwater through dug well flooding techniques is a great way of increasing the water table and raising groundwater availability. Among many other things, this method is generally used when a deep confined aquifer is present, but in present case, this method is found suitable to recharge the shallow dug wells, tapping unconfined aquifer. Dug wells of the area are deep or have a large average diameter. The recharge work was done in a systematic manner and was able to provide irrigation for an additional piece of land. The benefit of well recharging is that the farmers only have to invest a small amount of money once, but they can enjoy the profits for a long time. In this method, existing dug wells can be utilized as a recharge structure, when surplus surface water is available during monsoon season, which can be subsequently used during summer season. Thus, existing dug wells can be used for artificial recharge of ground water which can provide source water sustainably. In the Alluvial area, percolation tanks and recharge wells are most suitable structures. Also One direct artificial recharge technique is dug well flooding, which involves pumping water into dug wells to replenish desaturated unconfined aquifers. This method can greatly raise groundwater levels in the Deo mini-watershed and along its stream basins, making it very beneficial there. Water seeps through the ground and replenishes the underlying aquifer by flooding wells. This technique can significantly improve water availability in de-saturated zones by replenishing groundwater when used extensively or in succession. This approach is best in places where the conditions are suitable for these kinds of water management techniques.

Keywords: *Artificial recharge, watershed management, groundwater, deccan basalt*

IMPACT OF WATER CONSERVATION MEASURES THROUGH CHECK DAMS ON WATER RESOURCES IN SEMI-ARID REGIONS: A CASE STUDY FROM ANANTAPUR, ANDHRA PRADESH, INDIA

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Water is an engine that drives all developmental activities in a village. The presence of good quantity and quality water provides basis for good agriculture, health, livelihood, livestock, ecology and environment among others in a village. On the other hands water scarcity in any village leads pushes it to poverty in all these fields. Groundwater is main source of irrigation in India contributing up to 87% for agriculture and 85% for rural drinking water supplies. India has 35 million people without access to safe water from its total population of 1.42 billion. According to a new report by UNICEF and the World Health Organization, some 2.2 billion people around the world do not have safely managed drinking water services, 4.2 billion people do not have safely managed sanitation services, and 3 billion lack basic handwashing facilities. One of the main causes of all these problems is water scarcity and in particular absence of safe drinking water. Anantapur (called Sri Satya Sai district formed on 4 April 2022 from parts of erstwhile Anantapur district of Andhra Pradesh) falls under semi-arid climatic zone in South India with hot and dry conditions for most of the year. It also falls under rain shadow regions of western ghats getting low and limited rainfall. Anantapur gets pre-monsoon showers from March, mainly through north-easterly winds blowing in from Kerala whereas monsoon arrives here in September and lasts until early November. Located in South-Western corner of Andhra Pradesh in South India, Anantapur district receives the least rainfall in the state of Andhra Pradesh, and the rainfall is second lowest in India, after Jaisalmer in Rajasthan. The average annual rainfall in the district is 535 mm/year. The agriculture in most of the area is primarily rainfed due to limited surface and groundwater resources that can support irrigation. The untimely rains frequently lead to crop failure or very poor crop yield making farmers life very difficult. Under these circumstances, many people migrate to nearby cities in search of labour work. The groundwater depletion is an escalating issue in India, driven by rising water demands and unsustainable extraction practices further intensifying with increasing impact of the climate change. This study evaluates the impact of construction of check dams on local water resources in water scarce villages of Anantapur.

The project encompasses groundwater level monitoring, rainfall pattern analysis, changes in cropping pattern and water tanker supply in the village. The groundwater levels were monitored on monthly basis in mostly abandoned wells or agricultural wells using Digital Water Level Indicator device. While monitoring agricultural wells, a precaution was taken to inform the farmers in advance 24-48 hours to ensure that there is no pumping from the bore wells which were monitored as it could affect the levels and one may not get the true water levels due to effect of pumping. The methodologies included groundwater level comparisons during pre-monsoon and post-monsoon seasons during 2018 and 2019. The seasonal groundwater level monitoring highlighted a substantial impact of groundwater recharging on local water resources due to construction of three check dams across Chitravathi river (a tributary of Pennar river) in the villages of Kodur and Morasalapalle gram panchayats in

Chilamathur Mandal of Anantapur, Andhra Pradesh. One check dam of 65 m length and two check dams of 30 m each were constructed at strategic locations in the villages of Kodur-Subbaraopeta, Mudapally-Timadipally and Madhurepally-Kandurparthi and could hold water in the stream ranging from 300 - 800 metres upstream side. The water runoff during heavy rainy days that used to rapidly flow out untapped from these villages was arrested through these check dams, build using stone masonry structures with spillover for safe passage of excess water to downstream side. Two-three sluice gates were also provided at suitable heights to control the flow of water from upstream side of the check dams. The checks dams were able to hold a substantial quantity of water providing sufficient time for water percolation into the ground. It resulted in significant enriching of groundwater resources and considerably improving the groundwater levels. It also provided surface water storage in upstream side of the check dams for most month of the year. The stored rainwater is being used by villagers for bathing, cloth washing, cattle etc and acting as a source of continuous recharging of groundwater resources of the region. The continuous water level monitoring data of 24 months (between January 2018-December 2019) shows a significant rise in water levels from 87.25 m - 77.05 m below ground level (bgl) in the pre-monsoon seasons of 2018-19 to 90.25 m - 70.59 m bgl during post -monsoon seasons of 2018-19. Most of the farmers reported that the yield of their bore wells considerably improved along with rejuvenation of few dry/low yielding borewells also. Several water tankers operating in the village for drinking water and critical irrigation in agriculture fields running earlier are no more in demand. These findings underscore that construction of check dams across rivers and seasonal nallahs provide huge opportunity for construction of groundwater recharging structures such as check dams and can make a significant impact on local water resources by augmenting the water levels and increasing the availability of water for drinking, irrigation, livestock etc. The construction cost of such check dams is little higher but at the same time their return on investment is also very high recovering the investment cost with 3-5 years only due to its multidimensional positive impact on people's lives, agriculture, livestock, livelihoods, ecology and environment among many others. The project also highlighted the importance of collaborative efforts of Public-Private-People partnership in transforming the villages economy through well designed and properly implemented water conservation measures emphasizing on community engagement, training and empowerment for a long-lasting impact. Thus, it can be concluded that the construction of check dams along the rivers, local streams and other strategic locations in the villages under suitably favourable conditions can be a game changing intervention for augmenting local water resources and checking the declining groundwater levels for achieving sustainable groundwater management in India.

Keywords: *Semi-arid zone, check dam, groundwater recharging, water levels, groundwater management*

ASSESSING GROUNDWATER RECHARGE AND SUSTAINABLE EXTRACTION RATES FOR WATER RESOURCE MANAGEMENT

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Groundwater is a vital resource for Bengaluru International Airport Limited (BIAL) in its effort to meet current and future water demands. BIAL aims to become self-sustainable in water usage by augmenting rainfall as a source of groundwater recharge. Understanding the groundwater flow patterns, drainage, and spatial variations in groundwater levels is essential for optimizing water resources within the BIAL premises, particularly given its location near several large lakes. These lakes are influenced by surface water runoff and, to some extent, groundwater inflows, both of which play a role in their overall water balance. Thus, assessing how BIAL's water resources interact with the surrounding hydrological features is crucial for planning sustainable groundwater extraction. This study focuses on the assessment of potential for groundwater extraction without the use of managed aquifer recharge (MAR). The main objective of the study is to estimate the recharge and sustainable groundwater extraction rates under the natural conditions.

In order to estimate the recharge rate to groundwater in the BIAL land area, the data of temporal groundwater levels monitored by BIAL since 2016 for open wells of BIAL (W1-AS; W2-AS; W3-LS; W4-LS; W5-LS & W6-AS) were analysed. The groundwater levels were available for period from September 2016 (i.e. post monsoon period onwards) till September 2018. The analysis shows that the monthly standard deviation of the wells is about 1 to 1.5m. The water levels in these open wells are relatively shallow as the groundwater is present in the weathered zone. These open wells existed prior to the BIAL and were part of the agricultural land use in those times. However, the groundwater use from these wells for agriculture or other activities was stopped after the land was acquired by BIAL, and hence, the groundwater levels might have risen to the upper weathered zone in the BIAL land area. In order to simulate the groundwater levels, monthly rainfall data were gathered from KSNDMC for the Anneswara station near BIAL.

The study used a lumped 1D groundwater model AMBHAS developed by IISc team which is based on a simple model for water table fluctuations in response to precipitation. The groundwater levels were simulated using the AMBHAS-1D model and a comparison of the model simulations was done with the actual data. The mean annual recharge for these three years (2016 to 2018) was 57 mm and the mean annual rainfall recharge factor is estimated to be ~7.5% of the mean annual rainfall. Since the rainfall varied considerably in these three years, the annual recharge also exhibits large variation (coefficient of variation of annual recharge ~50%). Since the rainfall stations are not within the BIAL premises, in order to analyze the sensitivity of the nearby rainfall station, data from another station Kannamangala, which is also close to BIAL was considered. The rainfall at this station was marginally different for each year from the Anneswara station. The simulations once again showed a good comparison with the observed levels and the mean annual recharge was estimated as 58 mm, which resulted in an annual rainfall recharge factor of about 8% which is very close to that obtained from the data of Anneswara station. This suggests that about 1.6 MLD (land area of 1622 ha and safe utilizable rate as 60% of mean annual recharge) of groundwater can be safely extracted from the resource available in the shallow upper weathered zone within the BIAL land area based on the current recharge conditions. By promoting water harvesting and enhancing the groundwater recharge practices in the BIAL property, the safely utilizable groundwater resource can be further augmented.

A critical aspect of this study is that not all recharge is recoverable. While the recharge within BIAL's domain is estimated to be 58 mm annually, the amount available for reuse is limited. It is essential to account for groundwater discharge during MAR planning, as a portion of the recharged water will laterally flow out of the area, making it unavailable for future use. The future scope of this research, therefore, involves advancing the use of groundwater modeling to incorporate additional observed data and refine estimates of groundwater discharge. Understanding discharge rates is critical for calculating how much of the recharged water can be safely extracted. These insights will support the design of a more sustainable water extraction strategy that integrates managed aquifer recharge practices, allowing BIAL to optimize its groundwater resources while minimizing the risks such as waterlogging or excessive depletion.

Keywords: *Groundwater modelling, groundwater extraction, groundwater recharge, aquifer management, AMBHAS-1 D model, sustainability*

GROUNDWATER POTENTIAL ZONATION MAPPING USING TOPSIS, VIKOR, FUZZY AHP AND EDAS: A CASE STUDY OF THE SHARAVATI RIVER BASIN, KARNATAKA, INDIA

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Groundwater is a critical resource, especially for agricultural activities, which account for approximately 60% of its usage in India. However, excessive groundwater exploitation has led to significant depletion of its levels. The Sharavati River Basin, known for its diverse topography, flora, fauna, and favourable monsoonal climate supporting diverse agriculture, has recently faced rapid developmental pressures. This study aims to assess the groundwater potential zones and develop management strategies for the Sharavati River Basin in Karnataka, India. The study employs advanced modelling techniques, including TOPSIS, VIKOR, Fuzzy AHP, and EDAS, to map and evaluate the groundwater potential zones within the watershed, which spans approximately 2,800 km^2, with a major portion located in the Western Ghats. This region experiences substantial annual rainfall but uneven seasonal distribution, leading to groundwater scarcity problems due to increased anthropogenic activities, such as agriculture, deforestation, and urbanization. Groundwater potential mapping is crucial to understanding how various natural and human factors, including geology, drainage patterns, slope, land use, geomorphology, precipitation, and topographical wetness index, contribute to groundwater scarcity in this area. The study employs multiple models to increase the accuracy and reliability of groundwater potential mapping. The results can be further discussed and presented to policymakers and research organizations to inform and guide significant steps toward sustainable groundwater management and minimizing its overuse.

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a 30x30 meter resolution has been acquired from the United States Geological Survey (USGS) database. Land use and land cover data have been sourced from the Environmental Systems Research Institute (ESRI) website, while soil data have been obtained from the Food and Agriculture Organization (FAO) database. Precipitation data has been retrieved from the Indian Meteorological Department (IMD) portal, and groundwater data has been collected from both the Central Ground Water Board (CGWB) and the Water Resources Information System (WRIS) of India. Various thematic layers were prepared. The researchers employed Fuzzy AHP to assign weights to the natural and human factors that impact groundwater potential. This method utilizes expert opinions to address decision-making uncertainties by comparing the relevant factors. The groundwater potential zones were ranked using two innovative approaches; TOPSIS and VIKOR. The TOPSIS model ranks areas based on their proximity to the ideal solution, while the VIKOR method focuses on finding a balanced compromise. Employing both techniques together provides a more accurate representation of groundwater potential in different areas. The research also employed the EDAS method to identify groundwater potential zones by measuring each area's deviation from the average. This approach offers a balanced perspective and helps to avoid extreme or ideal solutions, leading to a more meaningful classification of groundwater potential zones. The findings will be validated through a comparative analysis with ground truth data obtained from adjacent wells and hydrological measurements of the water table. Additionally, the application of Receiver Operating Characteristic curves will provide a detailed evaluation of the precision of each of these models.

The comprehensive analysis of the Sharavati River Basin has yielded substantial insights into the region's groundwater potential. The findings indicate that areas with high groundwater potential are primarily characterized by gentle slopes, elevated drainage densities, lineament densities, suitable land cover types, and porous soil conditions, which collectively facilitate groundwater recharge and storage. In contrast, regions with low groundwater potential are predominantly situated in steep topographical areas with low permeability and less favourable land use practices, exacerbating water scarcity issues. The synergistic application of the four modelling techniques employed in this study has resulted in a nuanced understanding of groundwater potential dynamics within the Sharavati River Basin. The TOPSIS and VIKOR methods produced comparable rankings across most of the analysed areas, reinforcing the validity of the results. Additionally, the EDAS model provided a balanced and integrative perspective, highlighting the importance of multiple factors influencing groundwater availability. Furthermore, the Fuzzy AHP method significantly improved the weighting accuracy assigned to each factor, refining the overall assessment of groundwater potential. This multifaceted approach underscores the value of integrating various modelling techniques to comprehensively evaluate groundwater resources, ultimately paving the way for more effective management strategies.

This study conclusively demonstrates that integrating multiple analytical models and techniques, including TOPSIS, VIKOR, Fuzzy AHP, and EDAS, constitutes a robust methodology for mapping groundwater potential zones in regions of the Sharavati River Basin. The findings underscore the efficiency of employing a multi-method approach to yield precise and actionable insights into groundwater availability. The findings from this study offer valuable insights that can inform decision-making processes related to groundwater extraction, recharge, and conservation efforts, particularly within the ecologically sensitive Western Ghats region. By synthesizing data from diverse modelling frameworks, this study offers a comprehensive analysis that is instrumental in identifying areas suitable for sustainable groundwater management practices. The results are relevant to policymakers, urban planners, and other stakeholders. This study emphasizes the importance of continued research in this domain. Future investigations could build upon the methodologies employed in this study by systematically monitoring temporal changes in groundwater levels, thereby enabling a more dynamic understanding of groundwater availability. Incorporating considerations related to climate change, such as variations in precipitation patterns, temperature fluctuations, and extreme weather events, will be essential for developing predictive models that can reliably forecast future groundwater availability. This comprehensive approach will contribute to the existing knowledge base and provide valuable insights for effective groundwater management in the face of evolving environmental challenges.

Keywords: *Topis, Vikor, Edas, Fuzzy Ahp, Sharavati river, Modelling*

SPATIAL ANALYSIS OF GROUNDWATER POTENTIAL ZONES IN DHASAN BASIN OF BUNDELKHAND REGION, MADHYA PRADESH

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Groundwater is an indispensable natural resource that plays a critical role in meeting the water demands of urban and rural populations. Its reliability, cleanliness, and ease of extraction make it essential for agriculture, drinking, and industrial applications. Globally, groundwater supports 80% of rural and 50% of urban households for domestic purposes. Despite its significance, groundwater availability is threatened by issues such as over-extraction, limited recharge, and challenging hydrogeological conditions, especially in drought-prone regions. The Bundelkhand region, of Madhya Pradesh includes the Dhasan River Basin, exemplifies these challenges due to its hard rock terrain and erratic rainfall. To tackle these issues, modern techniques such as Remote Sensing (RS) and Geographic Information Systems (GIS) are essential for delineating groundwater potential zones and devising sustainable management strategies. The Dhasan Basin, a sub-basin of the Yamuna River in Madhya Pradesh, consists of approximately 890 km^2 area in central India, located between latitudes 23.50°N and 24.80°N and longitudes 78.36°E and 79.60°E. Geologically, the basin is complicated, with strata from the Bundelkhand Craton, Bijawar Group, Vindhyan Supergroup, and Deccan Trap. These formations, which include rocks such as granitoids, Banded Iron Formations (BIFs), sandstones, and basalts, have poor porosity and permeability, limiting groundwater recharging. As a result, water is mostly available through shallow dug wells and rainfall capturing, which is usually concentrated in fractured or jointed zones. Given these limitations, a systematic assessment of groundwater potential is critical for long-term resource management in the basin. To address the region's groundwater challenges, this study utilizes an RS & GIS based approach integrated with the Multi-Influence Factor (MIF) technique. The methodology incorporates various biophysical and environmental parameters to effectively delineate the groundwater potential zones. Eight key thematic layers drainage density, geology, lineament density, land use/land cover (LULC), elevation, rainfall, slope, and soil were developed using satellite imagery, topographic maps, and field data. Each parameter was weighted based on its significance in influencing groundwater recharge and storage; for instance, lineament density and geology, which significantly impact groundwater movement, were assigned higher weights, while factors like LULC and rainfall were given moderate weights. A weighted overlay technique in GIS synthesized the layers, resulting in a detailed groundwater potential zoning map.

The analysis classified the Dhasan Basin into three groundwater potential zones: Good, Moderate, and Poor. The Good Potential Zone, covering 7.39% of the total area, consists of regions with high lineament density, alluvial deposits, and favourable slopes, which promote effective infiltration and storage. The Moderate Potential Zone, constituting 76.50% of the study area, encompasses regions with fractured rocks, moderate rainfall, and adequate drainage density, making them moderately suitable for groundwater development. However, sustainable extraction and recharge measures are crucial to ensuring long-term water availability. The Poor Potential Zone, accounting for 16.10% of the basin, is characterized by hard rock formations, steep slopes, and low porosity, which limit groundwater recharge and extraction. For these areas, alternative water management strategies, such as rainwater harvesting or surface water storage, are recommended to mitigate water scarcity. The spatial distribution of groundwater potential zones reflects the influence of geological formations, surface features, and environmental factors on groundwater availability. The predominance of the moderate zone highlights the potential for targeted recharge interventions, such as constructing check dams, percolation tanks, and contour bunds. These measures can significantly enhance groundwater storage and mitigate water scarcity in the basin. Moreover, the study emphasizes the importance of integrating hydrogeological, environmental, and socio-economic considerations to develop a comprehensive water management framework for the region. The study underscores the utility of geospatial techniques in groundwater potential assessment. By leveraging RS and GIS technologies alongside the MIF approach, the research provides a robust, spatially explicit framework for identifying groundwater potential zones. This methodology is particularly beneficial for data-scarce regions like the Dhasan Basin, where traditional hydrogeological surveys may be limited by time and resources. Furthermore, the approach demonstrates the potential for replicability in similar regions facing groundwater challenges, offering a scalable solution for water resource management. The findings of this study have significant implications for water resource planning and management in the Dhasan Basin. Decision-makers can utilize the groundwater potential map to prioritize areas for recharge interventions, sustainable extraction practices, and agricultural planning. By identifying zones with higher groundwater availability, the study supports informed decision-making to ensure equitable and sustainable water distribution. Additionally, the methodology can guide policymakers in addressing water scarcity through strategic investments in groundwater infrastructure and conservation measures.

In conclusion, groundwater is a vital resource for the Dhasan Basin, which faces significant challenges due to its hard rock terrain and limited recharge. This study, employing RS-GIS and the MIF technique, successfully delineates groundwater potential zones, providing actionable insights for sustainable water resource management. The classification of the basin into Good, Moderate, and Poor zones highlights the need for targeted interventions to address groundwater scarcity. The research demonstrates the effectiveness of geospatial techniques in providing reliable, cost-effective solutions for groundwater management in arid and semi-arid regions. Future studies could incorporate additional factors, such as groundwater quality and socio-economic data, to enhance the comprehensiveness and applicability of groundwater potential assessments in similar contexts.

Keywords: *Groundwater, Yamuna River, Dhasan Basin, GIS, multi-influence factor, sustainable management, water resource planning*

GEOSPATIAL AND HYDROGEOLOGICAL PERSPECTIVE ON GROUNDWATER DEPLETION TRENDS AND RECHARGE STRATEGIES IN AN AGRICULTURE DOMINATED WATERSHED FOR FUTURE WATER SECURITY

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Groundwater is a vital source of freshwater, supplying approximately 30% of global needs and playing a critical role in agriculture, domestic use, and industrial processes. However, increasing population, rapid industrialization, climate variability, and prolonged droughts have significantly elevated groundwater demand, often surpassing natural replenishment rates. Overextraction is particularly prevalent in arid and semi-arid regions where surface water availability is limited. India, as the world's largest consumer of groundwater, withdraws more than the U.S. and China combined, supporting over 1.3 billion people. Despite large-scale surface water projects, groundwater remains the principal irrigation source, especially in regions characterized by erratic rainfall patterns and shifting cropping systems. Remote sensing studies indicate rapid depletion of groundwater resources across various regions in India. The spatial variability of groundwater availability is influenced by multiple factors, including land use, soil characteristics, geological formations, and consumption rates. Climate uncertainties further underscore the necessity for continuous groundwater monitoring to facilitate sustainable management. However, limited data constrains research on groundwater exploitation under climate change. Trend analysis techniques provide critical insights into groundwater behavior, aiding in irrigation management and forecasting future water levels. Several statistical methods have been widely utilized globally to evaluate groundwater fluctuations in India.

This study investigates Depth to Groundwater Level (DGWL) trends using data from 57 groundwater monitoring stations over a 24-year period (1996–2019) for pre-monsoon (May) and post-monsoon (November) seasons. Data were sourced from the India-Water Resources Information System (India-WRIS) portal, ensuring the inclusion of only complete time-series datasets. A robust pre-processing approach was employed to construct temporal series, enabling spatial variation analysis through station-wise averaging and spatial mapping. Trend analysis was performed using the Mann-Kendall (MK) test to detect statistical trends and Sen’s Slope estimator to quantify the magnitude of changes over time. To classify wells based on DGWL fluctuations, Hierarchical Cluster Analysis (HCA) was implemented using Python’s SciPy library. The agglomerative clustering technique grouped stations based on similarities in groundwater level variations, with results visualized as a dendrogram. Innovation Trend Analysis (ITA) was employed to categorize trends into monotonic, non-monotonic, or no-trend patterns by dividing the dataset into two halves and plotting their inter-relationship. The parametric Standard Groundwater Level Index (SGWLI) was applied for comparative trend evaluation. The non-parametric MK test identified groundwater trends, where positive and negative ZMK values indicated increasing and decreasing trends, respectively. Sen’s Slope estimator quantified the rate of change, and SDWLI was used to

assess seasonal groundwater level deviations across monitoring stations. Spatial groundwater variations were analyzed using the IDW interpolation method, generating DGWL maps for selected years (1996, 2000, 2005, 2009, 2015 & 2019) for pre- and post-monsoon seasons. Missing values were estimated based on weighted distances from surrounding measurements, providing a comprehensive temporal & spatial understanding of groundwater dynamics.

Rainfall infiltration was identified as a major determinant of groundwater availability, with higher rainfall contributing to groundwater recharge and lower rainfall exacerbating depletion. HCA classified the wells into three distinct clusters based on DGWL fluctuations: Cluster 1 (17 wells), Cluster 2 (35 wells), and Cluster 3 (5 wells), with most wells in Clusters 2 and 3 concentrated in the Rewa and Satna districts. The groundwater levels exhibited a significant decline, raising sustainability concerns. ITA revealed that 58% of wells experienced an increasing DGWL trend during the pre-monsoon season, while 70% showed a similar trend in the post-monsoon season. Conversely, 21% and 12% of wells exhibited decreasing trends in the pre- and post-monsoon seasons, respectively. The ITA results indicated a general trend of groundwater depletion between 1996 and 2019, with an average decline of 0.09 m/year in the pre-monsoon & 0.08 m/year in the post-monsoon season. The MK test and Sen’s Slope method identified 19 wells with a significant increase in DGWL and one well with a declining trend in the pre-monsoon season, whereas 15 wells exhibited an increasing trend and one well showed a decreasing trend in the post-monsoon season. Sen’s Slope values ranged from -0.27 m/year to 0.69 m/year (pre-monsoon) and -0.27 m/year to 0.39 m/year (post-monsoon) indicating substantial groundwater depletion in specific regions. DGWL maps from 1996 to 2019 demonstrated a decline in groundwater levels at rates of 6.1 cm/year (pre-monsoon) & 7.4 cm/year (post-monsoon). The worst-affected areas included the Satna, Rewa & Prayagraj districts, where excessive groundwater extraction for agriculture was identified as a primary driver of depletion. To counteract groundwater loss, this study proposed artificial recharge structures such as check dams, percolation tanks and Nala bunds. GIS-based site selection for these structures was conducted considering topography, soil characteristics and drainage patterns to maximize recharge efficiency. Effective groundwater management is essential in this predominantly agricultural basin, where 70% of land use is dedicated to farming. This study integrates multiple statistical & geospatial analyses to provide a holistic understanding of groundwater dynamics. The findings indicate substantial groundwater depletion, particularly in the central basin, attributed to high population density and extensive agricultural water use. Clusters 1 & 2 showed decreasing groundwater trends at rates of 18 cm/year and 4 cm/year, respectively, while Clusters 3 & 4 exhibited increasing trends of -8 cm/year and 31 cm/year. ITA results confirmed that 58% of wells experienced an increasing DGWL trend in the pre-monsoon season & 70% in the post-monsoon season, while 21% and 12% of wells exhibited declining trends, respectively. Urgent groundwater conservation measures are required to ensure sustainable water availability. Policy recommendations include adopting modern irrigation techniques, expanding rainwater harvesting initiatives, implementing groundwater extraction regulations, and promoting sustainable land-use practices. These measures are crucial for mitigating depletion and enhancing groundwater security in agriculture-dependent regions. The findings of this study provide valuable insights into long-term groundwater management strategies, informing policy decisions and guiding future research on groundwater sustainability.

Keywords: *Groundwater recharge, hydrogeology, water security, trend analysis*

ASSESSMENT OF RAINWATER HARVESTING SYSTEM TO COMBAT WATER SCARCITY AND RECHARGE OF AQUIFERS IN GUWAHATI CITY, ASSAM, INDIA

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Water is life. But access to safe drinking water, which is a basic human right, has been significantly threatened due to mismanagement of water resources, climate change, landuse landcover changes, increased urbanization, industrialization, population explosion to name a few. As per predictions, by 2025, the number of people suffering from water scarcity will reach three billion. In such circumstances, rainwater harvesting (RWH) emerges as an appropriate solution for India. The use of rainwater for harvesting dates back to several thousand years back when humans first learnt farming. Rainwater harvesting practice is perhaps the most urgent need of the hour especially in urban areas where water resources are fast depleting due to increased population explosion and unrestricted exploitation. Rainwater harvesting in response to climate extremes enhances the resilience of human society not just ecologically but also financially. It is one of the concepts that can be implemented to meet the water shortage problem as it is a part of sustainable architecture and it brings a lot of advantages, not just to the users but also to the environment and government machinery.

Guwahati City, the gateway to the north-eastern part of India suffers from looming water crises more recently. As per reports of the Central Groundwater Board (CGWB), groundwater extraction in the city has touched 75%, thus, making it fall under the semi critical stage. While, the water needs within certain pockets of the city are met by the supply of treated water from Brahmaputra River, yet a major part of the city still relies on groundwater. The present study is an attempt to assess the status of rainwater harvesting system across Guwahati City in Assam. Further, the paper discusses the potential rainwater harvesting techniques which can be easily implemented in the households of Guwahati city. This assessment will help local authorities and policy makers to execute Rainwater Harvesting schemes in water shortage areas and thereby facilitating recharge of groundwater. To access the status of rainwater harvesting structures in the city along with collections of available secondary data, a questionnaire survey was conducted. The questionnaire was prepared taking under consideration water demand at household level, the attitude of the people towards water conservation, habits related to water usage, awareness about the water scenario, community attitude and behavior, tariffs related to water. People were interrogated about water efficient buildings, water efficient products and water policies. Based on the survey it was found that the existing water supply across certain pockets of the city is unpredictable. Many localities like Chandmari, Lachit Nagar, Kahilipara, Kalapahar, Rajgarh, Milanpur, Shantipur, Lokhra, GS Road, RG Baruah Road etc. is under the threat of looming water crises. The expansion of the city along with increased urbanization and population growth has facilitated in reduction of the recharge areas across the city. Based on the questionnaire and socio-economic survey conducted across 50 households, it was found that only 5% households had rainwater harvesting structures. These structures again underwent severe wear and tear due to lack of proper operation and maintenance. While, there is a general lack of awareness on rainwater harvesting systems, the economic status and lack of availability of space in the households also was a key factor that led to these systems being unpopular among the communities. Approximately 55% of the surveyed household lacked appropriate space for installation of harvesting structures. Quality of the harvested rainwater remained a major concern among some of the households. Such concerns typically stemmed out from the utter lack of awareness about rainwater harvesting. Almost 90% of the surveyed households purchased water from tankers during the summer season. While the city received surplus water during monsoon, yet due to a lack of proper water management, most precipitated water gets lost as runoff. Communities thus expressed grievances for the high price they pay to for supply of water at their doorsteps. It was observed that due to irregularities of the public water supply, people have to heavily depend on these water tankers where the cost of 700 litres of potable water is as high as Rupees 250. It is, thus, imperative that efforts for increased awareness are made along with highlighting site-specific structures to facilitate communities to integrate harvesting systems in their households. This is turn will also reduce the recurrent flash flood events that occurs in the city during the monsoon season. Further, awareness on the ecological and financial benefits lured from implementation of rainwater harvestings structures would go a long way in ensuring that communities adopt conservation practices.

Keywords: *Rainwater harvesting, groundwater recharge, water scarcity, awareness*

EFFECTIVE MANAGED AQUIFER RECHARGE: INSIGHTS FROM GUJARAT USING PRECAST MODULAR SYSTEMS AND JOHNSON SCREENS

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Managed Aquifer Recharge (MAR) is a strategic approach aimed at enhancing groundwater resources, particularly critical in regions facing water scarcity. The innovative solutions are essential in case of Gujarat, where diverse topography and climate conditions challenge traditional water management practices. This study explores the integration of precast modular systems and Johnson screens to optimize aquifer recharge processes. Precast modular systems offer flexibility and efficiency in construction, enabling rapid deployment in various terrains. These systems are designed to facilitate effective water infiltration and storage, crucial for replenishing aquifers. Coupled with high-performance Johnson screens, which prevent sediment clogging while maximizing water intake, these technologies ensure sustainable recharge operations. This study highlighted the necessity of utilizing rain quantification systems to monitor and assess rainfall patterns, allowing for informed decision-making regarding recharge activities. By examining case studies from different regions of Gujarat, this research aimed to showcase successful implementations of MAR, demonstrating their impact on groundwater sustainability, agricultural productivity and community resilience. Through this investigation, we tried to underline the importance of innovative engineering solutions in addressing water scarcity challenges and promoting sustainable water management practices in Gujarat and beyond. Gujarat, located in western India, faces significant challenges in water resource management due to its semi-arid climate, variable rainfall patterns and increasing demands from agriculture, industry, and urbanization. The state relies on a combination of surface water from rivers, lakes, and reservoirs, as well as groundwater, which plays a crucial role, particularly in areas where surface water is scarce. MAR has emerged as a viable solution to address these challenges. Furaat Earth Private Limited has developed an innovative precast modular system that incorporates Johnson Screens for high-performance recharge wells. These systems have been designed to effectively channel surface water and harvested rainwater into aquifers, thereby enhancing groundwater levels and quality. Strategically placed near overflowing ponds, urban areas, and water-logged regions, these recharge wells are adaptable to Gujarat's diverse terrain. By capturing excess surface water during rainfall events and directing it into the aquifer, the MAR approach not only helps replenish groundwater supplies but also mitigates issues related to flooding and waterlogging. This initiative aims to foster sustainable water management practices, ensuring a reliable water supply for agricultural, industrial, and domestic use across the state. Key findings from the project revealed hydrological benefits of MAR, improvements in groundwater quality and increased storage capacity, enhanced ecosystem resilience to climate impacts, and the synergy of MAR with rainwater harvesting as a strategy to combat groundwater depletion and over-extraction.

The collaboration between Furaat Earth and Johnson Screens represents a significant advancement in promoting MAR in Gujarat, a region facing acute water scarcity challenges.

This partnership combines Furaat Earth’s innovative water management solutions with Johnson Screen’s expertise in high-performance well screen technology. In summary, the collaborative efforts benefits: (i) Enhancing Groundwater Sustainability: The primary goal is to improve groundwater levels and quality through efficient recharge systems. By utilizing Johnson Screens, the partnership aims to optimize water flow into aquifers while minimizing sedimentation and clogging (ii) Implementing Innovative Technologies: Furaat Earth’s systems for MAR, combined with Johnson Screens, offer a comprehensive approach to aquifer recharge. This includes modular systems that are adaptable to Gujarat’s diverse terrains, ensuring effective water infiltration across various environments (iii) Community Engagement and Education: The partnership emphasizes the importance of community involvement in water management. By conducting workshops and awareness programs, Furaat Earth and Johnson Screens aim to educate local communities on the benefits of MAR and sustainable water practices and (iv) Data-Driven Decision Making: Utilizing rain quantification and monitoring systems, the collaboration seeks to collect valuable data on rainfall patterns and groundwater levels. This information will guide recharge efforts and enhance the overall effectiveness of the implemented systems.

This study underscores the need for an integrated water resource management approach that addresses ecological, social, and economic dimensions, with MAR serving as a critical strategy for sustainable groundwater management in Gujarat. Through this partnership, Furaat Earth and Johnson Screens aim to significantly improve the resilience of Gujarat’s water resources. By addressing the pressing issues of groundwater depletion and salinity intrusion, the collaboration not only enhances agricultural productivity but also supports local communities in achieving sustainable water management. The initiative reflects a forward-thinking approach to environmental challenges, demonstrating how partnerships between innovative companies can lead to effective solutions for some of the most pressing water-related issues in the region.

Keywords: *MAR, Johnson screens, high-performance recharge wells, precast modular systems, rainwater harvesting, sustainable groundwater management*

Theme 9

COASTAL WATER RESOURCES MANAGEMENT

INVESTIGATING THE STRONG CORRELATION BETWEEN SALINITY AND SUBMARINE GROUNDWATER DISCHARGE WITH GROUNDWATER POTENTIAL ALONG A TROPICAL COASTLINE

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The present study explores the relationship between salinity, thermal anomalies in sea surface temperature (SST), hydrogeochemical characteristics, and groundwater availability along a tropical coastline, focusing on the factors influencing these interactions and potential mitigation approaches. The study focuses on the coastal plains of Odisha, covering an area of approximately 20,000 km² and encompassing five coastal districts: Balasore, Bhadrak, Kendrapara, Jagatsinghpur, and Puri. Odisha's coastal length spans around 485 km, featuring a fragmented shoreline with islands and deltas formed by the Mahanadi, Brahmani, Baitarani, and Suvernarekha rivers, which flow into the Bay of Bengal. The geographical extent of the study area lies between 21° 54′ 19.86″ N to 19° 37′ 19.28.59″ N latitude and 87° 02′ 48.50″ E to 85° 25′ 25.80″ E longitude. The region is characterized by a low-lying terrain with a gentle slope and is predominantly composed of fluvial-deltaic sediments such as sand, gravel, and pebbles, which progressively thicken toward the coast, forming significant groundwater reservoirs. Notable natural resources in the region include Chilika Lake, Asia's largest brackish water lagoon, and extensive mangrove forests that contribute to ecological sustainability. The region experiences an average annual precipitation of 1400 mm and has a subtropical climate with three distinct seasons: summer, monsoon, and winter. The coastal aquifers, despite their groundwater storage potential, face significant challenges, including saltwater intrusion in littoral zones.

Hydrogeochemical data were collected from 137 groundwater samples in 2021, sourced from the Central Ground Water Board (CGWB). Groundwater availability was assessed through recorded water table levels, with data spanning 2009 to 2021, obtained from the India Water Resources Information System (India-WRIS) website (indiawris.gov.in) and the CGWB reports for Odisha. The data was employed to examine the average groundwater level fluctuations during the specified period. The groundwater recharge zone was calculated using the groundwater table fluctuation method, as outlined by the CGWB (CGWB, 2017) for the year 2021. This method, particularly effective for shallow aquifers, estimates recharge by considering the specific yield of the aquifer and the peak water level rise or fall observed during the recharge period. An average groundwater fluctuation map was generated using the Inverse Distance Weighting (IDW) interpolation method in ArcGIS 10.8.2 software. The meteorological data for the years 2015 to 2021 was obtained from the POWER Data Access Viewer on the NASA website (https://power.larc.nasa.gov/data-access-viewer/). Salinity in the region was evaluated using electrical conductivity and chloride concentration, which serve as key indicators of salinity levels. Additionally, satellite-derived SST data from MODIS and LANDSAT-8 were imported and processed in ArcGIS to identify thermal anomalies. These anomalies were calculated by comparing the current SST readings from LANDSAT-8 images captured at 4:37:45 UTC with the baseline (average) SST values from April to August 2021. Raster analysis tools were used to generate anomaly maps,

highlighting areas with significant temperature deviations, which could indicate SGD or other thermal influences. Statistical analyses were conducted to examine correlations among salinity, thermal anomalies, and groundwater levels.

The analysis provides a comprehensive view of the hydrogeochemical dynamics impacting coastal aquifers along Odisha's coastline. The 12-month lag Standardized Precipitation Index (SPI) map highlights regions with abundant rainfall, with rainfall intensity increasing from 839 mm to 2000 mm during the period from 2015 to 2021. This trend highlights the presence of high groundwater recharge zones (GWRZ) in the area. Despite a high GWRZ, groundwater levels (GWL) continue to decline due to excessive extraction. Groundwater levels typically range from 0 to 2 meters below ground level (mbgl), and this over-extraction exacerbates the issue by intensifying seawater intrusion (SWI), particularly in the upper parts of the aquifers and along the coastal regions. The GWL and SST anomalies suggest probable zones of submarine groundwater discharge (SGD) in the southern and central regions, with lower GWL confirming SGD-prone areas. Hydrogeochemical parameters reveal that regions with high SGD exhibit lower TDS, Na^+, and Cl^- concentrations due to fresher water influx, while areas affected by SWI show significantly elevated levels. The GWL and temperature trends highlight probable SGD zones with declining GWL and lower temperatures. A strong correlation between GWL decline and salinity increase, indicating deep saline upconing due to extensive over-extraction. The ROC curve between SST and MODIS SST further validates SST-derived data reliability, confirming the reliability of the SST map. This multi-tiered analysis effectively identifies regions vulnerable to SWI and SGD, providing essential insights for sustainable groundwater management strategies in coastal aquifers.

This study underscores the significant vulnerability of Odisha's coastal aquifers to SWI and SGD, primarily driven by excessive groundwater extraction despite favorable recharge conditions. The identification of SGD-prone zones, supported by SST anomalies and validated through MODIS data, confirms the reliability of SST mapping for detecting such areas. Hydro geochemical analysis reveals distinct patterns, with lower salinity in regions affected by SGD and increased salinity and conductivity in areas influenced by SWI, highlighting the complex interactions within coastal aquifers. The impact of groundwater salinization is particularly severe in the eastern and upper southern regions, compromising freshwater quality and creating substantial challenges for coastal communities. Furthermore, SGD along the Odisha coast contributes to freshwater depletion and potentially introduces land-derived pollutants into the coastal-marine ecosystem, with implications for ecological balance. These findings emphasize the urgent need for sustainable groundwater management practices to mitigate salinization risks, ensuring water resource protection and ecosystem health. This multi-proxy approach provides a valuable framework for effective targeted interventions to preserve and manage coastal water resources.

Keywords: *Groundwater recharge zone, groundwater level, sea surface temperature, submarine groundwater discharge, seawater intrusion*

APPLICATION OF MULTI-SPECTRAL ANALYSES FOR ASSESSING HYDROLOGICAL CHANGES IN COASTAL AREAS OF SOUTHERN WEST BENGAL, INDIA

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The process of seawater encroachment and its impact on the behaviour of coastal aquifers has been well documented and assessed through various hydrogeological and geophysical techniques. However, with a universal emergence of irregular groundwater abstraction patterns in sea-side areas and unreliable climatic behaviour affecting the coastal environments at the global level, this correlation can no longer be characterized merely through conventional methods. Moreover, with such drastic changes in the hydrogeological environment, the possibility of sub-regional variations in the same coastal aquifer system would require an impetus of newer and more flexible methods to distinguish groundwater fluctuations and quality patterns at a local level. In this context, the study presented here tried to highlight the use of multi-spectral analysis in understanding the changes in coastal areas and its subsequent impact on regional aquifers systems associated with it. This assessment covered parts of South 24 Parganas and Purba Medinipur districts (Diamond Harbour, Nandakumar and Haldia blocks) in West Bengal, India. In addition to this, it also tries to correlate the impact of other factors such as the extent of cyclone vulnerability and human intervention in the form of urbanization and industrialization on persisting groundwater resources. The study includes a general hydrogeological assessment of spatiotemporal water table changes and hydrochemical facies variation to establish the current settings. Additionally, the changes in the coastal areas were explored through a multi-spectral analysis using different indices (Normalized Difference Vegetation Index or NDVI, Modified Normalized Difference Water Index or MNDWI, Normalized Difference Salinity Index or NDSI, Enhanced Water Index or EWI, and Soil-Adjusted Vegetation Index or SAVI) between 2018 and 2022. These indices were then used as proxies to indirectly assess groundwater conditions by analysing changes in salinity, open water, and vegetation as indicators of broader environmental shifts. The observations from these two aspects of the study were then evaluated simultaneously to give relevant inferences.

The NDVI ranges from -1 to +1, with negative values indicating non-vegetative areas like water, snow, or barren land, while higher values reflect denser vegetation. NDVI is essential for monitoring vegetation health, detecting deforestation, and assessing environmental disturbances, providing valuable insights into changes in vegetation patterns, structure, and extent. It is especially useful in coastal environments for tracking vegetation such as mangroves and salt marshes, which play a vital role in stabilizing shorelines and enhancing resilience to coastal hazards. The MNDWI also ranges from -1 to +1, with positive values signifying water bodies and negative values indicating non-water regions. Unlike the NDWI, MNDWI minimizes the influence of vegetation by utilizing the green band, making it more effective for distinguishing water from dense vegetation. This enhanced capability makes MNDWI particularly useful in coastal areas, where it aids in mapping land-water interfaces and monitoring shoreline dynamics, reducing misclassification errors that often occur in

vegetated regions. The NDSI is a valuable remote sensing tool for mapping salt concentrations in coastal and inland saline environments. With positive values indicating higher salinity, NDSI provides a reliable means for assessing salinity levels and monitoring the spatial distribution of salinized soils in coastal regions. The EWI improves water body detection, especially in complex coastal environments, by incorporating additional spectral information. It enhances sensitivity to water bodies, enabling the detection of smaller features and improving accuracy in areas with dense vegetation or complex land-water interfaces. Finally, the SAVI adjusts for soil brightness in regions with sparse vegetation or high soil reflectance. It is particularly useful in coastal areas, where soil types vary, as it improves the sensitivity to vegetation changes, helping monitor vegetation health and detect environmental stress.

The initial observations from the study showed that while the changes associated with these processes have affected its fragile coastal aquifer system were noticed in general, the minor changes in water levels and a peculiar trend of hydrochemical facies variations seem to refute the possibility of extensive regional-wide seawater intrusion in recent years. The impact of seawater encroachment on the groundwater quality is minimal and highly localized. Furthermore, the declining water table is likely attributed to scanty rainfall in the Diamond Harbour part, while in Nandakumar and Haldia, the impact of groundwater abstraction through human interventions had a stronger role in it. The general observations from the spectral analysis of the region showed an overall decrease in NDVI and SAVI and an increase in MNDWI, NDSI, and EWI values for the period between 2018 and 2022. This could be attributed to a variety of factors, including the growth of urban areas and rapid industrialization, the apparent rise of sea level and deforestation. Thus, it was observed that even though these indices provide little direct evidence of the relationship between the changes in coastal environments and groundwater systems, they did hint towards changes in coastal hydrogeology in the study area. In retrospect, the study highlights the scope of these analytical methods for hydrogeological characterization in complementing traditional methods, especially in areas with major upheaval in coastal processes and groundwater systems associated with them.

Keywords: *Coastal areas, groundwater, spectral indices, seawater intrusion, diamond harbour, Haldia*

SALTWATER INTRUSION DRIVING GROUNDWATER SALINIZATION IN COASTAL AQUIFERS OF GUJARAT: A HYDROCHEMICAL-ISOTOPIC ANALYSIS

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The present study focuses on understanding the causes and impact of saltwater intrusion and groundwater salinization in the coastal aquifers of Gujarat, specifically in the Kachchh and Anand districts, with the goal of providing practical recommendations for improving groundwater management and conservation efforts. Groundwater samples (n = 59) were collected from coastal aquifers in Kachchh and Anand districts, representing diverse hydrogeological settings. Samples were stored in high-density polypropylene bottles and categorized for cation, anion, and isotopic analysis. To ensure sample integrity, proper labelling and transport in insulated boxes were conducted. On-site measurements included pH, electrical conductivity (EC), and total dissolved solids (TDS), using a multi-parameter instrument. Carbonates and bicarbonates were quantified through titration following APHA guidelines. Major cations and anions were analyzed via ion chromatography, while stable isotopic compositions ($\delta^{18}O$ and δD) were determined at the Physical Research Laboratory, Ahmedabad. Hydrochemical data were analyzed to identify major geochemical processes, including weathering, ion exchange, and mineral dissolution, influencing groundwater composition. Isotopic data were compared to the Local Meteoric Water Line (LMWL) to trace salinity sources and assess evaporation effects on recharge. GIS mapping was employed to integrate spatial data, visualizing the extent and distribution of salinization.

The groundwater in the study area exhibited alkaline characteristics, with pH values ranging from 8.1 to 10.5, indicative of semi-arid to arid conditions. TDS ranged from 413 mg/L to 9850 mg/L, reflecting significant salinity variations. EC values varied between 1870 µS/cm and 15,900 µS/cm, with approximately half of the samples showing moderate salinity (1500–5000 µS/cm) and the remainder displaying high salinity (>5000 µS/cm). The ionic composition followed the order: Na^{+}> Ca^{2+}> Mg^{2+}> K^{+} for cations and Cl^{-}> HCO_3^{-}> SO_4^{2-}> $NO_3^{-}$for anions, indicating a dominance of Na-Cl water facies. This distribution highlights the impact of salinization and geochemical interactions within the aquifer system. Geochemical analysis revealed that silicate weathering and ion exchange were the primary processes controlling groundwater composition. Scatter plots of Ca^{2}+ Mg^{2+}versus HCO_3^{-}+ SO_4^{2-} indicated that most samples were below the 1:1 equiline, suggesting reverse ion exchange and carbonate dissolution.

The relationship between (Na^{+}+ K^{+}) and Cl^{-} pointed to significant contributions from soil salt dissolution and silicate weathering, demonstrating the complex interplay of geological and hydrochemical processes affecting groundwater quality. Stable isotopic analysis revealed $\delta^{18}O$ values ranging from -1.48‰ to -6.06‰ and δD values from -46.04‰ to -17.83‰ in Kachchh, while in Anand, $\delta^{18}O$ ranged from -0.61‰ to -3.0‰ and δD from -7.13‰ to -20.8‰. Regression analysis of δD versus $\delta^{18}O$ yielded slopes of 5.33 (±0.45) and 4.48 (±0.5) for Kachchh and Anand districts, indicating significant evaporation during recharge, influenced by high temperatures and low rainfall. The $\delta^{18}O$ versus Cl^-scatter plot showed most samples aligned along the regression line, suggesting a common origin. Samples with high Cl^- concentrations also exhibited enriched $\delta^{18}O$ values, indicating evaporative enrichment of saline water, particularly near coastal sampling points where rivulets facilitated saline intrusion. The integrated hydrochemical and isotopic analysis provides critical insights into the salinization processes affecting coastal aquifers in Gujarat. Key findings include:

Groundwater quality is primarily governed by natural geochemical processes such as weathering, ion exchange, and mineral dissolution, alongside anthropogenic factors including overexploitation and land-use practices. Saltwater intrusion is primarily driven by the upconing of underlying saline water, exacerbated by excessive groundwater extraction and coupled with evaporative enrichment during recharge. The study underscores the importance of employing integrated approaches that combine hydrochemistry, isotopic analysis, and GIS to unravel complex groundwater systems. There is an urgent need for sustainable groundwater management practices to mitigate salinization and preserve water resources in coastal regions. These findings offer critical insights for formulating effective management strategies aimed at mitigating salinization and ensuring the long-term sustainability of coastal aquifers on a global scale. Priority should be given to implementing policies that reduce groundwater overexploitation, enhance natural and artificial recharge, and establish robust monitoring systems to track and manage saltwater intrusion. Such integrated approaches are essential for preserving coastal aquifers as vital resources for future generations.

Keywords: *Coastal Gujarat, coastal aquifers, saltwater intrusion, groundwater salinization, hydro-chemical analysis, GIS,* ionic ratio, *geochemical processes, stable isotopes*

CONTRIBUTION OF GROUNDWATER DISCHARGE IN LOW FLOW SUSTENANCE OF THE BAITARANI RIVER BASIN

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Low flow is vital in catchment hydrology as it fulfils the non-rainy season water demand and is essential for ecosystem functioning. The World Meteorological Organisation states low flow as the streamflow observed during prolonged dry weather. It is seasonal and is part of the flow regime. Contrary to floods, the impacts of the decline in the low flows are creeping in nature and could have a long-lasting consequence. Aquifers recharged during monsoon contribute to streamflow during non-monsoon periods. Similarly, reservoir release also contributes to non-monsoon streamflow. Land use land use-land cover (LULC) determines the fractionation of precipitation to different components such as infiltration, recharge, evapotranspiration, and surface runoff. In addition to LULC change, erratic monsoons have declined recharge and reservoir storage. Consequently, the lean season flow is declining in many rivers worldwide, such as in the Baitarani Riven in eastern India. Hence, a detailed analysis of the conditions favoring sustained low flow would aid in better water management considering increased water demand, changing land use, and climatology. In this context, we performed hydrologic simulation to identify the fractional contribution of aquifer storage, surface runoff and reservoir release to streamflow of the Baitarani River basin in eastern India.

The study area selected is the Baitarani River basin in eastern India, within 20.67-22.28°N latitude and 85.16-86.89°E longitude. It originates from the Gonasika Hills towards the northern part of the basin at an altitude of 900 m above the mean sea level (MSL) and drains in the Bay of Bengal in the East, traversing about 350 km. The area can be physio-graphically divided from north to southeast as eastern ghats, central table land, and coastal plains. Tropical monsoon climate prevails over the study area, with 80% of precipitation occurring during June-September. It has been observed that the non-monsoon streamflow of the Baitarani River is declining, posing difficulty for water managers in water distribution to agriculture, domestic, and industry sectors. To perform the hydrological modelling and subsequent analysis, we selected the open-source model SWAT. The data procured for the model setup are the Digital Elevation Model (DEM) from the USGS Earth Explorer, meteorological observations of rainfall and temperature from the India Meteorological Department, LULC and soil from the Odisha Remote Sensing and Application Centre, and time series of discharge observation from the Central Water Commission. Based on the freely available 30 m resolution DEM, the entire basin was first delineated into 23 subbasins. Further, a total of 107 hydrological response units (HRUs) were derived based on the existing soil, LULC, and topography of the area. These HRUs behave similarly to any external forcing. The publicly available SWAT calibration and uncertainty (SWAT-CUP) program was used for model calibration. The Sequential Uncertainty Fitting 2 (SUFI-2) algorithm of SWAT-CUP was used to calibrate the model. For calibration, out of the available parameters, 12 parameters were identified based on expert knowledge and after conducting a literature review on the application of the SWAT model to identical basins. The parameters can be broadly categorized as surface response (e.g., CN2.mgt, CH_K2.rte, CH_N2.rte, ESCO.hru, OV_N.hru, SOL_K.sol, SOL.AWC.sol, and HRU_SLP.hru), sub-

surface response (e.g., ALPHA_BF.gw, GW_DELAY.gw and GWQMN.gw), and basin response (SURLAG.bsn) types. Sensitivity analysis was carried out to rank the selected parameters in the order of sensitivity. The Nash Sutcliffe model efficiency Coefficient (NSC) was chosen as the objective function while reproducing the discharge during calibration (1995 to 2007) and validation (2008 to 2013) at three gauging stations, representing headwater catchment, mid-reach, and delta regions.

Analysis of historical LULC shows that barren and built-up areas have increased by 145% and 70%, respectively, whereas the forest land cover has decreased by 13%. The agricultural land use has not been affected much. SWAT reproduced the observed discharge at the Akhuapada gauging station with an NSC of 0.64 and R2 of 0.68. As it is not economical to have gauging stations at the outlet of each sub-basin, the discharge simulated by the calibrated SWAT setup at the outlet of each sub-basin was assumed to be the observed discharge of that sub-basin. It was observed that the sub-basins draining to different river reaches contributed differently. The sub-basins of the headwater region contributed initially after the monsoon withdrawal, whereas the subbasins draining to the mid-reach contributed significantly throughout the year. Similarly, the subbasin-wise (LULC) data was analyzed to check the LULC type aiding in delayed low-flow. The contribution of aquifer in low flow is $\geq$ 90%. The outcome of this study would help the water managers understand the cause of the decline in low flows and its possible remedy through appropriate land management.

Low flow plays a vital role in lean season water supply. From this study, it was observed that barren land and built-up areas have increased after 1990. Consequently, the non-monsoon streamflow has decreased. Further, it was observed that groundwater discharge contributes $\geq$ 90% of streamflow during the lean season.

Keywords: *Low-flow, hydrological modelling, SWAT, baseflow, e-flow*

COMPARATIVE ASSESSMENT OF GROUNDWATER VULNERABILITY MODELS IN COASTAL ANDHRA PRADESH, INDIA: DRASTIC, SINTACS AND GOD APPROACHES

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This study compares three groundwater vulnerability models DRASTIC, SINTACS, and GOD—to determine which provides the most accurate assessment of groundwater vulnerability in coastal Andhra Pradesh, considering the region's specific conditions. Groundwater vulnerability models assess the risk of contamination by utilizing various hydrogeological parameters. Notable models include DRASTIC, uses seven parameters such as depth to water and hydraulic conductivity. Although comprehensive, its adaptability to local conditions can be enhanced by adjusting parameter weights. The SINTACS model, a DRASTIC adaptation, offers greater flexibility for Mediterranean environments and specific pollution risks, especially in coastal areas affected by agriculture and industry. Lastly, the GOD model simplifies assessments with three parameters: Groundwater confinement, overlaying lithology, and Depth to groundwater, making it efficient for rapid evaluations but potentially lacking detail for complex coastal regions. The primary objectives of the study include: (1) Compare the effectiveness of the DRASTIC, SINTACS, and GOD models for groundwater vulnerability assessment in coastal Andhra Pradesh. (2) validate model performance using observed groundwater quality data (e.g., nitrate levels, salinity). (3) Identify the most reliable model for predicting groundwater vulnerability in coastal regions with similar hydrogeological characteristics. (4) Provide recommendations for groundwater management based on the comparative results.

The study area includes Coastal Andhra Pradesh with an areal extent of 86,297 Sq.km. It spans between 78.5^0 E and 84^0 E longitudes and 13.5^0N and 19^0N latitudes approximately. This paragraph includes the method adopted in the study to obtain data and their inputs into GIS. The study integrates data on various hydrogeological parameters, including,1-Depth to water 2-Recharge 3-Aquifer media: 4-Soil type 5-Topography 6-Vadose zone impact.7-Hydraulic conductivity. Additionally, data on land use, climate, and pollutant sources are gathered to provide context for regional contamination risks. Groundwater quality data, such as nitrate levels and salinity concentrations, are collected for validation. Secondly, GIS-Based Data Integration, wherein GIS tools are used to map and integrate the collected data layers for each model. This allows for spatial analysis of groundwater vulnerability and the generation of vulnerability maps. Thirdly, Model Application, the three models. the DRASTIC SINTACS model, and GOD model. The Vulnerability Mapping is carried out with each model that generates a vulnerability map that visualizes areas of high and low contamination risk based on the integration of hydrogeological data. For validation and comparison, the model outputs are validated by comparing the predicted vulnerability zones with observed groundwater quality data. Statistical analyses, such as R^2 value computation, are performed to evaluate the accuracy of the models by measuring the correlation between model predictions and actual contamination levels.

The results of this study include the comparative analysis that reveals that the SINTACS model provides the most accurate vulnerability assessments for coastal Andhra Pradesh, as it incorporates region-specific factors, such as local soil types and pollution sources, which the DRASTIC and GOD models overlook. The SINTACS model's flexibility in adjusting parameter weights makes it more adaptable to the region's complex hydrogeological conditions, such as varying salinity levels and differing recharge patterns. The GOD model, while useful for quick assessments, lacks the detail required to capture the region's vulnerability accurately. In contrast, the DRASTIC model, though comprehensive, tends to overestimate vulnerability in this region when used without modification. A well location map was created and overlaid onto the GOD, DRASTIC and SINTACS maps. Nitrate concentrations were used as a direct indicator of groundwater contamination. The correlation between groundwater vulnerability risk levels and nitrate concentrations served as a measure of the reliability and accuracy of the applied methods. The positive correlation existed between both GOD, DRASTIC & SINTACS and nitrate value as shown in the R^2-values of 0.53, 0.64 & 0.67. For example, an R^2-value of 0.64 means that 64% of the variance in nitrate concentration can be explained by the DRASTIC index. However, the 36% unexplained variance suggests there are other factors (e.g., land use, agricultural practices, local geology, or additional hydrogeological conditions) influencing nitrate concentrations. Including such variables in future models might improve the prediction. Upon application of SINTACS method, nearly 54.91 % of study area is highly vulnerable and 40.81% is in moderate vulnerable range, and only 4.28% of the study area falls under low vulnerability. Upon application of DRASTIC method, nearly 49.46 % of study area is highly vulnerable and 39.98% is in moderate vulnerable range, and only 10.56% of the study area falls under low vulnerability. Upon application of GOD method, nearly 45.56 % of study area is highly vulnerable and 44.78% is in moderate vulnerable range, and only 9.66% of the study area falls under low vulnerability. The study concludes that the SINTACS model is the most effective for groundwater vulnerability assessment in coastal Andhra Pradesh, providing the most accurate predictions when compared to observed groundwater quality data. The findings suggest that SINTACS, with its flexibility and adaptability, is well-suited for coastal areas with complex hydrogeological conditions. For effective groundwater resource management in such regions, it is crucial to select a vulnerability assessment model that considers local conditions and pollution sources. This study provides valuable insights that can guide water resource management strategies in coastal areas facing similar challenges.

Keywords: *DRASTIC, SINTACS, GOD, groundwater, vulnerability, Andhra Pradesh*

SEAWATER INTRUSION ASSESSMENT FOR A COASTAL AQUIFER USING MESHLESS LOCAL PETROV-GALERKIN (MLPG) METHOD

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Seawater intrusion (SWI) is a significant environmental challenge that threatens freshwater resources in coastal aquifers worldwide. This phenomenon, driven by factors such as excessive groundwater (GW) pumping, urbanization, and sea-level rise, disrupts the availability and quality of freshwater essential for human and ecological needs. Coastal aquifers, particularly those with stratified structures, are highly vulnerable due to their inherent heterogeneity in hydraulic conductivity and porosity. Traditional approaches for modelling and mitigating SWI often rely on simplified empirical models or data-driven techniques that fail to account for the complex, non-linear interactions governing GW flow and solute transport. To address this gap, advanced numerical methods are necessary to accurately simulate these processes and provide actionable insights for GW management. Among these, the Meshless Local Petrov-Galerkin (MLPG) method has emerged as a powerful and flexible tool for GW modelling, offering computational efficiency and adaptability for complex scenarios. The MLPG method eliminates the need for structured grids or meshes, a significant advantage when dealing with systems characterized by irregular geometries or abrupt transitions in properties, such as stratified aquifers. This mesh-free framework uses radial basis functions (RBF) to construct trial and test functions for discretizing the governing equations of GW flow and solute transport. The method employs local weak forms derived from these equations, ensuring accurate representation of spatial variations across heterogeneous aquifer systems. Integration over local subdomains provides the foundation for assembling a global system of equations, which incorporates boundary conditions and is solved numerically. This study applies the MLPG approach to simulate variable-density flow and solute transport in stratified aquifers, characterized by distinct layers with varying hydraulic conductivities and porosities, to model the dynamics of the freshwater-saltwater interface under different stress scenarios.

In this study, the MLPG framework is implemented to simulate one-dimensional (1D) and two-dimensional (2D) aquifer systems. The study area, located along the coastal region in Chennai and Kanchipuram District, Tamil Nadu, India, is a critical zone for groundwater resources. It faces challenges like overexploitation and seawater intrusion due to sea level rise and anthropogenic pressures. The prepared models are defined with specific parameters, including porosity, hydraulic conductivity, and dispersivity. Boundary conditions are set to represent coastal interfaces and variable flux scenarios, such as groundwater (GW) pumping or recharge. The models are validated against established analytical solutions to ensure accuracy and reliability. Preliminary results demonstrated the method's capacity to resolve the sharp freshwater-saltwater interface with high accuracy, capturing the effects of aquifer heterogeneity on intrusion patterns. Sensitivity analyses revealed that high permeability contrasts between aquifer layers significantly influence the depth and shape of seawater intrusion, underscoring the need for precise aquifer characterization in GW modelling. The MLPG simulations showed good agreement with finite difference results, with an error margin of ±10%, further validating its potential as a robust numerical method.

Stratified aquifers pose unique challenges for SWI modelling due to their non-uniform flow patterns caused by spatial variability in hydraulic properties. Conventional grid-based methods often struggle with the complexities of these systems, as they require fine discretization to accurately capture transitions between layers, leading to high computational costs. In contrast, the MLPG method's flexible node placement enables efficient modelling of sharp gradients and irregular boundaries. By discretizing the governing equations locally, the method reduces computational overhead while maintaining accuracy. This makes it particularly well-suited for modelling variable-density flow in heterogeneous aquifers, where seawater intrusion is influenced by interactions between layers with differing properties. For example, in the simulated scenarios, layers with high permeability facilitated greater intrusion depths, highlighting the critical role of layer-specific hydraulic conductivity in controlling SWI dynamics.

The study also explored the influence of GW pumping rates on SWI, revealing a direct correlation between excessive pumping and increased intrusion. Variable flux boundaries are used to simulate hypothetical pumping scenarios, demonstrating the exacerbation of SWI as withdrawal rates intensified. These findings provide actionable insights for GW managers and policymakers, emphasizing the need for sustainable pumping practices and the importance of monitoring and managing withdrawal rates to mitigate SWI. Additionally, the research examined the impact of recharge rates, suggesting that enhanced recharge can act as a buffer against intrusion, further supporting strategies for artificial recharge in vulnerable regions. Despite its advantages, the MLPG method is not without challenges. The accuracy and stability of its solutions depend on the appropriate distribution of nodes, the selection of support domain parameters, and the formulation of trial and test functions. Further research is needed to establish standardized guidelines for these aspects to enhance the method's resilience and applicability to large-scale problems. The choice of RBF and the integration schemes used also play a crucial role in determining the method's performance, highlighting areas for potential refinement in future studies.

The results of this study underscore the potential of the MLPG method as a powerful tool for GW modelling, particularly in addressing complex challenges such as SWI in stratified aquifers. Its flexibility, computational efficiency, and ability to handle heterogeneous systems make it a valuable addition to the suite of numerical methods available for GW research. By providing detailed insights into the dynamics of variable-density flow and solute transport, the MLPG approach supports the development of sustainable management strategies for coastal aquifers. These strategies are essential for preserving freshwater resources in the face of growing environmental pressures, including urbanization, population growth, and climate change.

Keywords: *Seawater intrusion, groundwater, Meshless Local Petrov-Galerkin (MLPG) method, numerical methods, modelling*

SALTWATER INTRUSION MODELING AND GROUNDWATER DYNAMICS IN THE COASTAL AQUIFER SYSTEM OF THE MAHANADI DELTA, ODISHA: A CYCLONE-PRONE REGION OF INDIA

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Coastal aquifers play a crucial role in supplying freshwater to densely populated regions that depend on groundwater for agriculture, domestic needs, and industrial activities. Their significance is especially pronounced in deltaic areas like the Mahanadi delta, where they support local economies and livelihoods. However, these aquifers are highly vulnerable to seawater intrusion due to their proximity to the sea, heavy groundwater extraction, and changing climate patterns. Jagatsinghpur district, covering approximately 1,600 km², is part of the Mahanadi Delta on India's eastern coast near the Bay of Bengal. The region faces rising groundwater salinity due to seawater ingress and human activities, which alter the hydrochemical composition of aquifers and pose a threat to freshwater availability. Several factors, including over-extraction, reduced recharge, and aquifer geology, contribute to this phenomenon. Cyclones, common in this region, worsen seawater intrusion by pushing saline water inland, temporarily raising aquifer salinity. Post-cyclone conditions, such as disrupted surface water supplies and increased groundwater extraction, create favourable conditions for intrusion. Additionally, changes in river discharge and reduced recharge further intensify the risk. This study explores the hydrogeochemical evolution of groundwater in the Mahanadi delta, using geochemical tools and numerical modeling to understand the dynamics of seawater intrusion in this cyclone-prone region. The research aims to inform sustainable water resource management in vulnerable coastal aquifers.

A total of 30 groundwater samples from the Mahanadi delta revealed a wide range of electrical conductivity (EC), indicative of varying salinity levels. Freshwater zones exhibited EC values as low as 146 µS/cm in the northwest, whereas saline zones near the coastline recorded values as high as 33,900 µS/cm. The ionic composition followed distinct trends, with cations dominated by $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and anions by $Cl^- > HCO_3^- > SO_4^{2-}$. These variations reflect the progressive mixing of seawater and freshwater, with hydrochemical facies transitioning from Ca-Mg-Na-HCO_3 types in the upper delta to Na-Cl types near the coast. Ion exchange processes were identified as key drivers of these transitions. A robust correlation ($r > 0.9$) between chloride and major ions, including Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and K^+, highlighted the significant influence of seawater on groundwater chemistry. Ionic ratios such as Na^+/Cl^-, HCO_3^-/Cl^-, Mg^{2+}/Ca^{2+}, and SO_4^{2-}/Cl^- provided further evidence of salinity ingress. The stable isotope composition ($\delta^{18}O$ and δ^2H) ranged from -1.86‰ to -6.87‰ for $\delta^{18}O$ and -10.79‰ to -45.42‰ for δ^2H, indicating a mixing trend between saline and freshwater in the coastal zones.

Using PHREEQC, the saturation indices of carbonate minerals such as calcite and dolomite were calculated. Negative indices (<1) in the upper delta indicated fresh groundwater conditions, supported by calcium-rich water with Mg^{2+}/Ca^{2+} ratios below 1. The proportion of seawater in groundwater was estimated to vary from 0% in the upper delta to 72% near the coast. A conceptual model was developed to illustrate the spatial variability in salinity and ion concentrations across the coastal aquifer system. Shallow wells near the Bay of Bengal exhibited lower Na^+ and Cl^- concentrations and lower EC values, suggesting minimal seawater influence. In contrast, deeper coastal wells displayed elevated ionic concentrations, indicating pronounced seawater intrusion.

Numerical modeling was conducted using Visual MODFLOW to simulate the dynamics of groundwater flow in the Jagatsinghpur coastal district. The hydraulic head ranged from 1 m to 15 m above mean sea level (MSL), with an average of 6 m in low-lying coastal areas. These areas were found to experience significant groundwater abstraction for agricultural purposes, leading to overdraft conditions. Aquifer properties, including horizontal hydraulic conductivity (40–45 m/day) and specific yield (0.05–0.07), were determined using the Parameter Estimation Technique (PEST). The model was calibrated using data from 2004 and 2007 and validated against observations from 2008 to 2009. Results indicated that net recharge to the coastal aquifer ranged from 247.89 to 262.63 million cubic meters (MCM) during the study period. River inflow was estimated at approximately 34 MCM during pre- and post-monsoon seasons, while aquifer discharge to the river system during monsoons ranged from 23 to 27 MCM. Water level contour analysis revealed significant hydraulic gradients, steep in the upper delta and sluggish in the lower regions. These gradients were influenced by seawater intrusion, which reduced groundwater movement in the lower delta. Overextraction and urbanization further exacerbated the decline in hydraulic head, intensifying salinity ingress.

The findings underscore the dual challenges posed by natural and anthropogenic factors in managing coastal aquifers. The Mahanadi delta's aquifer system is under pressure from declining recharge rates, excessive abstraction, and salinity ingress due to seawater intrusion. Hydrochemical analysis highlights the critical role of ion exchange and mixing processes in determining groundwater quality. Stable isotope signatures provide robust evidence of saline-freshwater interactions, crucial for demarcating vulnerable zones. Numerical modeling offers insights into groundwater flow patterns and their implications for aquifer sustainability. By estimating recharge, discharge, and hydraulic properties, the model aids in identifying regions at risk of seawater intrusion. These findings are vital for formulating targeted interventions, including controlled groundwater pumping, artificial recharge, and sustainable water use practices. This research integrates hydrochemical and numerical modeling approaches to comprehensively analyze seawater intrusion in the Mahanadi delta. The study demonstrates the importance of combining ionic, isotopic, and geochemical tools with groundwater flow modeling to unravel the complexities of coastal aquifer systems. The Ersama block of Jagatsinghpur district, the most affected area during the 1999 Super Cyclone, exhibits the highest groundwater salinity, indicating significant seawater intrusion. Fluctuations in hydraulic head suggest that seawater ingress is a temporal phenomenon, predominantly occurring during the pre-monsoon period. The findings provide a framework for managing seawater intrusion not only in the Mahanadi delta but also in similar coastal regions worldwide. As coastal aquifers continue to face growing threats from seawater intrusion and overexploitation, implementing sustainable management practices is imperative. Strategies such as restricting groundwater abstraction, enhancing recharge through managed aquifer systems, and monitoring salinity dynamics can help mitigate the adverse impacts of seawater intrusion. By addressing these challenges, this study contributes to safeguarding freshwater resources & ensuring the long-term resilience of coastal aquifers.

Keywords: *Mahanadi delta, saltwater intrusion, groundwater dynamics, hydrochemical composition, numerical modelling, MODFLOW, isotopes*

APPLICATION OF ADVANCE SCIENTIFIC INNOVATIONS AND POLICY REGULATIONS FOR SUSTAINABLE COASTAL GOVERNANCE AND RESOURCE MANAGEMENT FOR COASTAL INDUSTRIALIZATION TO AIM TOWARDS VIKSIT BHARAT @2047

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This paper seeks to define how the following scientific innovations: AI monitoring, Minimum Support Price (MSP) and eco-coasts for industrialisation policy designs interact. This paper aims to analyse the involvement of scientific innovation and policy regulation in effective coastal management. Now technological innovation in marine sector in combination with the legislative steps like Coastal Regulation Zone (CRZ) norms and ICZM has made available opportunities for synchronized development. This research is in consonance with the concept of Viksit Bharat@2047 and means the transition for sustainable industrialisation from exploitative constructional models. Through the use of such modern concepts as geospatial applications and predictive analysis with the application of governance frameworks, this research has the objective of providing recommendations on the management of coastal resources. This research uses both quantitative and qualitative methods to assess sustainable coastal governance practices. Primary data is collected from face-to-face interviews with policymakers, industry representatives and environmentalists. Secondary data comprises of reports of good experience in implementing coastal management methods in India and other parts of the world. A range of expert resources supported by GIS and marine research indices work to evaluate resource availability and the industrial footprint. The nature of policy evaluation emphasizes the comparison of existing policies to the benchmark of the best practices. Using policy simulations based on intelligent agents, future effects of policy actions on coastal environments are modelled. The work also uses cost-benefit approaches to examine the consequences of implementing new technologies within the industrialization of coastal areas.

The study highlights that promoting the introduction of newer scientific advances into the strategies used to regulate the industrialisation process, strongly contributes to making the industrialisation of the coastal regions more sustainable. It reveals a 25% efficiency of AI-based tools in supervising ecological consequences while geospatial tools enhance the marine spatial planning minimizing resource contradictions 30%. The analysis shows drawbacks of the current policy, including deficits in the practical application of policies, specifically the absence of sufficient ways to enforce proposed policies and the lack of involvement of the local population in the policies' formulation. Carrying out of the ICZM practices alongside the use of the advanced technologies the emission of carbon by the coastal industries can be brought down to as low as 40%. Economic evaluation outcomes show a high economic benefit for developing an eco-friendly innovation, which supports the idea that it is feasible to implement these solutions on a large scale. In all, these findings highlight the role of harmonised innovation and policy in measuring and achieving sustainable coastal governance.

This paper identifies the cross-hybridization of innovative technology with policy laws to be a major foundation for a sound and sustainable coastal Rican governance- Sustainable coastal Rican governance" deals with the way that coastlines in Costa Rica – often called "Rica" in this country's name, "Costa Rica" – should be run in order to be sustainable in terms of using energy sources, having fair rights distribution and economic stability. This covers the conservation and sustainable use of coastal and marine biological diversity, as well as taking care of the welfare of coastal inhabitants and developmental interests, not forgetting the protection of coasts from factors such as over fishing, pollution and climate change through policies informed by science. Coastal sustainability management is an approach to sustaining the coastal environment and resources, supporting growth of sustainable economic activities and developing policies that enables the involvement of coastal users in policy making for ultimate benefit of future generations. Tools such as AI or geospatial analysis do act as tools for monitoring but also solutions to enable effective decisions. Consequently, eight overall conclusions were extracted from the analysis of literature on ICZM by the authors: The findings emphasize the involvement of stakeholders in the application of ICZM practices. There are still many issues in reconcile various interests, especially while promoting the development of industry and preserving the environment. The lessons from the Netherlands' Delta Program reveal that India needs more synergy between science and policy to effectively respond to flood risks. Cognizant of the complexity of coastal problems, policy suggestions focus on such aspects as the development of appropriate human and institutional capital, decentralized management, and organized learning. This discussion strengthens the idea of Viksit Bharat@2047, that calls for an efficient coastal industrialization plan for an inclusive India.

As such, hurricane, science, and policy analyses have central perspectives in understanding the future and future success of sustainable coastal governance. Applying technologies, which include, but are not limited to, artificial intelligence and geospatial technologies, while incorporating diverse elements of marine biodiversity monitoring into the adaptive governance of structures that Industrial Development Corporation of Odisha (IDCO) employs to foster coastal industrialization, can guarantee sustainable development of the coast. Outcomes confirm that mutually complementary policies can contribute to the future-oriented consideration of the factors for the development of both nature protection and economic development. Policy implications mean increased rigor of enforcement changes in stakeholder engagement, and increased spending towards environmentally friendly technologies. This research forms a guideline for achieving sustainable coastal management and foster India's vision of Viksit Bharat 2047. Therefore, in the future development of structural and economic security of the coastal regions, there will be need to encourage cooperation between the government, industry, and the local people. Recommended sustainable agenda for coastal governance and resource management under Viksit Bharat@2047 the next two decades should be implemented in the following steps. Solutions in the timeframe of one to five years cover all aspects of regulation and pilot initiatives. Mid-term (6-15 years) promotes scaling innovations, and the long-term (16-20 years) ensures the reassessment of nationwide sustainable practices.

Keywords: *Coastal governance, marine biodiversity, Viksit Bharat, economic security, AI, fishing, aquaculture*

DELINEATION OF AQUIFER GEOMETRY AND FRESH SALINE INTERFACE IN COASTAL PARTS OF KASAI - SUVARNAREKHA BASIN, EASTERN INDIA

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Water is regarded as the origin and sustainer of life and held sacred by most of ancient races. The accelerated growth in population, industrialization and urbanization is leading to increasing demand for water in several sectors. The groundwater is the major source of water for irrigation, domestic and industrial uses resulting in scarcity of resources. Water being the life line of all living being, is noteworthy for research purpose to uplift socio economic factors. The present study is mainly focused on the alluvial tracts of the Kasai-Suvarnarekha (KS) basin. Despite the average rainfall of the area being medium to high (~1234-4136 mm), the area experiences acute scarcity of groundwater, especially during summer as the area is an agrarian, have created conflicts between various stakeholders in the coastal area. Waterlogging during the rainy season affects and results in loss of crops in the area. Due to unscientific drilling and improper identification of the aquifer zone, failure of wells, reduction in discharge rate, and saline water up coning is a common phenomenon in the area.

This study demonstrates a practical approach to delineating the fresh and saline water interface and its geometry in a coastal alluvial plain. The combined geophysical integrated and coupled with EC of formation water samples of respective aquifer zones has been attempted to accomplish this goal. The accurate determination of aquifer groups will allow a proper groundwater management plan and well field design to abstract the fresh water resource judiciously and saline water aquifers to be utilized for industrial development in the area to conserve and protect the freshwater system. Geophysical logs play a unique role in synthesizing the lithology and defining the marker horizons. The present study attempts on a regional scale to provide the hydro-stratigraphy and aquifer groups in alluvial parts of KS basin, eastern India, using in-situ electrical and gamma properties using all the available boreholes. The logs have helped in identifying the aquifer groups in alluvial parts of the Kasai-Suvarnarekha basin. The in-situ electrical and gamma properties were used using 58 geophysical logs and 126 lithologic logs, which have penetrated the aquifer system's base to correlate the geophysical markers and determine their relation to significant stratigraphic boundaries at a wider scale. For a meaningful hydrogeological study, a hydro stratigraphic unit on a regional scale is defined covering both the area of recharge and discharge zone, i.e., up to the coast. The hydro stratigraphic cross-section of the area reveals five distinct hydro stratigraphic features according to their vertical distribution and lithological composition. Regionally three aquifer groups namely Aquifer-I, Aquifer-II and Aquifer-III have been delineated in the area. Pinching out of individual sand and clay layers within the single aquifer group are not ruled out. The major clay groups intervening between these aquifer groups extend regionally and pinch out at the alluvial area's extreme northern boundary. The presence of three different potentiometric surfaces generated from hydraulic heads measured through various wells in the area also confirms three regionally extensive aquifer groups. The thickness of sediments varies from 100 m in the North to more than 450 m in the southern part. The aquifer group-I extends all over the basin with varying thicknesses. It is composed

generally of coarser sediments as compared to other groups. It is underlain by an extensive clay group that is about 10 to 15 m thick and separates the aquifer group-II. It is also inferred that the deeper aquifer i,e., the Aquifer-III is more than 300 m thick in the southern part forming a single aquifer system. Iso-conductivity maps were prepared showing variation of EC of respective aquifers. The fresh and saline water interface map shows that in the northern part of the basin, groundwater is fresh at all levels. In the southeastern part of Kasai River, there is no groundwater prospect in shallower zone (Aquifer-I). The groundwater of Aquifer-II in this section is mostly saline. However, Aquifer-III in this section is mostly fresh. But there is a thin saline water bearing sand exists just below the grey clay horizon. Care must be taken while designing the well, so that the deeper fresh water zone is tapped and there should not be any leakage from the upper saline water part. The upper saline part needs to be sealed properly in order to avoid mixing of the water. It is further suggested to tap the Aquifer-III in general as there is limited groundwater development at this level. The upper two zones are mostly exploited and there will be risk of further movement of interface towards the land. The geo-electric sections revealed that the area near to the coast has been intruded by saline water. Attempt has been made to demarcate freshwater and saline water zone, both vertically and laterally through resistivity method. The saline water ingression in this aquifer cannot be ruled out. Deeper aquifer which is yet to be exploited needs to be explored for sustainable development of the area in the coastal part.

The results presented in this research work show the effectiveness, reliability and usefulness of available geophysical, lithological and hydrogeological data that results to a complete and realistic aquifer model prior to drilling that can lead to reduction of drilling failure and to solve environmental issues alluvial areas and coastal areas in particular. The combined study of electrical logging with lithological variation is in fair correlation with chemical quality of formation water. From the study, it is possible to integrate geophysical data to define salinity, thickness of various granular zones forming the aquifer and the intervening clay layers. The establishment of hydro stratigraphy and aquifer groups along with its characteristics in these alluvial parts of the Kasai-Suvarnarekha basin will help minimize the risk related to resource availability, deliverability, impact on the environment and conflict with the stakeholders. In turn, efficient water wells design will further reduce the operational issues, drilling, and lower the risk of saline water up coning. Detailed mapping in GIS will help policy makers to minimize risk in water resource planning. This study is meant to develop a robust multilayer hydro stratigraphic model prior to groundwater modeling experiment which is an important step in the overall process that leads to understanding a ground system. The findings of present study will help national, local policy makers and various water user agencies in planning and management of water resources.

Keywords: *Grey clay, aquifer groups, marker clay, up coning, Kasai-Suvarnarekha*

ADDRESSING GROUNDWATER DEPLETION IN KOLKATA, INDIA: SUSTAINABLE STRATEGIES FOR URBAN GROUNDWATER MANAGEMENT

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Groundwater is a vital resource for sustaining life, supporting economic development, and meeting the urban water demands of Kolkata. However, rapid urbanization, population growth, and unregulated groundwater extraction have led to significant challenges including declining groundwater levels, land subsidence, water quality degradation, and loss of natural recharge zones. These issues are further exacerbated by climate change, which impacts recharge rates, increases evapotranspiration, and poses risks of saltwater intrusion in coastal areas. This research aims to develop sustainable and climate-resilient strategies for groundwater management in Kolkata. The primary objectives include assessing the spatial and temporal changes in groundwater levels, analyzing the effects of urbanization on groundwater resources. Additionally, the study proposes effective strategies for sustainable groundwater usage and recommends policies to regulate extraction in critical zones, protect recharge areas, and integrate blue-green infrastructure into urban planning frameworks.

The study adopts a macro-level approach to provide comprehensive insights into groundwater challenges across the Kolkata Municipal Corporation (KMC) area. The macro-level study spans all 144 wards of KMC, utilizing secondary data sources such as groundwater monitoring well records, borewell data, and land use maps to evaluate overall extraction rates, impacts on the piezometric surface, and critical zones of depletion. Cluster analysis is applied to group the wards based on groundwater challenges. Secondary data is used to evaluate overall extraction rates and the impact on the piezometric surface, while primary data is collected through field surveys, stakeholder interviews, and observations to understand groundwater usage patterns, local impacts, and the feasibility of proposed interventions. Remote sensing and GIS are employed for spatial analysis, including mapping groundwater extraction patterns, recharge zones, identifying critical areas, and the impacts of urban land use on groundwater resources. Key techniques used include: (1) Multi-Criteria Decision-Making (MCDM): To evaluate and rank areas based on their susceptibility to groundwater depletion, considering criteria such as land use, groundwater extraction rates, groundwater levels, population, and recharge potential. (2) Groundwater Water Resource Carrying Capacity (WRCC): To evaluate the sustainable limits of groundwater extraction in critical zones. This method provides insights into the balance between groundwater availability and urban water demand. (3) Cluster Analysis: To group wards with similar groundwater characteristics, enabling the identification of specific zones for targeted interventions and the prioritization of policy actions. This integrated methodology ensures a data-driven understanding of Kolkata's groundwater issues, providing a basis for formulating actionable policies aimed at groundwater regulation. The study's initial findings highlight several critical issues driving the depletion of groundwater in Kolkata.

Excessive reliance on groundwater accounts for nearly one-fourth of Kolkata's total water consumption, amounting to approximately 310,000 m^3 daily. A large portion of this water is drawn from private motorized wells and municipal sources, surpassing the sustainable recharge capacity of aquifers. Overextraction has resulted in land subsidence, with an average annual rate of 13.53 mm. This subsidence poses serious risks to urban infrastructure and increases vulnerability to flooding. Persistent cones of depression in the eastern, western, and northern parts of the city highlight severe pressure troughs. These zones show inadequate groundwater recovery, even after seasonal rainfall. Rapid urbanization, characterized by the expansion of impermeable surfaces and the encroachment on natural wetlands, has drastically reduced natural recharge zones. Critical areas facing severe depletion include locations such as Science City, Garden Reach, and Tollygunge. The analysis identifies critical zones of groundwater depletion and calls for immediate policy-driven interventions to regulate extraction and protect recharge areas. The study emphasizes prioritizing targeted policies in these zones, including implementing extraction limits, promoting the use of alternative water sources, and encouraging sustainable practices to reduce groundwater dependency. Proposed strategies include enforcing policies to protect recharge zones and integrating blue-green infrastructure to enhance recharge capacity. The research also highlights the need for a conjunctive use approach, recommending increased reliance on surface water sources, such as the Hooghly River, to alleviate groundwater stress. This research underscores the urgent need for sustainable groundwater management strategies to address the challenges posed by overextraction, urbanization, land subsidence, and the loss of natural recharge zones in Kolkata. Through comprehensive spatial analysis techniques, the study identifies high-priority zones severely affected by groundwater depletion and in need of immediate intervention. These findings contribute to developing a comprehensive framework that integrates policy interventions, artificial recharge strategies, and urban planning practices to ensure long-term water security. Implementing large-scale rainwater harvesting systems, protecting natural recharge zones, and promoting green infrastructure tailored to the city's dense urban fabric to support infiltration and groundwater recharge. Establishing stricter controls on groundwater abstraction through licensing and monitoring, particularly in critical and overexploited zones, to ensure sustainable usage. Optimizing the combined use of surface and groundwater resources to balance demand and ensure sustainable utilization. Raising awareness and involving local stakeholders in groundwater conservation efforts to ensure the success of proposed strategies and encourage sustainable practices. The implications of this study extend beyond Kolkata, offering replicable strategies for urban groundwater management in other rapidly urbanizing cities facing similar groundwater challenges. By integrating scientific analysis, innovative techniques, policy frameworks and participatory approaches, this research contributes to climate-resilient urban water planning and sustainable development.

Keywords: *Groundwater depletion, sustainable groundwater management, urban water security, groundwater regulation, recharge zones, MCDM, cluster analysis, Kolkata*

REGULATORY FRAMEWORK AND POLICY IMPLICATIONS FOR SUSTAINABLE GROUNDWATER MANAGEMENT THROUGH ADVANCED SCIENTIFIC INNOVATION FOR VIKSIT BHARAT@ 2047

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The study focuses on water management specifically regarding groundwater practice emerges as a critical necessity for India because its groundwater infrastructure remains the main water supply foundation that sustains diverse sector operations. Groundwater as a sub-surface water source is increasingly subject to severe damage from pollution and over-extraction which underscores the pressing necessity for improved management systems to support sustainable development. The journey to achieve Viksit Bharat@2047 in India demands a union of scientific innovation and effective legal protections when managing groundwater. This research first examines how technological solutions work for sustainable groundwater management, then establishes a legal structure to promote this practice. On track with the Viksit Bharat@2047 vision, India will solve its acute water resource dilemmas and bring an end to water scarcity. The research combines documentary analysis with survey data for studying India's groundwater management practices and legal structures. The analysis studied successful scientific innovation implementations through case studies across various territories to discover best practices. A thorough examination of international groundwater management policies was performed to help understand efficient global approaches. The analysis used stakeholder mapping techniques to determine how individual communities, policymakers, and scientific bodies participate in hydrological system and groundwater management operations. The analysis received additional depth through twenty-five semi-structured interviews performed with environmental scientists alongside water management experts and civil servants to assess policy and technological situations. India faces a dual challenge in groundwater management. The combination of agricultural water use inefficiency and inadequate water management strategies exists nationwide. The agricultural practice of flood irrigation combined with water overuse continues to deplete groundwater resources. Natural evolution in technology includes remote sensing alongside GIS, Artificial Intelligence (AI) and Machine Learning (ML) that create powerful possibilities. Water-related technologies facilitate precise measurement of water availability and assessment of climate change impacts and over-extraction effects. The combined wealth of data from these technologies enables informed decisions for groundwater recharging projects together with resource management strategies. The National Water Policy (2012) and the Groundwater Management and Regulation Bill need stronger scientific and technological foundations within their detailed implementation plans to establish effective governance.

The study explores essential function of technology emerges as a cornerstone in present-day groundwater management networks. An immediate requirement is the development of an online warning system which monitors groundwater in real-time. Levelled advancements in GIS applications and satellite data together with AI and ML create systems that enable

quantitative groundwater determinations while revealing hydrological deficits during procedure development for recharge operations. The effective implementation of these technologies requires an established legal framework which both provides mechanisms for user accountability and increases public understanding of conservation. India needs an exhaustive nationwide groundwater operational legislation which should specify maximum extraction measures and minimum replenishment conditions together with effective consequences for excessive consumption. Water tariffs should adopt pricing structures which accurately represent borehole well extraction costs in order to motivate water preservation activities.

Long-term success in groundwater management depends fundamentally on active community involvement. Local involvement with scientific techniques works together for sustainable groundwater management resulting in more efficient resource development. The integration of surface management strategies together with groundwater management strategies should become part of strategic policy frameworks especially in areas affected by water depletion. Water-resilient design measures which include rainwater collection systems and artificial groundwater enhancement must find integration during infrastructure and construction development. Low-cost environmental management solutions should be taught to local stakeholders to enforce sustainable water use norms. India needs to make responsible groundwater utilization a nationwide priority if the nation wants to reach its Viksit Bharat@2047 aims. Groundwater management gets elevated by advanced technologies which include artificial intelligence and machine learning and remote sensing capabilities for obtaining precise up-to-date data. The success of advanced technologies depends on a regulatory infrastructure with both monitored controls and local public partnership support. India needs to develop legal infrastructure which combines scientific or technological progress with local governance obligations to establish effective groundwater control systems. Collaboration between government entities scientists and groundwater users will create pathways for India to become water secure. Scientists and governments must work together as a team to achieve scientific groundwater management which will result in sustainable resource preservation for future needs. The success of enhanced groundwater management practices depends on three key elements: strong policies along with technological advancement and engaged community involvement. Sustainable water management science that supports Viksit Bharat@2047 will emerge through India's combined conservation efforts.

Keywords: *Groundwater, water management, Viksit Bharat, AI, ML*

INTERSTATE WATER DISPUTES IN INDIA AND THE ROLE OF GROUNDWATER

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Water is a vital resource for socio-economic development of any country, including India. However, in the Indian context, its unequal distribution in space and time is many a times responsible for disputes among various states over sharing of river waters. With over 20 major river basins shared among multiple states, interstate water disputes are a recurring feature of India's federal structure. The demands from many competing sectors like agriculture, industry, domestic use, and ecological needs aggravate these conflicts. To add to the conflict situation, the heavy use of groundwater, accounting for almost 85% of drinking water and 70% of irrigation demands, has deepened the issues of water management and dispute. India's legal and institutional structures, while strong in areas, have yet to effectively cope with the emergent difficulties of sharing water. On the one hand, the Interstate River Water Disputes Act 1956 offers a procedural mechanism that can be used for resolution; but tribunal processes are drawn out and taking it to court raises difficulties; again, this process ignores ground water. Furthermore, the continued over-exploitation of groundwater in the country which is linked to surface water flows exacerbate these conflicts and requires urgent attention.

India's vast and diverse geography, combined with its complex socio-political landscape, has led to several inter-state water disputes. These conflicts primarily arise from competing claims over shared river waters, often exacerbated by regional disparities in water availability, population pressure, agricultural demands and increasing variability in the patterns of climate. Interstate water disputes are further complicated because of the federal system of Indian Governance whereby the states are allowed to hold rights over the waters falling within their jurisdictions. Major disputes include the Kaveri River dispute among the States of Karnataka, Tamil Nadu, Kerala and Puducherry rooted in the colonial era agreements and competing irrigation demands; the Ravi-Beas conflict involving Punjab, Haryana, and Rajasthan, again rooted in the reorganization of Punjab in 1966 highlighting the complexities of river linking through the Sutlej Yamuna Link (SYL) canal; and the Mahanadi River dispute primarily involving Odisha and Chhattisgarh which gained prominence in recent years when Chhattisgarh initiated several dam constructions and irrigation projects upstream, which Odisha claimed, is negatively impacting its water supply and agricultural activities. Each of these disputes highlights the challenges of equitable water sharing in a federal system, where state interests can clash, leading to prolonged legal battles and political tensions.

Groundwater, often considered as a cushion in times of surface water scarcity, remains an un-acknowledged aspect of interstate water disputes. India's position as the world's biggest consumer of groundwater testifies to its significance but also to its vulnerability to over-withdrawal. Therefore, groundwater plays a pivotal, yet unexplored role in inter-state water conflicts as: (i) groundwater as a cushion/unseen reservoir, (ii) inequity in groundwater availability, (iii) surface-groundwater interactions and (iv) lack of regulation. Given that groundwater plays a crucial role in sustaining agriculture and also supplies drinking water, with its governance being fragmented, the issue arises in various challenges such as: (i) Inadequate data regarding the availability of groundwater, recharge rates, and groundwater extraction hampers the design of effective policies, (ii) lack of an overall framework for managing both the surface and groundwater resources promotes inefficiency, (iii) declining rainfall, increasing temperatures, prolonged droughts, and over-extraction of groundwater have resulted in further depletion of aquifers, decreasing the reliance on groundwater as a potential source, (iv) interstate water disputes resolution in India will require a complete paradigm shift towards Integrated Water Resources Management (IWRM) which takes into account the surface water and groundwater as an inter-connected system various key strategies like: (a) IWRM: Basin-level planning that includes surface and groundwater dynamics can be the basis of equitable sharing of resources, (bi) Groundwater Mapping and Monitoring: Technological application, like advanced remote sensing data and GIS tools, may assist in the identification of overexploited aquifers at a finer resolution and monitor the groundwater usage on a regular basis, (c) Legal Reforms: A complete national groundwater policy that would be integrated with the policy related to surface water is the need of the hour. Provisions regarding interstate aquifer sharing and cooperative management should be incorporated, (d) Water-Use Efficiency: Shifting from water-intensive crops, promoting micro-irrigation techniques, and improving water-use practices can reduce stress on both surface and groundwater, (e) Institutional Reforms: River basin organizations that include stakeholders from all riparian states can facilitate cooperation and dialogue, while tribunals should explicitly account for groundwater's role in disputes, and (f) Community Engagement: Participatory approaches to groundwater management can foster sustainable practices and equitable resource allocation at the grassroots level.

Interstate water disputes in India represent a pertinent example of the challenges of managing shared natural resources in a large, populous and multi-cultural country. Addressing these disputes requires robust legal frameworks, inter-state agreements, and cooperative management strategies that prioritize sustainable water use and conflict resolution. The inter dependence of surface and groundwater systems calls for an integrated strategy of water management. Groundwater is very often overlooked, but it is significant in both aggravating and potentially easing the tensions. For effective water distribution, sustainable resource usage, and long-term water security, the right mix of legal, institutional, technological, and community-driven solutions is necessary. Overcoming the challenges of groundwater governance, in conjunction with surface water disputes, can take India a step closer to a more cooperative and resilient water management framework. This paper highlights the need for an interdisciplinary and cooperative approach to the management of water resources, with a special focus on the often-neglected role of groundwater. Sustainability in the governance of water resources is critical not only for resolving disputes but also to support the broader developmental goals of India in times of increasing water stress.

Keywords: *Water disputes, groundwater, governance, IWRM, India*

GROUND WATER VISION 2047: ENSURING WATER SECURITY IN A CHANGING CLIMATE THROUGH SUSTAINABLE MANAGEMENT PRACTICE FOR INDIA

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India's hydrological diversity, spanning the Himalayan mountains, Indo-Ganga-Brahmaputra floodplains, western aeolian-alluvial deposits, basalt flows, and coastal regions, presents both opportunities and challenges for groundwater management. As the world's largest extractor of groundwater, India relies on this resource for over 60% of irrigation and 85% of drinking water needs. However, rampant overexploitation, aquifer depletion, and deteriorating water quality have severely strained groundwater reserves. Climate change-induced variability in rainfall patterns, prolonged droughts, and extreme weather events further exacerbate these challenges, demanding a comprehensive and sustainable approach to groundwater management. This study introduces "Groundwater Vision 2047" a strategic framework aimed at ensuring long-term groundwater sustainability in India by integrating a multidisciplinary approach encompassing hydrological assessments, advanced monitoring technologies, policy reforms, and community participation.

The methodology includes a comprehensive assessment of India's diverse hydrological regions, such as the Himalayan mountains, Indo-Gangetic plains, and coastal zones, to identify region-specific challenges like overexploitation, salinity intrusion, and geogenic contamination. The study highlights alarming trends in declining groundwater levels across India's plateaus. For instance, in the Deccan Plateau, groundwater levels have declined by 0.5–1 m/year due to over-extraction for agriculture and urbanization. Similarly, in the Malwa Plateau, levels have dropped by 0.8–1.2 m/year, with arid regions like Rajasthan experiencing severe depletion. The Chota Nagpur Plateau faces declines of 0.3–0.7 m/year, primarily due to mining activities and reduced recharge. These trends underscore the urgent need for region-specific interventions to address groundwater depletion.

A key component of the vision is Managed Aquifer Recharge (MAR) and urban water harvesting, which leverage artificial recharge structures such as check dams, farm ponds, and percolation tanks to enhance groundwater replenishment. Additionally, sustainable agricultural practices, including drip irrigation, crop diversification, and the adoption of genetically modified drought-resistant crops, are explored to optimize water usage efficiency. The increasing reliance on groundwater demands efficient water allocation mechanisms, where technological advancements play a crucial role. The integration of artificial intelligence (AI), the Internet of Things (IoT), and GIS facilitates real-time monitoring of groundwater levels, improved water allocation, and early warning systems for drought and flood management. Furthermore, tools like MODFLOW aid in identifying sustainable pumping rates and recharge zones, helping to mitigate groundwater depletion. The adoption of these innovative technologies can transform groundwater governance, ensuring efficient utilization and conservation of this vital resource.

Climate resilience is a central focus of the framework, addressing region-specific vulnerabilities. In flood-prone areas like Assam and Bihar, floodwater harvesting mitigates runoff and enhances recharge, while drought-prone regions like Rajasthan benefit from adaptive conservation strategies. Ecological restoration, including afforestation and wetland conservation, boosts natural recharge and reduces water loss. Ensuring groundwater quality requires stringent pollution control, such as zero liquid discharge policies and decentralized wastewater treatment. Adaptive wastewater management, including reuse for agriculture, reduces freshwater dependency. Public awareness campaigns promote sustainable water use and behavioral shifts toward responsible groundwater consumption. These measures collectively enhance groundwater sustainability, ensuring resilience against climate variability and securing water resources for future generations.

Policy and governance reforms are critical for effective groundwater management. Strengthening regulations, enforcing extraction permits, and promoting participatory governance empower local communities in decision-making. Public engagement through water management boards and advocacy fosters collective responsibility. India's annual freshwater withdrawals surged from 380 Bm^3 in 1975 to 647.5 Bm^3 in 2020**,** driven by population growth, urbanization, and infrastructure expansion. Groundwater depletion is severe in the Indo-Gangetic plains and hard rock regions, with declining water tables and contamination by arsenic, fluoride, and nitrates. Coastal zones face salinity intrusion, while arid regions suffer acute water scarcity. Addressing these issues requires stringent monitoring, policy reinforcement, and investment in water-saving technologies. MAR efficient irrigation, and technological advancements have improved sustainability. Micro-irrigation has cut agricultural water use by up to 50%, and community-led watershed management has restored degraded aquifers. Industries must adopt water audits, recycling, and stricter regulations to reduce groundwater stress. Transboundary water management is also essential to prevent over-extraction and conflicts in shared river basins.

"Groundwater Vision 2047" offers a roadmap balancing economic growth, ecological conservation, and social equity. By leveraging advanced technologies, enforcing policies, and fostering community participation, it aims to achieve water security and resilience against future uncertainties. The study highlights the need for an integrated, region-specific approach combining scientific advancements with traditional knowledge for sustainable groundwater management. Strengthening institutional capacity and legal frameworks is crucial to address emerging challenges. Future research should explore adaptive governance, economic incentives for sustainable water use, and innovative conservation technologies. Additionally, understanding the socio-economic impacts of groundwater depletion and developing community-driven models are essential for holistic sustainability. The framework integrates scientific research, policy interventions, and public engagement to tackle India's groundwater crisis. By addressing socio-economic, environmental, and governance aspects, it aims to foster a resilient, water-secure future. Urgent action, combining innovation, policy support, and community involvement, India can successfully navigate its water challenges and secure its groundwater resources for future generations.

Keywords: *Sustainable water management, rainfall patterns, aquifer recharge, climate resilience, groundwater governance*

MULTI-STAKEHOLDER LED INITIATIVE ON RIVER-WETLAND CO-MANAGEMENT IN THE ARIL RIVER BASIN, UTTAR PRADESH, INDIA

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Ramganga and its tributaries are aquifer fed river systems that are being subjected to loss of connectivity and degradation of river health (flows, water quality, biodiversity) due to over-abstraction of groundwater, diversion of surface water, unsustainable agriculture practices, pollution, land use change), encroachment etc. To improve river health, maintaining its 3-dimensional connectivity viz lateral (floodplain), Longitudinal (Upstream to downstream) and vertical (river-groundwater) connectivity is essential to maintain. Wetlands are crucial in supporting base flows in the river system through groundwater replenishment apart from providing a myriad of ecosystem services to communities and biodiversity. To address some of these issues, WWF-India had adopted a unique approach of river-wetland co-management to demonstrate rejuvenation of an aquifer fed and degraded river Aril (right bank tributary of Ramganga river) through wetland restoration, emphasizing multi-stakeholder engagement.

Situational analysis of Ramganga basin and its tributaries were carried out by generating several layers of information including landuse changes, groundwater scenario, mapping of influent and effluent streams etc. were developed. WWF-India along with its technical partners, IIT-Kanpur, mapped all the wetlands (>2.5 ha) in the Ramganga basin and assessed their degradation status overs last 3 decades and analysed the connectivity with their catchments. Tributary catchments of Ramganga basin were scanned and Aril River basin (a right bank tributary) was selected to showcase river-wetland co-management work based on its degraded catchment, groundwater scenario and status of wetlands. Spatio-temporal mapping of Aril basin indicated that about 60% of wetlands were in a degraded state. Based on the wetland's status and connectivity to river floodplains, 20 plus wetlands were field surveyed to collect baseline information which indicated that there are several major threats to the wetlands including excess weed growth, siltation, choked inlets/outlets, sewage, fragmentation, intensive chemical usage in agriculture LULC changes, to ownerships. Using a prioritization matrix three wetlands were selected viz. Khangawa Shyam (10.6 hectares (ha), Lilaur Lake (42 ha), Bahoda Kheda (7.42 ha) in Bareilly district. Detailed scoping surveys were carried out for these wetlands and baseline data on connectivity, inlet/outlets, water quality, invasives, biodiversity, groundwater level etc were collected. Individual wetland restoration plan was developed for all four wetlands.

A multi-stakeholder-led collective action approach was adopted from baseline data collection to implementation and monitoring where the District Administration (Bareilly), various line departments (Revenue, Irrigation and Water Resource Department, Forest Department, Rural development etc), District Ganga Committee, Bareilly (U.P.), riparian community, farmers and WWF-India contributed to improve the ecological health of river through river-wetland co-management. Over 500 farmers and community members across five villages were enrolled as Aril River Mitras or friends of river (volunteer network of citizens) trained in various aspects of conservation including wetland health monitoring, better management practices in agriculture, generating organic inputs and several restoration activities

The conservation and restoration efforts involved a range of activities, including community mobilization, technical support, training, capacity building, and physical restoration measures such as channel rehabilitation, de-weeding, desilting, waste to compost etc. Synergies were established with government schemes like MNREGA to leverage resources and accelerate restoration. The collective action approach yielded significant positive impacts with significant improvement in hydrological health of wetlands, river and enhanced resilience of riparian communities. Post restoration, the three wetlands received additional inflows of 2.7 billion litres of additional water between 2022-2024 as compared to baseline condition. This not only improved the wetland health and local water security but also rejuvenated the Aril River. Aril river, through a connected outlet channel from Khangawa Shyam wetland was rejuvenated by over 200 million litres of water. The increased water availability in wetlands led to an increase in groundwater levels by 4-5 feet in vicinity of wetlands thereby improving aquifer health and water security for communities

To improve wetland health and promote organic farming in the wetland zone of influence, 2500 quintals of wet weed were removed and turned into 700 quintals of compost which is being used by farmers in their crops. Apart from this 500 plus farmers were trained on the preparation and adoption of biofertilizers and biopesticides (Amrit Paani and Amrit Khaad) and follow better management practices in agriculture through customized Package of Practices (PoP). Farmers reported an increase in the length of the wheat spike, improved plant health, 20-25% reduction in water requirement, and substantial reduction in chemical application, through the adoption of PoP. Synergies with government schemes like MNREGA were built and through leveraging funds, 8 new inlets were created and 4 inlet channels were rehabilitated which brought more surface water inflows into wetlands. WWF-India provided the technical and on ground research and monitoring support. The enhanced flows and removal of weeds in specific wetlands resulted in improved concentration of dissolve oxygen which increased by 50-100%. (from 4 mg/l to 6-8 mg/l). The Improvement in wetland health provided conducive habitats for aquatic species and avian fauna.

All wetlands are ecologically and hydrologically important for river basin health. This pilot initiative successfully demonstrated the concept of river-wetland co-management and how wetlands can play crucial role in rejuvenating rivers and improving groundwater levels to improve the baseflows. There are about 754 wetlands in Ramganga basin (>2.5 ha area) and 97 plus wetlands in Aril basin, 60 % of which are in degraded state. Restoration of these wetlands through similar approach and collective action will not only help improving 3-dimensional connectivity in rivers-wetlands but also enhance resilience of riparian community and provide conducive habitats for dependent biodiversity.

Keywords: *Wetland restoration, sustainable agriculture, groundwater recharge, biodiversity conservation, Ramganga River Basin, Aril River, river rejuvenation, wetland hydrology*

COMMUNITY BASED RESUSCITATION OF MINOR WATERWAYS IN UPPER GBM DELTA: CASE OF BURI GANGA, WEST BENGAL, INDIA

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In the Upper Ganga-Brahmaputra-Meghna (GBM) Delta, Minor Inland Waterways (MIW) form principal sources for groundwater-dependent ecosystems (GDEs). These GDEs are under increasing pressure from Anthropocene actions. The actions are modifying the temporal patterns of the groundwater levels in the area. They are also hampering the essential ecosystem services such as providing freshwater supply for fishing and agriculture, protection against urban flooding and arsenic contamination, and sustaining aesthetic, cultural, spiritual and educational values of the MIWs. The study tries to understand why few MIWs could be successfully resuscitated while others could not. At the same time, it tries to understand MIW's importance on local socio-economic, cultural and environmental condition and vice versa. To bridge this gap, the current study tries to examine one such successful example of resuscitation of an MIW named Buri Ganga, located at Chakdaha, West Bengal. The study argues that MIWs are extremely important for local socio-economic, cultural and environmental conditions. As it focuses on the interplay between context and actors to explain the outcome, it starts from a critical realist ontology. It assumes that context is complex and actors only partially influence the outcome, but their decisions reproduce or transform the context. It also argues that actions done by actors are governed by their past beliefs and present pressures. The study tries to comprehend the process of community-based resuscitation through above-mentioned ideas. At the same time, to understand the impact of resuscitation of a MIW, the study tests Elinor Ostrom's theory on environmental commons governance (ECG). According to Ostrom, ECG is easier to achieve if five prerequisite conditions are met. These conditions are if a) resources are monitored easily, b) there are moderate changes in resources, c) dense social networks are present d) outsiders can be easily excluded and e) users support the monitoring of resource. The study tries to understand, to what extent these conditions changed after the MIW was resuscitated. The study adopts mixed-method research that consists of a combination of qualitative (process tracing and anthropology) and qualitative research (interview) methods. The main rationale for using mixed-method is that it provides complementary answers to the question of governance challenges. The study uses case study method as it allows to work with small units and large variables. The five prerequisite conditions are operationalized and questionnaire are formed. The qualitative data was gathered via surveying residents living in appurtenant urban, peri-urban and rural areas. The qualitative data is collected via interviews done in a semi-structured way to allow wide range of topics to be discussed. This also helped in deepening the understanding of the outcomes from the quantitative data analysis. Finally, both data were triangulated by using process tracing and document analysis.

Results indicate that the process of community-based resuscitation of a MIW involves multiple streams like problem streams, solution stream, political stream, choice stream and their temporal intensity. These streams create the several opportune moments in the process. These moments snowball and move forward towards certain directions, which in turn develops into positive outcomes. Results also indicate that land records department, irrigation department, water resource department, fisheries department, district development committee

and district advisory committee for river, and Kolkata Port Trust are connected to Buri Ganga. However, institutional monitoring is absent. People especially whose livelihood are dependent on the river, monitor the day-to-day changes on the river. Systematic monitoring over time by CBOs helped in its successful rejuvenation. Buri Ganga, is relatively free from pressure of urbanization and legacy intervention. There is also distinct change in the livelihood opportunities due to influx of freshwater in the MIW. Current study finds that due to increasing education, past association with the MIW and support from local government is helping in increasing the social capital in the area. However, there is non-participation by the common people and therapy by the local government. It is found that, extent of social capital is very high in Buri Ganga. Qualitative results show that continuous monitoring and campaign for twenty years by CBOs, inclusion of stake-holders (fishermen and jute farmers) in the decision-making process, support from non-stakeholders, triggering of decision-making process via protest, and snowballing of decision-making across the entire stretch of MIW helped in successful rejuvenation of Buri Ganga. At the same time, recent intervention by irrigation department (in July 2023) finally resulted in successful rejuvenation of the MIW. This shows that presence and action of outsider is extremely important for ECG. Finally, the study shows that rising level of education, growing environment awareness, increasing public engagement, and political will are increasing for both the MIW. However, loss of association with the river, organizational rigidity, lack of technical financial capacity, lack of knowledge of rights and environmental laws, and pauperization are negatively affecting the same.

The study finds that natural resources are often too big with different biophysical conditions. These varying conditions forge different levels of association with the user groups. Also, the occupation of the user group plays significant role on the association with the natural resource. Heterogeneity of users makes ECG quite challenging. Hence, for successful rejuvenation of MIW, mapping of stakeholder, their level of awareness, understanding, association and dependency on MIW is important. As current research suggests that user support is highly dependent on occupation, social strata and past association with resource, it can be said that tailormade strategic plans targeted at specific communities/ stakeholders should be made for creating user support. The study also finds that MIWs are exploited systematically over a long time, but the effect was not significant due to fewer users. Since 2000, with sudden population explosion, the effect has suddenly become prominent. Therefore, MIWs should be researched in their own rights. Most of the MIWs are situated in fast growing peri-urban areas, hence they contribute to the local socio-economic, cultural and environmental conditions. At the same time, MIWs are often used as drainage channel. Therefore, their rejuvenation is necessary. For the successful rejuvenation, along with continuous thrust factor, continuous exposure, triggering and gaining momentum plays a major role in building social capital. This can be achieved by creating multi-stakeholder platforms, participatory workshops, evaluation, feedback loops, and incremental improvements based on feedback. Finally, according to the study, action of outsiders is extremely important for successful rejuvenation. A milieu of actor-institution integration in the form of public-CBO-private can result in very strong forward-looking decisions. This can be achieved by building rapport with local government organizations, updating them about the situation of MIWs, and finding legal grounds for the rejuvenation of MIWs.

Keywords: *Upper GBM Delta, minor inland waterway, community-based initiative*

Theme 10

POLICY, REGULATION AND GOVERNANCE FOR GROUNDWATER MANAGEMENT

Theme 11

APPLICATION OF AI, ML, IoT, CLOUD COMPUTING AND OTHER ADVANCED TECHNIQUES IN GROUNDWATER

COMPLEXITY AND CONNECTIVITY IN GROUNDWATER SYSTEMS: ROLE OF CHAOS THEORY AND COMPLEX NETWORK THEORY

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Groundwater constitutes more than a quarter of the world's available freshwater resources. Over the past few decades, population growth, improved living standards, diminishing per capita availability of surface water of required quality, and advancements in technology have, in one way or another, significantly increased the exploitation of groundwater resources. It is important to note that groundwater serves as the only reliable source of safe drinking water and domestic supply in many countries and is also a primary or sole water source for irrigation in many regions. As a result, there are already serious concerns about the exploitation and sustainability of groundwater resources. Climate change and environmental degradation are expected to exacerbate this problem in future. Ensuring sustainable planning and management of groundwater resources, including conjunctive use, is vital for our future water, food, and energy security. To achieve this, a thorough understanding of groundwater flow and transport dynamics is one of the essential requirements.

Over the past several decades, a wide range of methodologies and mathematical models have been developed to study groundwater flow and transport. Despite significant advancements in such theoretical developments and their practical applications, many challenges in groundwater modelling still persist, especially in representing the complexity and connections in groundwater systems. In recent times, there have been some significant theoretical developments in the field of complex systems science, to study the complexity and connections in the systems. Among these, chaos theory and complex network theory have been gaining significant attention in hydroclimatic studies, including identification of the system complexity, prediction, catchment classification, propagation of droughts and other extreme hydroclimatic events, performance assessment of General Circulation Models (GCMs), and downscaling of outputs from GCMs. These theories offer unique perspectives on the complexity, connectivity, and nonlinearity of hydroclimatic systems. Despite their relevance and usefulness in hydro-climatology, these theories have not gained much attraction in studying groundwater systems, especially when compared with the volume of studies on surface water hydrologic systems.

The present study explores the application of chaos theory and complex network theory to examine the complexity and connectivity in groundwater systems. In particular, the study focuses on the temporal dynamics of groundwater levels at various locations across a region. For implementation, a groundwater level monitoring network of 200 wells across the United States has been considered. These 200 wells are spread across California, Arkansas, Nebraska, Idaho, and Texas, which collectively account for 46% of the total fresh groundwater withdrawals across all categories and have significant groundwater usage for irrigation. Daily groundwater level data observed over the period 2010–2020, obtained from the US Geological Survey (USGS), have been studied.

For studying the temporal dynamics of groundwater levels, each well has been considered as part of the network. Chaos theory-based methods have been coupled with complex network

theory concepts to construct the groundwater level network. In particular, phase-space reconstruction and the False Nearest Neighbor (FNN) algorithm, two popular chaos theory-based methods, have been employed. The concept of phase space reconstruction has been applied to transform the single-variable groundwater level time series into a multi-dimensional phase space using an embedding technique. The optimal embedding dimension for reconstruction has been determined using the FNN algorithm. During the network construction process, each reconstructed vector in the phase space is treated as a node, while the connections between these nodes, established based on a distance threshold for the reconstructed vectors, are defined as links.

Five complex networks-based measures—clustering coefficient, degree centrality, closeness centrality, betweenness centrality, and shortest path length—have been used to analyze the properties of the groundwater level network. The clustering coefficient measures the extent to which nodes in the network form tightly connected groups. In groundwater systems, high clustering indicates regions with similar hydrologic behavior, reflecting localized patterns of recharge or pumping. Degree centrality identifies the number of connections a node has, highlighting its influence within the network. Wells with high degree centrality are critical as they may impact groundwater flow across broader areas, making them essential for monitoring and management. Closeness centrality evaluates the efficiency of information transfer across the network. Wells with high closeness centrality represent areas where groundwater dynamics are highly interconnected. Betweenness centrality measures the extent to which a node acts as a bridge in the network. Wells with high betweenness centrality are pivotal for maintaining network connectivity and can play a crucial role in transferring water or contaminants. Finally, shortest path length quantifies the efficiency of a network in transmitting information between the nodes in the network, indicating how quickly changes, such as recharge or contamination, propagate through the wells.

The results obtained from the present analysis have been interpreted to provide significant insights into the characteristics of the groundwater levels. For example, the FNN dimensions obtained for the groundwater level time series from the 200 wells have been interpreted to describe the complexity of groundwater level dynamics. The results from the five complex networks-based measures have been used to identify the extent of temporal connections in groundwater level dynamics and type of network. These results further help in identifying the appropriate model for studying the groundwater monitoring network. Based on the results from the present study, the important role of coupling chaos theory and complex network theory in advancing future research on groundwater systems has also been emphasized.

Keywords: *Groundwater systems, nonlinearity, chaos theory, complex networks*

PRIORITIZATION OF SUB-WATERSHED OF PHALGU RIVER BASIN (PRB), MIDDLE GANGA PLAIN, INDIA USING INTEGRATED PCA AND MACHINE LEARNING APPROACH

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Watershed is defined as an area where the incoming rainwater is drained as surface runoff into a water body. Morphometric analysis of watershed aids in managing water crisis, soil erosion and prioritizing watershed with respect to its vulnerability. The traditional method of watershed prioritization includes activities like digitizing stream networks, contours in the toposheet, manually measuring stream length or extensive field survey. The manual survey, in particular, is labour intensive, time-consuming and expensive. Modern day tools like Remote sensing (RS), GIS and Machine learning (ML) have reduced the expenses and enhanced the accuracy in morphometric analysis for prioritizing the sub-watersheds for sustainable water and land resources management. This study highlights the effectiveness of the satellite data and machine learning approach to prioritize the sub-watersheds (SW) of the Phalgu river basin using morphometric parameters, PCA-WSA (Principal component analysis – weighted sum approach) and linear discriminant analysis (LDA).

The Phalgu River Basin which covers the major districts of Bihar and Jharkhand states in India. The Phalgu river basin is located between the geographic coordinates 24°00’00"N to 25°30'00"N latitude and 84°30’00" E and 85°30’00"E longitude and covers total area of around 6286 km^2. The river Falgu is a tributary of river Ganga and is a major river system of the south Bihar. The river originates in the Chotanagpur plateau by the confluence of the two rivers namely Lilajan (also known as Niranjan or Nilanjan) and Mohana at Bodhgaya. In this study, most of the morphometric parameters have been extracted and analyzed with the help of Shuttle Radar Topography Mission (SRTM-DEM) which have 30 m spatial resolution. The river basin elevation ranges from 46 to 762 m above mean sea level (amsl). The watershed has been delineated using the SRTM-DEM obtained from USGS Earth Explorer website along with utilization of Python toolkit in the Jupyter integrated development environment (IDE) for statistical and machine learning approaches (PCA and LDA). Sub-watersheds (SW1 to SW9) have been classified using the spatial analyst tool of ArcGIS 10.8.2. The morphometric parameters studied and classified to understand the river morphology are linear, relief and areal or shape parameters. A total 22 morphometric parameters have been selected and analysed. The rank of each parameter in each sub-watershed is determined after all morphometric values for individual sub-watersheds have been calculated. The linear and relief parameters are directly related to soil erosion. The sub-watershed with the highest value in these parameters is ranked 1st, and so on. On the other hand, soil erosion is indirectly related to shape parameters. The sub-watershed with the lowest value in relief parameter is ranked 1st, and so on. Following the determination of all ranks for each parameter in an individual sub-watershed, the compound parameter (C_p) value for the individual sub-watershed has been determined. When all of the ranks of SW1 are combined and divided by 22, C_p comes out to be 6. The same process has been performed for all the other sub-watersheds. Based on the C_p values, the sub-watersheds were classified as high, medium, and low.

The 22 morphometric parameters have been further reduced to 7 important components for analysis of rotated component matrix. The rotated component matrix shows that each component considers some most highly correlated parameters. The scree plot also includes the component loading matrix, which offers a visual representation of the loadings for each component. The top five components account for 95.1% of the overall variance in the actual information and are clearly considerable. After rotated component matrix, the primary morphometric parameters derived from PCA are lemniscate ratio, hypsometric integral, drainage texture, stream frequency, form factor, basin relief and circulatory ratio. Subsequently, these factors have been used to prioritize the 9 sub-watersheds of the Phalgu river watershed. Further, the WSA was used along with preliminary priority ranking obtained from PCA derived parameters, to obtain the compound factors to categorize them into three groups namely high, medium, and low.

LDA is a dimensionality reduction approach that keeps as much information as possible while reducing the number of dimensions or parameters in a dataset. LDA determines the eigen value/vector of the product of scatter matrices and it has been found that the first two eigen values corresponding to bifurcation ratio, and drainage texture have significant. The linear discriminants are then obtained by multiplying the standardized data with the eigen vector matrix. The two linear discriminants represent the 22 parameters data to prioritize the sub-watersheds. The important morphometric parameters derived from LDA are the bifurcation ratio and drainage texture. The LDA method produces two highly correlated parameters which have been ranked and prioritized as per the standard method.

The study has used three methods: morphometric analysis, PCA and LDA to prioritize Phalgu sub-watersheds. Using the morphometric analysis, higher priorities have been designated for SW5, SW8 and SW7 sub-watersheds. Using PCA, higher priorities have been assigned to SW8, SW7 and SW6 sub-watersheds. Utilizing LDA, higher priorities have been designated for SW7, SW8 and SW9 sub-watersheds. Thus, it has been observed that different methods may yield varying priority levels. However, when two out of the three methods consistently indicate a similar priority for a particular sub-watershed, it is reasonable to consider that priority. By identifying the overlapping results and considering the consistency among multiple methods, a reliable assessment of sub-watershed priority can be achieved. Accordingly, based on the results obtained in the study, sub-watersheds SW7 and SW8 have been determined to have a high priority as both SW7 and SW8 sub-watershed consistently exhibit similar high priorities across all the three distinct methods. SW3, SW5, SW6 and SW9 sub-watersheds have been assigned a moderate priority, while SW1, SW2 and SW4 sub-watersheds have been categorized as having low priorities. Thus, based on the prioritization analysis carried out under the study, sub-watersheds SW7 and SW8 are recommended for focused conservation efforts and effective land management practices. These high priority sub-watersheds are of utmost importance for decision makers and management authorities because it will aid in best conservation and land management practices against soil erosion and flooding. It has also been observed that because of the limited data availability, a deep learning model couldn't be implemented in the present study. As a way forward, there is a plan to expand the data collection efforts to include more micro-level watersheds, which will help in continuation of the classification study using deep learning models, which would further improve the results.

Keywords: *Watershed prioritization, morphometric parameters, PCA-WSA, LDA*

ADVANCING GROUNDWATER LEVEL PREDICTION USING PHYSICS-INFORMED NEURAL NETWORKS AND MACHINE LEARNING FOR TRANSIENT HEAD VARIATION

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Groundwater (GW) management is a critical component of sustainable water resources planning, particularly in regions facing water scarcity. Accurate prediction of GW head is essential for effective monitoring and management. Traditional methods often struggle with poor resolutions, necessitating advanced approaches. This study explores the potential of ML models, including XGBoost, Bayesian regression, and ANN, alongside a Physics-Informed Neural Network (PINN) to predict transient GW head variations. A hypothetical MODFLOW model was developed to simulate the dynamic behavior of GW heads under varying boundary conditions and pumping scenarios, providing a dataset for model training and evaluation. The study employed a conceptual MODFLOW model, designed to simulate transient GW head variations with 8 pumping wells. The boundary conditions were specified as fluxes, with an inflow of 20 m^3/d at the left boundary and an outflow of -30 m^3/d at the right. The generated test dataset covered a range of time steps to capture the dynamic nature of the system. The data was used to train three ML models: XGBoost, Bayesian regression, and ANN. Additionally, a PINN was trained, integrating the governing physical equations of groundwater flow into the neural network architecture to improve prediction accuracy. For the ML models, the objective was to minimize the mean squared error (MSE) during training, using a train-test split for model validation. The PINN was designed to incorporate the physical equation of transient groundwater flow. This equation was embedded into the PINN's loss function, combining data-based and physics-based components. The optimization process aimed to balance the physics-based loss with the data-fitting loss, making PINN particularly suitable for data-scarce conditions.

The performance of each model was evaluated using error metrics including Root Mean Square Error (RMSE), Coefficient of Determination (R^2), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). The results indicated that the PINN outperformed the traditional ML models in capturing the spatial and temporal variations of GW head. The performance evaluation of the different models based on RMSE, R^2, AIC, and BIC reveals significant variations in their predictive capabilities. The PINN achieved the lowest RMSE value and an R^2 indicating its superior accuracy in predicting groundwater head. Its ability to integrate physical laws into the learning process is further reflected in the lowest AIC and BIC values, which suggest a better balance between model complexity and fit. Among the ML models, XGBoost also demonstrated strong performance with an RMSE and an R^2, albeit slightly less effective than the PINN in terms of AIC and BIC. The ANN provided relatively good results with an RMSE and an R^2, though its AIC and BIC values were higher than those of the PINN and XGBoost. In contrast, the Bayesian Regressor struggled to achieve comparable accuracy, with a notably higher RMSE and a lower R^2, alongside higher AIC and BIC values. These results underscore the advantages of using PINN for capturing complex spatial and temporal variations in groundwater head, while XGBoost and ANN serve as competitive alternatives in less complex scenarios.

The study demonstrates that PINNs offer a highly effective and innovative approach for predicting transient groundwater head variations, significantly outperforming traditional ML models. PINNs leverage the integration of physical governing equations with data-driven learning, enabling them to achieve exceptional predictive accuracy while maintaining consistency with hydrogeological principles. This dual advantage addresses the limitations of purely data-driven models, particularly when dealing with sparse or unevenly distributed datasets, which are common in groundwater studies. The PINN model achieved the lowest RMSE and the highest R^2 indicating superior accuracy in capturing both spatial heterogeneities and temporal dynamics of groundwater heads. Its superior performance is further validated through model selection criteria such as the AIC and the BIC. These results reflect an optimal balance between model complexity and goodness-of-fit, confirming the robustness of the PINN approach in complex groundwater systems. Comparatively, XGBoost also performed well, achieving a competitive R^2 of 0.9999. However, its slightly higher RMSE and AIC suggest that while XGBoost excels in predictive accuracy, it may not fully capture the non-linear and transient variations inherent in groundwater flow dynamics as effectively as PINNs. This limitation arises from XGBoost's reliance on statistical learning alone, which lacks the physical constraints embedded in the PINN framework. The ANN provided reasonable predictive accuracy but lagged in model efficiency and stability, likely due to its dependency on large training datasets and the absence of physical constraints. Similarly, the Bayesian Regressor struggled to capture the complex variations of groundwater heads, reflected in its higher error metrics and suboptimal AIC and BIC values, indicating poorer fit and higher model complexity. These findings underscore the transformative potential of PINNs for groundwater modeling, particularly in regions with limited or unreliable observational data. By embedding physical laws within the learning process, PINNs not only reduce data dependency but also ensure physically realistic outputs, making them highly applicable for hydrogeological systems with varying spatial and temporal complexities. Moreover, the ability of PINNs to integrate observed and simulated data makes them a powerful tool for reducing uncertainties in groundwater head predictions under changing hydrological or anthropogenic stress conditions. From a water resource management perspective, the accuracy and reliability of PINN-based predictions can significantly enhance decision-making processes. For instance, more precise estimations of transient groundwater head variations allow water managers to design optimal pumping strategies, identify critical recharge zones, and develop sustainable groundwater extraction policies. In data-scarce regions, where traditional models often fail due to insufficient data, PINNs can provide reliable insights, enabling proactive management to mitigate groundwater depletion and ensure long-term resource sustainability. The future research directions should focus on scalability and generalizability of PINNs across diverse hydrogeological settings, including heterogeneous aquifers, karst systems & regions with strong river-aquifer interactions. Additionally, coupling PINNs with real-time data acquisition systems, such as IoT-based sensors, can further enhance predictive capabilities by integrating live observational data into the learning process. This would facilitate the development of dynamic groundwater management frameworks, adaptable to changing climatic & anthropogenic conditions, thereby ensuring the sustainable use and resilience of groundwater resources.

Keywords: *Groundwater modeling, physics-informed neural networks, machine learning*

GROUNDWATER POTENTIAL ZONES MAPPING USING ARTIFICIAL INTELLIGENCE TECHNIQUES FOR SURAT DISTRICT, INDIA

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Groundwater is a vital component of the hydrologic cycle and its depletion rate is the serious concern. Monitoring and controlling groundwater are crucial in many regions, requires advanced technology and methods. Global population expansion, urbanization, industrialization, and agricultural operations have resulted in an increase in groundwater consumption. Approximately half of India's total water requirements are met by the groundwater used in agriculture. About 60% of the water utilized for irrigation is extracted from groundwater to meet the requirements. The groundwater level has been declining in most parts of India in recent decades due to population growth at an alarming rate and subsequent significantly higher extraction rate from the groundwater than recharging rate. For the sustainable use of groundwater water resources, groundwater management is essential. The Surat district relies heavily on agriculture, which has led to the extraction of massive amounts of groundwater for drinking and irrigation. There are 35 monitoring stations in the district. The depth to groundwater level in the district is between 0 and 31.5 m. A water level of 5 m to 10 m below ground level covers the central area of the district. Factors related to topography, hydrology, geology, and atmosphere affect the availability and movement of groundwater. Geographic information systems (GIS) and Remote sensing (RS) applications including frequency ratio, multi-criteria decision analysis, weight of evidence, and analytical hierarchy processing, have been used in numerous studies for groundwater potential mapping. However, the efficiency of the groundwater potential evaluation under these studies was insufficiently precise and was subjective because the models used in these researches are based on conventional weighted techniques or expert opinion. Using the Analytical Hierarchy Process, weights are often assigned manually. The results of past studies show that artificial intelligence (AI) techniques integrating with RS and GIS for groundwater potential zone mapping are faster and more accurate than traditional multi-criteria decision analysis and analytical hierarchy processing techniques. The primary goal of this study is to create groundwater potential maps for the Surat area of India applying AI techniques such as support vector machine (SVM) and boosted regression tree (BRT). Surat district situating between 20°30’: 21°35’N and 72°35’:74°20’ E has a total geographical area of 4,414 km2. The district is located in the south of the Gujarat state. It is bounded by Bharuch district in the north, the Arabian sea in the west, the Tapi district in the east and the Valsad district in the south. Groundwater level data were obtained from Central Groundwater Board (CGWB) and Rainfall data were procured from the India Meteorological Department (IMD) for May, August and November, (pre-monsoon, peak monsoon, and post-monsoon respectively) for the year 2023. Thematic layers of the groundwater potential determining factors were created using Arc GIS software after gathering information regarding the groundwater potential determining factors, including rainfall, slope, elevation, aspect, topographic wetness index, and distance from streams. BRT is one of the most popular methods for improving a single model's performance and prediction accuracy. It can fit numerous models and combine them for prediction. The SVM model employs kernel functions to identify a hyperplane in an infinite-dimensional space that optimizes the distance between datasets using data pattern and regression recognition. In this study, predication of groundwater potential maps has been done by the cell analysis of thematic maps. The observed groundwater potential maps, which were produced using a spatial interpolation approach such as the inverse distance weighted technique, were used to validate the predicted groundwater potential maps. The resilience and accuracy of the groundwater potential maps were assessed using performance assessment measures such as root mean square error (RMSE), coefficient of determination (R2) and mean square error (MSE). The equal break categorization system was used to divide groundwater potential maps into five categories. Predicted groundwater potential zone mappings showed that the SVM model was superior for pre-monsoon with performance evaluation measures of 0.57, 0.32 and 0.97 for RMSE, MSE and R2 respectively and for peak-monsoon with the performance evaluation measures of 0.42, 0.17 and 0.93 for RMSE, MSE and R2 and respectively. The BRT model was superior for post-monsoon with performance evaluation measures of 0.57, 0.32 and 0.94 for RMSE, MSE and R2 respectively. The study concludes that the developed SVM and BRT models produce good predictions of groundwater potential zone mappings. The study findings indicate that, for the prediction of groundwater potential zone mappings, the SVM model performs better for pre-monsoon and peak-monsoon months while the BRT model performs better for post-monsoon months.

Keywords: *Artificial intelligence techniques, groundwater potential maps, SVM, BRT, remote sensing, GIS*

GROUNDWATER QUALITY PREDICTION USING MACHINE LEARNING

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Groundwater, an essential natural resource is highly susceptible to contamination from agricultural runoff, industrial waste, and natural geochemical processes. Monitoring and predicting groundwater quality is essential to avoid public health issues arising from waterborne contaminants such as heavy metals, harmful chemicals, and microbial agents. Recent advancements in machine learning have demonstrated the potential to leverage data-driven models for environmental monitoring, which could revolutionize traditional approaches by reducing reliance on costly laboratory-based testing. Our study aims to develop a machine learning model capable of predicting groundwater potability with high accuracy using readily available water quality indicators, thus, offering a valuable tool for resource management and decision-making.

The dataset for this study was obtained from an open-source platform, Kaggle, and comprises a total of 3,276 samples of groundwater quality measurements. Each sample includes nine physico-chemical parameters: pH, Hardness, Solids, Chloramines, Sulfate, Conductivity, Organic Carbon, Trihalomethanes, and Turbidity. These parameters provide an extensive profile of water chemistry and are commonly used indicators of water quality. The dataset also includes a target variable, *Potability*, which labels each sample as potable (drinkable) or non-potable based on these chemical attributes. Our approach began with data pre-processing to prepare the dataset for analysis and modelling. One key challenge was handling missing values, particularly in parameters such as pH and Sulfate. We addressed this issue by using statistical imputation techniques to estimate missing values based on the distribution of existing data, thereby preserving the dataset's integrity and improving model accuracy. Furthermore, to account for varying measurement scales across different features, we applied feature scaling, normalizing each parameter to ensure that no single attribute disproportionately influenced the model outcomes.

Exploratory data analysis (EDA) was conducted to gain insights into the data distribution and identify any patterns or correlations among features. Visualizations, including histograms and scatter plots, helped highlight the variations in parameters like pH and Turbidity, which play significant roles in determining water quality. Potability distribution was also assessed to ensure the data was not imbalanced, as this could affect model training. Statistical tests were applied to verify the significance of correlations between potability and the nine features, assisting in feature selection by narrowing down the attributes most influential in predicting groundwater quality.

After pre-processing and feature selection, we implemented a range of machine learning classifiers to evaluate their suitability for groundwater quality prediction. These included: (i) Random Forest Classifier: An ensemble learning method that operates by constructing multiple decision trees and combining their outputs for improved accuracy. Random Forest was selected for its robustness in handling noisy datasets and complex data relationships, (ii) Gradient Boosting Classifier: This boosting method sequentially builds models to correct errors from previous iterations, often resulting in high predictive performance but at the cost of longer training times, (iii) Decision Tree Classifier: Known for its interpretability, the

Decision Tree algorithm builds a model based on feature splits, which is particularly useful for identifying key decision points in potability determination, (iv) K-Nearest Neighbors (KNN): A simple, instance-based method that classifies samples based on the majority label among the nearest neighbors in feature space, and (v) Logistic Regression: Although not as powerful with nonlinear data, Logistic Regression was included as a baseline to evaluate performance against more complex algorithms.

Model training and evaluation were performed using a split of 80% for training and 20% for testing. Additionally, we applied grid search and cross-validation to optimize hyperparameters for each classifier, ensuring maximum model accuracy and generalizability. For model assessment, accuracy, precision, recall, and F1-score metrics were used, providing a comprehensive evaluation of each algorithm's performance. Among the classifiers, the Random Forest model achieved the highest predictive accuracy, with an accuracy score of approximately 65.10%, outperforming other models in both sensitivity and specificity for potability prediction. The ensemble nature of Random Forest allowed it to manage the high-dimensionality of the dataset effectively, particularly in distinguishing potable from non-potable samples based on nuanced feature interactions. The Gradient Boosting model also demonstrated competitive performance, albeit with a slightly lower accuracy than Random Forest. However, it exhibited excellent precision and recall scores, indicating a strong ability to generalize across diverse groundwater samples. On the other hand, the K-Nearest Neighbors model displayed lower accuracy, likely due to sensitivity to feature scaling and noise in the dataset. Logistic Regression and Decision Tree classifiers provided reasonable baseline results, yet they were less robust compared to the ensemble methods.

This study demonstrates that machine learning models, particularly ensemble methods such as Random Forest, can be effective tools for predicting groundwater quality. By leveraging key water quality indicators, these models can classify water samples as potable or non-potable with high accuracy, providing a valuable resource for environmental monitoring agencies. Our findings underscore the potential of data-driven approaches in groundwater quality assessment, enabling scalable and rapid evaluations that can complement traditional water quality testing. The implementation of machine learning for groundwater quality prediction has broader implications for water resource management, particularly in areas with limited access to laboratory testing facilities. Future work will involve expanding this model to include additional chemical and biological parameters, enhancing its predictive capabilities. Additionally, the model's application could be extended to real-time water quality monitoring systems, facilitating proactive responses to water contamination events.

Keywords: *Groundwater quality, machine learning, Random Forest, water potability, environmental monitoring*

INTEGRATING REMOTE SENSING, GIS, AND MACHINE LEARNING FOR GROUNDWATER LOGGING DETECTION AND FORECASTING IN AGRICULTURE-DOMINATED REGIONS

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Waterlogging is a persistent and critical environmental issue, especially in agrarian regions like Punjab, India. Excessive water accumulation in the soil leads to saturation and reduces oxygen availability for plant roots, which can result in crop damage and long-term soil degradation. In the Punjab state of India, the irrigation intensity and the region's seasonal rainfall make it particularly prone to waterlogging. Addressing this issue requires a robust monitoring and forecasting system supporting proactive water management strategies. Traditional ground-based methods, though valuable, have limitations in scalability and efficiency. Therefore, this study aims to evaluate the effectiveness of integrating Geographic Information Systems (GIS) and remote sensing techniques with advanced machine learning (ML) methods to monitor and forecast waterlogging in Punjab.

Combining GIS-based analysis and ML modelling, this study seeks to identify waterlogged regions and forecast future occurrences based on environmental and agricultural factors. Historical data from the Central Ground Water Board (CGWB) is used here, alongside satellite-derived data, to establish a reliable methodology. The study's main objectives are two-fold: first, to establish the accuracy of GIS-based techniques for waterlogging detection, and second, to develop and validate an ML-based predictive model that forecasts waterlogging under various environmental conditions. This framework is intended to serve as a tool for managing waterlogging risks, ensuring agricultural productivity, and guiding policy decisions in Punjab and similar regions facing waterlogging challenges. The primary dataset for observed waterlogged areas (from 2001 to 2015) for pre- and post-monsoon was obtained from CGWB records, which serve as a reliable ground truth reference. In addition to CGWB data, LANDSAT satellite imagery is utilized to analyze and quantify the waterlogging across Punjab. This dataset is complemented by environmental and agricultural factors, including precipitation records, groundwater abstraction, irrigation demands, soil types, and slope data for a more detailed understanding. Historical precipitation and temperature data were acquired from the Indian Meteorological Department (IMD; https://mausam.imd.gov.in/responsive/rainfallinformation_swd.php), while soil characteristics and slope data were obtained from the National Aeronautics and Space Administration Earthdata (https://www.earthdata.nasa.gov/). This analysis includes precipitation to understand its role in waterlogging, especially during monsoon heavy rainfall periods, when soil properties such as texture and infiltration rate can affect water retention. Irrigation demand data reflect agricultural practices that may enhance waterlogging. Integrating these data sources provides a comprehensive view, enabling the ML model to capture complex relationships between contributing factors and waterlogging.

The GIS analysis begins with standardizing LANDSAT images for consistent temporal and spatial analysis. Using spectral indices like the Normalized Difference Water Index (NDWI) and Modified NDWI (MNDWI), waterlogged regions are identified and delineated based on significant changes in water content. These indices clearly distinguish water bodies and saturated soil areas from surrounding dry land clearly, making them suitable for waterlogging detection. To ensure the robustness of this detection method, GIS-detected waterlogged areas were cross-validated with CGWB's data. Microwave satellite data is also analysed for temporal validation, especially from 2016 to 2024. Microwave data, known for penetrating vegetation and cloud cover, is beneficial for detecting waterlogged areas during the monsoon season or in densely vegetated regions. The resulting GIS-based waterlogging maps are compared with CGWB data to establish the method's accuracy, laying the foundation for further analyses.

To forecast waterlogging, we develop an ML model here using data from 2001 to 2014 sourced from CGWB. The model considered factors like precipitation, irrigation demand, soil type, and slope influencing water retention and drainage. Precipitation, especially during monsoon seasons, directly affects soil saturation. High irrigation demand in rice-growing areas can exacerbate waterlogging. Similarly, soil type for low-permeability soils and slope, which influences drainage, also play significant roles. By incorporating these factors, the model can effectively predict waterlogging risk. After preprocessing, including normalization and handling of missing values, we evaluated several ML algorithms for predictive accuracy, including Random Forests, Decision Trees, Gradient Boosting Machines, Extreme Gradient Boosting Machines and Long-Sort Term Memory. Model performances were assessed using metrics such as Root Mean Square Error (RMSE) and R^2 values. Feature importance analysis was also conducted to identify the most influential variables, providing insights into key drivers of waterlogging in the region.

After model validation, the best ML model was employed to forecast waterlogging patterns from 2015 to 2024, relying on projected values for environmental and agricultural factors. This prediction simulated various future scenarios and assessed the model's generalizability. Simultaneously, a GIS analysis using microwave satellite data was used to monitor waterlogging across Punjab independently for the same period. Comparing the GIS results with the ML predictions validates the robustness of the ML model in real-world applications, offering a dual-layered validation framework for future forecasting accuracy. The study yielded two key outputs: (1) a set of GIS-derived waterlogging maps from 2001 to 2024 and (2) an ML-based model capable of forecasting waterlogged regions. The remote sensing and GIS-based analysis revealed waterlog-prone areas, particularly in regions with high irrigation demands and certain soil types, confirming the feasibility of such waterlogging detection techniques. The cross-validation with CGWB data quantified the GIS method's accuracy, providing a basis for reliable spatial detection. The model performance metrics depicted the best model with corresponding accuracy in identifying waterlogged areas based on environmental predictors, particularly during monsoon seasons. The variables such as precipitation intensity and irrigation levels emerged as primary factors driving waterlogging. The forecasting capability of the model, validated by microwave data comparisons, provided an insightful prediction framework, enabling proactive water management strategies. By evaluating model performance against real-world data from 2016 to 2024, we established the model's reliability for practical forecasting applications.

This research established a comprehensive methodology combining remote sensing, GIS, and ML to detect and forecast waterlogging in Punjab, India. The GIS-based technique, using LANDSAT and microwave data, demonstrated a high spatial accuracy, validating its usage for large-scale waterlogging detection. The cross-validation with CGWB data underscored its reliability, and temporal validation using microwave data supported its suitability over the

years. The ML model was a robust predictive tool for waterlogging forecasting, with potential applications in various environmental and agricultural scenarios. The model provided a detailed understanding of the conditions under which waterlogging occurs by quantifying the influence of factors such as precipitation, irrigation, soil type, and slope. Its forecasting capability will allow policymakers and water resource managers to take preemptive actions, mitigating the impact of waterlogging on agriculture and the environment. In conclusion, combining GIS-based mapping with ML predictions offered a powerful and scalable solution for waterlogging management. The results from this study supported the utility of GIS in detecting waterlogged areas and affirmed the predictive power of ML models when integrated with comprehensive environmental data. While applied in Punjab, this framework is adaptable and could be implemented in other waterlogged regions facing similar challenges, offering a versatile and data-driven tool for sustainable water management and planning.

Keywords: *Groundwater, water logging, remote sensing, GIS, machine learning*

DATA-DRIVEN GROUNDWATER MANAGEMENT IN WATER STRESS AREA OF CENTRAL INDIA: A MACHINE LEARNING ALGORITHM BASED ANALYSIS OF AQUIFER DYNAMICS AND OVER-EXTRACTION RISKS USING HIGH FREQUENCY DATA

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This study investigates groundwater (GW) dynamics in the over-exploited Ratlam district of Madhya Pradesh, where GW extraction has reached a critical 130% as of the GWRE 2024 report. The region's reliance on groundwater for agriculture and limited surface water resources make it highly vulnerable to water scarcity, especially during the dry season when wells and hand pumps often dry up. Residents frequently resort to tanked water from distant areas and drill deep bore wells, sometimes reaching 363 m. The area's black cotton soil, highly suitable for agriculture, further drives groundwater demand. In addition, surface water from rivers is occasionally used for irrigation, but during the non-monsoon months, bore wells become essential. This study employs high-frequency data collected via Digital Water Level Recorders (DWLRs) installed in 14 strategically chosen wells. These DWLRs capturing water levels four times daily from 2023 to 2024, provided a comprehensive dataset for examining temporal and spatial variations in groundwater levels. Monthly rainfall data from the IMD was also paired with groundwater data to assess correlations between rainfall and GW levels. This is one of the first studies in central India to use such high-resolution, machine learning (ML)-enhanced methods, marking a significant contribution to sustainable GW management in a semi-arid region facing extreme extraction pressures.

The DWLR data was aggregated daily and averaged monthly to create structured time series data for each well, allowing for the assessment of both seasonal and short-term fluctuations in GW levels. Applying a rolling mean to the GW level data provided a clearer view of long-term trends by smoothing out short-term variability. This comparison between the rolling mean and the raw data helped us identify deviations, potentially indicating over-extraction or climate impacts, while enhancing trend clarity. The Augmented Dickey-Fuller (ADF) test was used to check stationarity in the data, distinguishing between seasonal fluctuations and persistent trends. Autocorrelation analysis was also conducted, revealing the time-dependent relationships within the GW levels, such as patterns driven by monsoon cycles and lagged recharge responses. Several analyses were performed to study the relationship between groundwater levels and rainfall. Scatter plots allowed for a visual inspection of linear and non-linear relationships, while heat maps provided an overview of rainfall-GW correlations across various wells and time periods. Cross-correlation analysis helped determine the lagged response of groundwater levels to rainfall, showing the time, it takes for rainfall events to impact the aquifer system in specific areas. Granger causality tests were applied to assess whether changes in rainfall could predict GW level fluctuations, helping to distinguish causative relationships from mere correlations. This method allowed us to identify wells where GW levels are highly sensitive to rainfall, providing insight into which areas are most vulnerable to GW depletion under changing rainfall patterns. Python programme was used to analyze the data, employing libraries such as Pandas for data processing, NumPy for

computations, Matplotlib and Seaborn for visualizations, and Statsmodels for advanced statistical testing. SciPy supported autocorrelation and other statistical analyses.

In Ratlam, the pattern of GW decline is notable, particularly in deeper wells used for irrigation. This pattern involves a sharp decrease in water levels after October, peaking in January, and then stabilizing at a deeper level. The average GW decline in January is on an average 0.039 m mbgl per day assessed from all wells. The maximum extraction is as high as 0.13 mbgl/day in some areas. Prolonged, intense pumping leads to depths of up to 38 mbgl. High GW fluctuations, ranging from less than 1 m to over 30 m annually, suggest a complex aquifer response influenced by seasonal rainfall, extraction rates, and soil type. The study found that deeper aquifers exhibit more pronounced GW level fluctuations, especially during winter cropping than the shallower piezometers. During January, for e.g., deeper wells experienced declines of up to 0.1 mbgl/day, compared to 0.0009 mbgl/day in shallower wells. This stark difference implies that agricultural extraction targets deeper aquifers, which face prolonged recovery times, thereby creating GW sustainability issues.

Spatial analysis revealed that recharge mainly occurs between August and September, few months after the monsoon onset, across all wells. Recharge rates were faster in certain wells but almost all wells showed prolonged periods of drawdown after recharge in monsoon due to agricultural use, especially in rural, agriculture-dominated areas. These areas displayed more pronounced declines relative to semi-urban areas where surface water supply decreases the groundwater demand. Our correlation analysis of GW levels and rainfall demonstrated that over 50% of wells had a strong positive correlation with rainfall, some wells show perfect correlation up to 0.9, indicating the region's reliance on rainfall for aquifer recharge. Cross-correlation analysis provided insight into delayed recharge response times, varying across wells and revealing that certain areas are more dependent on rainfall and hence, more susceptible to seasonal GW depletion. Spatial correlation analysis indicated that wells in certain zones showed synchronous GW level fluctuations, suggesting interconnected aquifer sections, while others exhibited isolated behaviour indicating localized depletion. These findings help in determining critical regions in Ratlam region where the aquifer system is either highly responsive to natural recharge or vulnerable to prolonged drawdowns.

The integration of ML techniques has enabled a comprehensive understanding of district Ratlam's aquifer dynamics, revealing intricate relationships between rainfall, GW extraction, and aquifer recharge. The study's high-frequency monitoring and data-centric analysis highlight critical trends and zones of fluctuation, essential for addressing GW management in semi-arid, water-stressed areas. Our analysis suggests that the aquifer's response to recharge is highly variable, with deeper confined aquifers showing slower recuperation rates, especially under heavy agricultural extraction. Given the district's reliance on rainfall, our findings stress the need for proactive water management strategies to mitigate extraction pressures and develop resilient GW systems. We have tried to identify high-risk zones based on extraction rates, recharge patterns, and also periods of high GW depletion. The high-resolution data coupled with ML-based analysis provides valuable insights into central India's groundwater dynamics, advancing the scientific understanding of aquifer behaviour in over-exploited regions. The approach is scalable, offering a framework for similar studies in regions facing GW depletion challenges, essential for sustainable resource management due to rising demands and climate uncertainties.

Keywords: *Over-extraction, groundwater, data-driven management, machine learning*

DEVELOPMENT OF USER INTERFACE FOR SUSTAINABLE GROUNDWATER MANAGEMENT BY INTEGRATING THE AI, ML, IOT, CLOUD COMPUTING AND OTHER ADVANCED TECHNIQUES

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Groundwater is a vital resource for billions of people worldwide, providing a significant portion of the freshwater used for drinking, agriculture, and industry. However, over-extraction, contamination, and the impacts of climate change have created an urgent need for more effective groundwater management. Traditional methods of managing groundwater are increasingly inadequate in addressing these challenges, necessitating the adoption of advanced technological solutions. Recent advancements in Artificial Intelligence (AI), Machine Learning (ML), the Internet of Things (IoT), Deep Learning (DL), Artificial Neural Networks (ANN), Fuzzy Logic Models, and Cloud Computing have opened new avenues for improving groundwater management. These technologies enable real-time monitoring, predictive analysis, and data-driven decision-making, offering significant potential to optimize groundwater use, detect contamination, and enhance sustainability. Despite the promise of these technologies, their full potential remains untapped due to fragmented systems and a lack of integration across platforms. The objective of this paper is to present and explore the significance of the Development of a User Interface for sustainable groundwater management by integrating AI, ML, IoT, Cloud Computing and other advanced techniques. By creating an intuitive platform, the research aims to enable stakeholders from farmers to policymakers to make data-driven decisions that enhance groundwater sustainability. The user interface will combine real-time data collection from IoT sensors, AI-driven predictive models, and Cloud Computing to process and analyze large datasets, allowing for better decision-making and resource management. By articulating this ideology, the paper seeks to provoke critical reflection and discussion, ultimately contributing to Sustainable Development Goals (SDGs).

The development of the user interface for sustainable groundwater management involved several key stages: system design, data integration, algorithm development, and user interface (UI) design. These stages were informed by existing literature, case studies, and expert input. The system should be designed to integrate multiple technologies, including IoT sensors for real-time groundwater monitoring, Cloud Computing for scalable data storage and processing, and AI/ML algorithms for predictive modeling and decision support. The architecture will include IoT-based groundwater sensors that measure parameters such as water levels, temperature, and water quality indicators (e.g., pH, turbidity). These sensors transmit data to a cloud platform, where the data is processed and analyzed using AI and ML models to forecast water availability and quality trends. In data integration and analysis, the system should be designed to integrate historical groundwater data, weather patterns, land usage data, and sensor data into a centralized Cloud database. The AI and ML algorithms, including regression models and neural networks, should be employed to analyze the data and predict future groundwater trends, identify potential contamination risks, and optimize resource management. In the User Interface (UI) design, the user interface should be developed to be accessible to a wide range of stakeholders, including water resource

managers/Engineers, farmers, and local governments. The UI should have features of interactive dashboards, real-time monitoring tools, trend analysis visualizations, and predictive analytics. Users can view current groundwater conditions, forecast trends, and receive alerts for potential issues (e.g., over-extraction or contamination).

In the testing and validation, the system should be tested using data from several regions with varying groundwater conditions. User feedback was collected to refine the UI and improve system functionality. Performance metrics such as system accuracy, response time, and user satisfaction should be evaluated. The data requirement is essentially consisting of groundwater sensor data mainly Real-time data from IoT sensors installed in boreholes and wells in different regions. Parameters include groundwater levels, temperature, electrical conductivity (EC), pH, and turbidity and historical groundwater data on past groundwater trends, including historical water levels and usage patterns, sourced from regional water management authorities and weather and climate data consisting of precipitation, temperature, and evaporation rates from meteorological sources, used to inform the system's predictive models. Finally, the geospatial data that includes geographic data on land use, population density, and water demand, is integrated into the Cloud system to provide context for groundwater management decisions. The development of the user interface for sustainable groundwater management should result in a functional prototype integrating IoT sensors, AI/ML-based predictive modeling, and Cloud data storage. Key results should include a) Real-time Monitoring: The system should capture accurate groundwater data, displayed via interactive maps and dashboards. Alerts were triggered when water levels or quality parameters (e.g., pH, turbidity) exceeded predefined limits. b) Predictive Modeling: AI and ML algorithms should accurately forecast groundwater trends (weekly, monthly, seasonal) based on historical and real-time data, identifying drivers of depletion and contamination, such as over-extraction and agricultural runoff. c) User Experience: Groundwater professionals should find the UI intuitive and actionable, enabling informed decision-making for water allocation and resource conservation. The integration of multiple technologies should improve data accessibility and interpretation. d) System Performance: Cloud-based architecture should provide scalable data storage and quick processing of large datasets, with fast response times for real-time monitoring and predictive analysis.

The development of a user interface integrating AI, ML, IoT, and Cloud Computing for sustainable groundwater management will be a successful approach to addressing the challenges of groundwater depletion and contamination. The system should demonstrate the ability to monitor groundwater resources in real time, predict future trends, and provide stakeholders with actionable insights to guide resource management decisions. This paper presents ideology by highlighting the potential of advanced technologies to transform groundwater management practices by developing a user interface. However, further studies are needed to refine the system's algorithms, enhance data accuracy, and explore additional features, such as decision-support tools and scenario modeling. Adopting such integrated systems can play a crucial role in ensuring the sustainable use of groundwater resources in the face of growing demand and environmental challenges. Future research should focus on expanding the system's applicability to different geographical regions, integrating additional data sources, and improving user customization features to meet the specific needs of various stakeholders.

Keywords: *Artificial intelligence, machine learning, IoT, deep learning*

REAL-TIME GROUNDWATER PREDICTION MODELS USING RNN AND LSTM TECHNIQUES

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Accurate real-time groundwater level predictions are essential for proactive water resource management, especially in regions facing acute water scarcity and heightened vulnerability under climate variability. Groundwater depletion and fluctuating recharge rates create urgent challenges for sustainable management, particularly in semi-arid regions like Madhya Pradesh. This state experiences varied geology, ranging from ancient Archean rocks to Deccan volcanic formations, which greatly influence its groundwater dynamics. State relies heavily on groundwater, and with over 1,600 observation wells monitored by the CGWB, data from this region provides a crucial foundation for understanding groundwater dyanamics. This study presents an AI-powered, real-time groundwater prediction model that incorporates advanced neural network architectures specifically, recurrent neural networks (RNN) combined with long short-term memory (LSTM) techniques. These architectures are well-suited to the sequential nature of groundwater data, allowing the model to provide high spatial and temporal resolution predictions. By synthesizing inputs from satellite-based observations, historical records from national databases, and localized monitoring stations, this model delivers accurate localized and real-time groundwater predictions. Our research focuses on three key challenges: (1) achieving model adaptability across diverse climatic and geological regions, (2) ensuring data accuracy through multi-source integration, and (3) improving spatial data interpretation in regions where observational data is limited. The model incorporates an error-correction mechanism and spatial data interpolation techniques, which are particularly beneficial for data-scarce areas. This integrated approach enhances the model's robustness and potential utility in groundwater management, especially in regions where conventional data may be sparse or inconsistent.

Groundwater serves as a primary source of drinking water and irrigation in many regions, yet its availability is increasingly compromised by climate-induced variability and over-extraction. The Madhya Pradesh exemplifies the challenges associated with groundwater management, given its geological complexity and regional disparities in recharge rates and extraction levels. From the Archean rocks in the northern and southeastern parts to Deccan Trap formations in the west, the geological diversity affects groundwater storage and movement. The India-WRIS provides extensive data on rainfall, soil characteristics, and other critical factors, which when integrated with satellite observations and CGWB well data allows for a comprehensive approach to groundwater prediction. However, traditional monitoring and management methods often lack the resolution and immediacy needed to respond effectively to these challenges. By leveraging AI-driven neural networks, this study aims to address these limitations and offer a predictive model adaptable to the diverse hydrogeological contexts found within State and beyond.

The methodology centers around a robust framework designed to incorporate and process multi-dimensional groundwater data. These include comprehensive data integration, model design and adaptive mechanisms to refine predictions over time. The architecture utilizes RNN-LSTM layers for processing time-series data effectively, enabling a nuanced approach to groundwater prediction. The model draws on multi-source data inputs. This data is enriched by satellite-based precipitation and terrestrial water storage data (e.g., GRACE) and historical groundwater records from national databases. Additional data on rainfall, temperature, and humidity from India WRIS allow the model to incorporate essential climatic factors impacting groundwater recharge and demand. The model's architecture is rooted in RNN, enhanced by LSTM layers that allow it to capture both short-term and long-term dependencies in groundwater data. RNN layers process sequential data effectively, while the LSTM component manages prolonged dependencies influenced by seasonal and annual climatic patterns. Backpropagation through time (BPTT) optimizes model weights, ensuring that each layer accurately learns from the historical groundwater data patterns. This design enables the model to accommodate cyclical fluctuations in groundwater levels and adapt to climatic changes. Recognizing that certain regions have limited observational data; the model employs an error-correction mechanism and spatial data interpolation. These mechanisms adjust predictions dynamically, compensating for data gaps by leveraging geological and hydrological data from nearby locations. For instance, in areas like the Deccan Traps, where data is scarce, spatial interpolation based on geological similarities improves prediction accuracy. The error-correction component continually refines model outputs, adapting over time to reduce prediction errors and enhance reliability, especially in data-limited settings. Multi-source integration is vital to the model's functionality, blending real-time data from satellite observations, well data, and climatic inputs to improve overall accuracy. A cloud-based processing system manages these data streams, ensuring continuous adaptability to environmental changes. By harmonizing data from diverse sources, the model captures groundwater level fluctuations in response to both local and broader climatic events, providing a realistic and timely representation of groundwater conditions across Madhya Pradesh's varied landscapes. The model's design allows for scalability and adaptability across regions with diverse geological features. This adaptability is tested within Madhya Pradesh's hydrogeological contexts, such as the hard rock regions of the north and alluvial plains in the central areas. By integrating parameters specific to local geology and climate, the model dynamically adjusts its calculations, enabling deployment across regions with differing groundwater behaviors. This scalability is crucial for extending the model's utility to other regions facing similar groundwater challenge.

The real-time groundwater prediction model developed in this study has critical implications for groundwater management and policy-making. By delivering localized, high-resolution predictions, this framework equips decision-makers with actionable insights to address regional groundwater stress proactively. In water-scarce regions like Madhya Pradesh, where demand often outpaces recharge, predictive insights can inform decisions on sustainable extraction limits, recharge initiatives, and water conservation strategies. Additionally, the model's capacity to identify high-risk extraction zones and potential recharge areas is invaluable for targeted interventions, such as implementing rainwater harvesting in vulnerable regions. As climate change intensifies hydrological variability, real-time prediction models provide the flexibility needed to adapt groundwater management practices to fluctuating conditions. This adaptability not only supports immediate decision-making but also contributes to long-term resource sustainability. By integrating AI-driven analysis with multi-source data, this model presents a scalable approach to groundwater management that can be applied in regions facing similar water security challenges globally.

Keywords: *Real-time groundwater prediction, RNN-LSTM models, AI, water management*

A HYBRID APPROACH TO MODELLING ETO AND GROUNDWATER RECHARGE

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This research focuses on developing a hybrid predictive model for estimating reference evapotranspiration (ETo) and understanding its relationship with groundwater levels using cloud computing and machine learning techniques. ETo is a critical component of the hydrological cycle and plays an important role in water resource management, irrigation practices, and climate adaptation strategies. The accurate estimation of ETo is crucial in cities, where it is influenced by several climatic factors such as temperature, humidity, wind speed, and solar radiation. This study seeks to address this challenge by leveraging hybrid machine learning models for improved ETo predictions, while using cloud-based data processing to handle large-scale computations and provide real-time predictions for surface and ground water management. The research relies on NASA Power's climate data as the primary source for estimating ETo. NASA's Power API provides global climate data, which includes key variables like temperature, humidity, wind speed, and solar radiation. These variables are essential for estimating ETo, particularly when using the Penman-Monteith equation. However, the traditional Penman-Monteith approach does not fully capture the complexities of urban climates, and hence, a hybrid machine learning approach is used to improve the accuracy of the predictions. The hybrid model combines the strengths of multiple machine learning algorithms to provide a more robust and accurate prediction of ETo under varying climatic conditions. This hybrid model is designed to handle non-linear relationships and adapt to the variable and complex nature of urban environments.

In this study, the hybrid prediction model integrates multiple machine learning algorithms to generate more reliable estimates of ETo. While basic machine learning models like Random Forest (RF) and Support Vector Machines (SVM) are effective in capturing non-linear relationships, the hybrid approach combines these algorithms with additional techniques to improve prediction accuracy and adaptability. The hybrid model's ability to combine different methods ensures better generalization across different urban environments with varying climates and urbanization levels. This approach is particularly useful when using climate data from NASA Power's API, which offers valuable global climate information but requires sophisticated models to account for the complexity of urban settings. The use of API-based data extraction is central to the methodology of this study. NASA Power's API provides accessible, from 1990s to near real-time climate data that can be used directly for calculating ETo. The API allows for easy retrieval of necessary climate variables, such as temperature, wind speed, humidity, and solar radiation, which are critical inputs for the hybrid model. Through an automated process, data for specific urban locations can be extracted directly from the cloud-based API, ensuring accurate and timely access to the most up-to-date climate information. This method eliminates the need for manual data collection, making the process more efficient and scalable. It also allows for dynamic data retrieval, which is essential for continuous monitoring of ETo and groundwater levels over time.

To process and analyse the large datasets generated from NASA Power's API, the research utilizes cloud computing platforms. These platforms enable the execution of complex calculations for ETo estimation and hybrid model predictions in a scalable and cost-effective manner. Cloud computing provides the computational power necessary to run the hybrid machine learning models without the limitations of local hardware resources. By leveraging cloud infrastructure, the study can process large volumes of climate data, perform real-time calculations, and deliver quick predictions. This cloud-based approach allows the model to be scalable, flexible, and adaptable to different urban locations, making it an efficient tool for urban water management and climate adaptation strategies. The study also explores the relationship between ETo and groundwater levels. Groundwater plays a significant role in urban water systems, and its levels are affected by multiple factors, including precipitation, soil characteristics, and evapotranspiration. As ETo increases, water is lost through evaporation and transpiration, which can reduce the amount of water available for groundwater recharge. Conversely, lower ETo can facilitate increased infiltration, promoting groundwater replenishment. By integrating groundwater data with the hybrid ETo model, this research aims to provide a better understanding of how variations in ETo influence groundwater recharge and water resources. The relationship between ETo and groundwater is dynamic and location-specific, making it crucial to use flexible, data-driven models for accurate predictions.

To evaluate the accuracy of the hybrid model, the study uses root mean square error (RMSE) and mean absolute error (MAE) metrics to quantify prediction accuracy. These metrics are used to compare the ETo estimates generated by the hybrid machine learning model with the values calculated using traditional methods, such as the Penman-Monteith equation. By validating the model with real-world data, the study aims to demonstrate the effectiveness of the hybrid approach in urban settings. Preliminary evaluations suggest that the hybrid model provides more accurate predictions compared to traditional methods, as it is better equipped to account for the non-linear interactions between climatic variables. This improved accuracy is particularly important for surface and ground water management, where precise ETo estimates are crucial for irrigation and groundwater conservation. While the results of the study are still under analysis, initial findings indicate that the hybrid machine learning model, when combined with cloud computing and API-based data extraction, significantly enhances the accuracy and flexibility of ETo predictions in urban areas. The integration of real-time climate data from NASA Power's API allows for continuous updates and predictions, making it a powerful tool for decision-makers involved in urban water resource management. The study also demonstrates the potential of cloud-based models for scaling predictions across diverse urban environments, offering a valuable tool for sustainable urban development. In conclusion, this research highlights the potential of using hybrid machine learning models combined with cloud computing to estimate ETo and analyse its impact on groundwater recharge. By leveraging NASA Power's climate data through API access, the study provides a scalable and flexible approach for estimating ETo in real-time, which is crucial for urban water management. This work represents a significant step toward using data-driven approaches for sustainable urban water resource management and climate adaptation.

Keywords: *Evapotranspiration, hybrid modelling, groundwater recharge, API, climate data*

COMPARATIVE PERFORMANCE ANALYSIS OF LINEAR REGRESSION, KNN, AND RANDOM FOREST FOR MODELING TOTAL DISSOLVED SOLIDS IN GROUNDWATER: A CASE STUDY

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Total Dissolved Solids (TDS) refers to the whole concentration of dissolved substances in groundwater, encompassing minerals, salts, and organic material. The amounts of Total Dissolved Solids significantly influence water quality, contingent upon its use in residential, agricultural, and industrial contexts. Excessively high or low TDS negatively impacts the potability of drinking water, irrigation practices, and aquatic ecosystems. Therefore, it necessitates the implementation of suitable monitoring and management strategies for groundwater resources. Conventional TDS measurement methods are laborious and costly. Consequently, the advancement of more efficient methodologies is imperative. Machine learning model-based techniques offer a promising approach to forecasting groundwater quality indicators, including TDS, by including several chemical and physical water characteristics. The performance of three different machine-learning algorithms: Linear Regression, K-Nearest Neighbours (KNN), and Random Forest, is compared in the context of modelling TDS levels in groundwater. All these models have pros and cons related to complexity, interpretation, and effectiveness of forecasts. Linear Regression is one of the most elementary statistical techniques that assumes a relationship to be linear between variables and the target. Hence, it is both easy and powerful. KNN is an instance-based non-parametric learner that is versatile and capable of fitting any kind of non-linear interactions. It is, however, sensitive to data scaling. Random Forest, on the other hand, is an ensemble learning technique using several decision trees to enhance predictive accuracy and prevent overfitting. This study seeks to identify which model most accurately predicts total dissolved solids in groundwater, hence enhancing water quality management.

Data was collected from 60 groundwater sample locations for pre-monsoon season for this investigation. Each sample provides a collection of water quality characteristics, including pH, Salinity, Electrical Conductivity (EC), Total Alkalinity (TA), Total Hardness (TH), Sodium, Potassium, Magnesium, Calcium, Chloride, Nitrate, Sulphate and Fluoride. Prior to the implementation of machine learning models, the dataset underwent multiple preprocessing stages. All missing values were replaced with the median value of each parameter to preserve data integrity. All input variables were standardized to a uniform scale to ensure that all features contribute equally to the model, particularly for algorithms such as KNN, which depend on distance metrics. Feature selection approaches were employed to determine the most relevant factors for predicting TDS and to minimize noise. Linear Regression, KNN, and Random Forest models were developed and trained using the pre-processed dataset.

The linear regression model assumes a linear relationship between water quality parameters and TDS. Ordinary least squares were used to decrease sum of squared differences between expected and actual data. Simple linear regression shows how each parameter influences TDS. K-Nearest Neighbours (KNN) is non-parametric method prediction based on training set data similarity. KNN may describe non-linear interactions, however it is computationally expensive for large datasets and requires accurate distance measurements. Random Forest learning method combines decision trees to avoid overfitting and increase accuracy. In order to ensure diversity, each decision tree is trained on a random sample and has random feature selection at each split. To predict, all tree projections were averaged. Random Forest can express complex, non-linear relationships and manage large datasets without much change. Metrics like Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and R-squared (R^2) were plotted to assess performance of each model. A correlation matrix was also built to assess the relationship between all measures of water quality and TDS, elucidating the contribution of each component to TDS prediction.

The Linear Regression model showed outstanding performance, as evidenced by a significantly high R^2 value (0.9987), suggesting that the model accounted for almost all the variance in TDS. The MSE and MAE values were comparatively low, indicating that the model accurately predicted the TDS values. This suggests that the total dissolved solids in the specified groundwater dataset exhibit a linear trend. Random Forest had superior performance, although lacked the accuracy of Linear Regression. The R^2 value (0.9715) indicates that the model accounted for almost 97% of the variance in TDS, therefore, representing a favourable outcome. Nonetheless, the MSE and MAE values were greater, signifying that the prediction errors of the model exceeded those of Linear Regression. Typically, Random Forest exhibits more resilience to complex and non-linear data; but, in this instance, it performed inferiorly than Linear Regression. The overall performance of the three models was overshadowed by the other two, since KNN exhibited the poorest performance. The MSE and MAE values were significantly elevated in comparison to the Linear Regression and Random Forest models, indicating greater prediction errors. The R^2 score is 0.8475, indicating that the model accounts for around 85% of the variance in TDS, which is acceptable but significantly lower than the other models.

The performance comparison of Linear Regression, Random Forest, and KNN in predicting TDS in groundwater reveals that Linear Regression is the superior model, exhibiting the lowest MSE and MAE, along with the highest R^2 value. The straightforwardness of adopting the linear relationships between input factors and TDS contributes significantly to its performance in this context. Robust and adaptable, Random Forest exhibited marginally inferior performance compared to Linear Regression, however yielded satisfactory results. KNN had the highest prediction errors and the lowest R^2 value, perhaps due to its sensitivity to hyperparameter adjustments and the data's complexity. This study advocates for the utilization of Linear Regression as the model for predicting TDS in groundwater due to its accuracy and interpretability. Future work may involve refining the KNN model, or exploring alternative machine learning techniques such as support vector machines or neural networks to enhance the prediction of groundwater quality.

Keywords: *Ground water quality, TDS prediction, machine learning, KNN, linear regression, random forest*

UTILITY OF OPEN AND SATELLITE-BASED DATA FOR GROUNDWATER RESOURCE ESTIMATION USING WATER ACCOUNTING PLUS (WA+) FRAMEWORK FOR AN INDIAN PENINSULAR BASIN

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Water resources, particularly groundwater, play a critical role in drinking, agriculture, and forestry. Although, Central Groundwater Board (CGWB) is the central nodal agency, the onus of groundwater development and management is mainly a state subject, and lies with respective Groundwater divisions of State Governments. Unless a resource is properly quantified, its management and conservation is a far cry. In case of groundwater, its estimation is a tedious, time consuming and expensive activity. However, with technological advancements, high computational capabilities, use of open and satellite-based data for estimation of groundwater resource is gaining momentum these days. Although, these estimates will never replace the field-based observation accuracy, but provide considerable information on the groundwater resource of a region with comparable accuracy. The python-based water accounting plus (WA+) framework, developed by IHE-Delft, The Netherlands is a step in this direction. The framework utilizes open and satellite-based data, and accounts the water resources of a basin utilizing the outputs from specially developed 'WaterPix' model with the concept of blue and green water pixels. The blue and green water pixels indicate the type of water used in a region. Precipitation and soil moisture comes under green water, whereas surface water and deep groundwater which are basically a form of delayed precipitation, comes under blue water. This concept of green and blue water also applicable to rainfed and irrigated area. Yield from rainfed area is only contributed by green water, whereas, an additional supply as irrigation (blue water) along with the green water contribute the yield in case of irrigated area. In the present study, WaterPix model was set-up for the Mahanadi basin. The Mahanadi basin is one of the major multi-states (Chhattisgarh and Odisha), east flowing peninsular river basin with a geographical area of 1,41,589 km^2 (Chhattisgarh – 75136 km^2, Odisha – 65580 km^2). The major significant tributaries of Mahanadi River are Pairi, Seonath, Hasdeo, Mand, Kalma and Jonk, which joined above the Hirakud dam, whereas the Ong and Tel rivers join below the Hirakud dam. The basin has a subtropical climate, with the average temperature during the summer months being about 29°C and in winters about 21°C. The average annual rainfall of 106 years (1901–2006) is about 1400 mm, out of this about 90% rainfall received during the monsoon period (June–September). As the waters of the Mahanadi basin are not yet allocated or abstracted completely, the basin provides ample scope for evolving an integrated approach for equitable, democratic and sustainable management of its resources. However, rapid changes in the Mahanadi basin, especially during the last two decades, suggest that not only is the water use increasing, but new problems are emerging in the inter-sectoral allocation and also between the two major riparian states, Odisha and Chhattisgarh. One of the root causes of riparian disputes is trust deficit in the methods and criteria adopted in the estimation of water availability particularly for basins spread of multiple states and transboundary in nature. In a situation like this, a well-defined, unbiased scientific approach which mostly utilizes the remote sensing based open data for accounting the basin's water resources is handy in addressing conflicts. Initially, the input data such as precipitation, evapotranspiration, soil moisture, net dry matter (NDM), leaf area index (LAI), GRACE (Gravity Recovery and Climate Experiment), etc. were downloaded from open sources at daily and monthly scales. Then, the hydrological model WaterPix was set-up and simulated for the period 2004-2020 to assess soil moisture and water balance in the basin. The model estimates the surface runoff, total runoff, changes in water storage, percolation, base flow and the supply of green and blue water, based on soil moisture water balance. Prior to that, Globcover and NRSC LU, Population density, MIRCA irrigated, MIRCA rainfed, WDPA, and crop data from IWMI were used to develop the water accounting-based land use (WALU). It is one of the essential inputs before setting up the WA+ model. Finally, WA+ sheets were generated for utilized flow, surface water, groundwater, and resource base. In the paper, the factsheet on groundwater (Sheet 6) is discussed in detailed. The groundwater sheet estimates vertical recharge both natural and man-made as well as GW abstraction, return flows, changes in storage, and baseflow contributions. The basin's average annual recharge, groundwater abstraction, change in aquifer storage, and baseflow were computed as 110.47 BCM/year, 53.67 BCM/year, 19.02 BCM/year, and 73.8 BCM/year, respectively. The assessment supports the development of sustainable groundwater management plans, such as safeguarding against excessive drawdown, issuing extraction permits, and advancing managed aquifer recharge (MAR) techniques to enhance long-term water security. Similarly, the mean change in water storage fluctuated between −52 mm and 26 mm across the basin, with negative values indicating a decrease in water storage. This decline was most prominent in the northern and southeast parts of the basin, largely attributed to the imbalance between water withdrawals and return flows (such as groundwater recharge). Percolation rates also showed significant variation, ranging from 744 mm to 2,157 mm throughout the basin. Overall, the analysis suggests that WA+ is an effective tool for assessing water availability and usage of surface water and groundwater in river basins. The study helps the decision-makers particularly the basin authority to enhance resource planning, mitigate risks, and optimize water use for long-term sustainability and resilience in the face of growing water challenges.

Keywords: *Groundwater, WA+, WaterPix, Mahanadi basin, green and blue water*

PREDICTION OF GROUNDWATER LEVEL USING MACHINE LEARNING TECHNIQUES OF THE WESTERN ARAVALI RANGE, RAJASTHAN, INDIA

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Groundwater is of paramount importance and serves as a primary water source for arid and semi-arid regions. Groundwater level (GWL) prediction is crucial in arid and semi-arid region due to the uneven distribution of rainfall and unsystematic utilization of groundwater at both global and regional scales. Over the past few decades, groundwater resources have experienced substantial decline due to over irrigation practices, infrastructure development, day-by-day increase of population, increase of industry area etc. The GWL is direct and simple estimation of groundwater availability and accessibility. Having a proper understanding of past, present and future scenario of GWL can provide proper planning of water resources, formulation of new policy of central/state level and practitioners in hydrology sectors with better insight of and perception to develop strategies for the water resources planning, development and management, to ensure sustainable socio-economic development. Although the western Aravali region has been identified as a significant for groundwater level changes. The primary goals of the current investigation are (1) to predict the GWL based on standalone and ensemble machine learning algorithms for the Ajmer city, Rajasthan, (2) to compared the proposed and existing models over the study area, and (3) to compared between the observed and predicted GWL over the study area.

GWL has been predicted using the suggested AdaBoost, Classification and Regression Tree (CART), Random Forest (RF), and REP tree models. An ensemble modelling method for GWL prediction is the AdaBoost model. It is pointing to a classification tree boosting strategy that is adaptable. It is a non-parametric approach that effectively separates outliers without requiring the learners to be defined. AdaBoost begins by giving the data set equal weights in order to create an initial decision tree (DT) for training. The fitted model provides the whole training in the following stage. The larger weights are labelled as misclassified, whereas the weight of the accurate predictors is marked as fixed. With respectable results, CART has been used extensively for groundwater modelling, including GWL prediction. Since the CART is regarded as an unstable model, we can enhance the model's performance by using the bagging strategy. An ensemble approach known as the RF model is used to model streamflow, rainfall-runoff, and groundwater. In order to improve model accuracy and prevent training overfitting issues, the suggested RF model is built using the random subspace method to create a multiple decision tree with controlled variance. Regression and classification are the primary uses for the Reduce Error Pruning tree (REPTree) model. For groundwater modelling, particularly GWL prediction, CART has been utilised extensively with respectable results. We can enhance the model's performance by using the bagging strategy, since the CART is regarded as an unstable model. An ensemble algorithm for streamflow, groundwater, and rainfall-runoff modelling is the RF model. The suggested RF model is built using the random subspace approach, which creates a multiple decision tree with controlled variance to improve model accuracy and prevent overfitting during training. Cut Down on Error the Pruning Tree (REPTree) model is mostly utilised for regression and classification. The REPTree model is an extremely effective methodology for quick learning that creates decision/regression trees using reduced error pruning strategies. The model

efficiently prunes the tree by employing back-fitting with reduced error, which lessens instability and mitigates mistakes brought on by overfitting.

Its primary objective is to create a set of guidelines for making decisions based on predicted factors. One of the main methods for building decision trees is the REPTree model process, which builds regression trees based on variance data by using condensed error pruning. By creating numerical ranges inside the model, this technique makes predictions that are more reliable and accurate. The water resources department of Rajasthan State in India provided the GWL data for this study, which was gathered between 2011 and 2023. In this investigation, data from 252 wells mostly drilled and piezometric wells were included. Both the Central Groundwater Board (CGWB) and the State Groundwater Department (SGWD) of the planned study region measure the GWL data. Similarly, the NASA power platform has been used to gather the pre-monsoon and post-monsoon datasets for average rainfall, average temperature, maximum temperature, and lowest temperature. The models' ideal input combination was assessed using a number of different methodologies, including the average rainfall, average temperature, maximum temperature, and minimum temperature before and after the monsoon. The suggested models have been trained, validated, and tested using a total of 3984 data sets. As a result, 70% of the dataset was used for model training, 20% for model validation, and 10% for testing the suggested models.

The model's performance was evaluated against that of alternative methods using four statistical indices: correlation validation coefficient (CC), Nash-Sutcliffe Efficiency (NSE), root mean square error (RMSE), normalised root means square error (nRMSE), and four visual representations: scatter plot, violin plot, radar diagram, and Taylor diagram, in that order. According to the GWL prediction results, the boosting models (AdaBoost & REPTree) had a lower NSE (0.98) and CC (0.97) than the bagging models (RF & CART). In general, the RF model performs better than the CART, AdaBoost, and REPTree models. In the areas of watershed management and aquifer management, researchers, academics, and policymakers can all benefit from the prediction of GWL in this study by preserving an optimal harvest from these valuable natural resources.

Keywords: *GWL, bagging technique, boosting technique, Aravalli range*

DESIGN, IMPLEMENTATION AND VALIDATION OF AN AUTOMATED INFILTROMETER

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This study introduces the design, development, and calibration of an automated infiltrometer primarily focusing on modifying a conventional Double-Ring Infiltrometer system using sensors and a data acquisition system. Infiltration is a vital hydrological parameter with applications in rainwater harvesting and contaminant transport analysis. Traditional infiltrometer systems often require labor-intensive manual operations and lack precision for diverse soil and environmental conditions. The automated system retrofits a double-ring infiltrometer with sensors, a microcontroller, and a data acquisition configuration to enable real-time monitoring and precise measurement of water loss. Systematic calibration involving rigorous laboratory testing to establish baseline performance ensures measurement accuracy and reliability. Preliminary results demonstrate the potential of this automated infiltrometer to deliver high reliability and accuracy compared to traditional methods, enhancing its utility in applications such as water resource management, agricultural planning, and environmental monitoring. Its modular, cost-efficient design facilitates widespread adoption and scalability, particularly in resource-constrained settings. The system's compatibility with existing hydrological models further extends its utility, allowing seamless integration into watershed simulations and climate resilience studies. This work represents a significant advancement in hydrological instrumentation by addressing critical challenges in infiltration measurement. Future efforts will focus on integrating predictive algorithms for real-time data analysis and refining the system's portability for broader field applications. The automated infiltrometer offers a practical and efficient solution to modern water resource challenges, contributing to sustainable management practices in the face of increasing climate variability.

***Keywords**: Double ring infiltrometer, soil infiltration measurement, real time data collection, hydrological applications, data acquisition system*

GEOSPATIAL INTELLIGENCE FOR GROUNDWATER MANAGEMENT

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Groundwater, the vital elixir of sustainability, is increasingly an important resource for drinking water, irrigation, and industrial processes. However, unsustainable practices and a lack of information has led to its overexploitation and contamination. This is where geospatial intelligence (GEOINT) emerges as a game-changer for effective groundwater management. High-resolution satellite imagery, aerial photography, and Light Detection and Ranging (LiDAR) data can be used to create detailed maps of aquifers, including their extent, depth, and potential yield. By integrating geospatial data with rainfall records, evaporation data, and geological information, hydrologists can build models to simulate groundwater flow and predict recharge areas. Repeated satellite radar measurements can detect changes in ground elevation with high precision, allowing us to monitor groundwater depletion and identify areas with declining water tables. Remote sensing techniques can help identify potential sources of groundwater contamination, such as agricultural runoff or industrial waste disposal sites. GEOINT provides objective data and insights, enabling informed decisions on well placement, pumping rates, and artificial recharge projects. Locating productive aquifers and optimizing well locations can reduce drilling costs and energy consumption associated with groundwater extraction. Monitoring groundwater levels and quality helps ensure sustainable use of this precious resource and prevent long-term depletion or contamination. By tracking changes in groundwater levels and identifying potential contamination sources, GEOINT can help trigger early warnings to prevent water crises.

This study employed a comprehensive approach to demonstrate the application of GEOINT in groundwater management. The research began with a thorough review of existing literature on GEOINT and groundwater management to identify best practices and challenges. Three case studies from India, California (USA), and Africa were then analyzed to demonstrate the successful application of GEOINT in groundwater management. The first case study relates to India where geospatial data is being used to map and manage groundwater resources in drought-prone regions, enabling targeted interventions like rainwater harvesting and well construction. The CGWB utilizes geospatial data to create aquifer maps, monitor groundwater levels, and assess groundwater quality across the country. The National Remote Sensing Centre (NRSC) has developed various geospatial technologies for groundwater management, including satellite-based drought monitoring and groundwater potential zonation. Several state governments are actively using geospatial data to tackle drought and water scarcity challenges. For example, the Maharashtra government's Jal Yukti Shivar Abhiyan leverages geospatial data to identify and prioritize areas for rainwater harvesting structures. However, given the enormity of the problem with rising population and fast depleting resource, much more needs to be accomplished in this domain. The next case study is about the Central Valley which is California's agricultural heartland, but it also relies heavily on groundwater for irrigation. Decades of over-pumping have led to declining water tables, causing land subsidence (sinking) and impacting agricultural productivity. Climate change with less precipitation and higher temperatures further exacerbates the situation. California's Central Valley relies on geospatial modeling to track groundwater levels and implement sustainable water management practices in the face of prolonged drought. The

California Department of Water Resources (DWR) utilizes the California Central Valley Groundwater Model (CVM) to assess groundwater availability, evaluate drought impacts, and inform sustainable water management practices. The CVM helps water managers understand how changes in groundwater pumping, surface water deliveries, and climate can affect groundwater levels throughout the Central Valley.

The third case study discusses about several African countries which are utilizing GEOINT to identify suitable locations for drilling wells in remote areas, improving access to clean water for rural communities. For example, The United Nations International Children's Emergency Fund (UNICEF) has used GEOINT in Ethiopia and Madagascar to identify drilling locations for water wells. By pinpointing areas with higher likelihood of groundwater, GEOINT significantly increases the success rate of well drilling projects, saving time, resources, and money. Focusing drilling efforts on promising locations minimizes environmental impact and avoids disruption to pristine areas. The study yielded several key findings that demonstrate the effectiveness of GEOINT in groundwater management.

The analysis of geospatial data revealed that GEOINT can accurately map and monitor groundwater resources, including aquifer extent, depth, and potential yield. For instance, the case study in India demonstrated that GEOINT-based mapping enabled the identification of potential groundwater recharge zones, which informed the development of effective groundwater management strategies. The study found that GEOINT can optimize well placement and pumping rates, reducing drilling costs and energy consumption. The case study in California showed that GEOINT-based analysis enabled the optimization of well placement, resulting in a significant reduction in drilling costs. The analysis revealed that GEOINT can establish early warning systems for groundwater depletion and contamination. The case study in Africa demonstrated that GEOINT-based monitoring enabled the detection of groundwater contamination sources, allowing for proactive measures to prevent further contamination. The study also emphasized the importance of capacity building and data accessibility in ensuring the effective use of GEOINT in groundwater management. The case studies highlighted the need for training and capacity building programs to enhance the skills of water management professionals, policymakers, and local communities in interpreting and utilizing geospatial data.

In a nutshell, the study demonstrates the potential of GEOINT in supporting effective groundwater management. The application of GEOINT enables improved mapping and monitoring of groundwater resources, allowing for better decision-making. By adopting a GEOINT-based approach, groundwater management can be transformed, ensuring the sustainable use of this vital resource for future generations. Future advancements in remote sensing technologies will provide even more detailed information about groundwater recharge zones. Making geospatial data readily available and accessible can empower local communities, researchers, and entrepreneurs to participate in developing innovative solutions for groundwater management. Equipping water management professionals, policymakers, and local communities with the skills to interpret and utilize geospatial data is essential for maximizing the impact of GEOINT initiatives. GEOINT can support the integration of surface water, groundwater, and treated wastewater resources, optimizing water use efficiency and ensuring long-term sustainability.

***Keywords**: GEOINT, groundwater management, SAR, remote sensing*

ASSESSING GROUNDWATER RESOURCES IN SIKKIM, INDIA USING REMOTE SENSING, GIS AND GOOGLE EARTH ENGINE

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Groundwater is a critical component of the hydrologic cycle. It represents a vital component of Earth's freshwater resource as it accounts for 99% of the total unfrozen freshwater on earth. It's significant role in supporting ecosystems, agricultural, industrial and domestic water supply warrants its sustainable management, especially in fragile ecosystems. Therefore, accurate, periodic, and low latency observation is paramount for its effective sustainable management. However, due to lack of ground observations, particularly in remote or challenging terrains, quantifying spatio-temporal changes in groundwater resource are difficult by employing conventional methods that require in-situ data collections. In such cases, remote sensing data can be beneficial for providing frequent estimates even in inaccessible or remote areas. Traditional GIS and Remote Sensing (RS) platforms work on local computer systems that are prone to machine failure and computations are time consuming. These drawbacks can be circumvented by using cloud-based platform such as Google Earth Engine (GEE). GEE has more than 600 datasets with many products potentially instrumental in performing water resources assessment. Additionally, its parallel processing capabilities results in faster computations facilitating quicker decision making. This study employs a water balance approach to estimate changes in groundwater storage for the north eastern Indian state Sikkim, where the components of the water balance have been computed using remote sensing products from GEE catalogue. To assess the stress on groundwater resources, the Stage of Groundwater Development (SGD) has also been computed and potential remedial measures have been suggested.

Sikkim is a north eastern state of India and is a part of eastern Himalaya with an approximate area of 7100 km^2. The entire state exhibits slope mostly greater than 20% where the conventional groundwater estimation methods often prove to be inadequate, making it an ideal study area of employing the remote sensing and GIS based water resources assessment methodology. Sikkim is a part of Teesta catchment that provides runoff to Teesta River that flows from North-west to South-eastern direction. The majority of the area (>57%) is covered by trees and 12% of the area is covered by snow. Water bodies and built-up area cover around 0.6% and 0.2% of the study area. Analysis of the collected lithological data exhibits large spatial variability with schist, phyllites, clays and pebbles constituting the majority of formations. Akin to the majority of India, Sikkim receives majority of its annual rainfall (>75%) in monsoon season that spans from June to September and rest of the rainfall is received in non-monsoon season. Apart from the domestic and agricultural usages there are currently 10 pharmaceutical industries in the south-eastern part of Sikkim that relies on groundwater for their industrial consumption. Additionally, the entire population of Sikkim relies heavily on springs as a source of freshwater, and for their domestic use. This over-reliance, and limited groundwater recharge due to the topography, and hydrogeology of the area poses significant risks of aquifer depletion, water quality issues, and ecological and hydrological deterioration. The depletion of the groundwater resource is evident in the decline in the observed water tables. Proposed methodology employs an integrated approach that amalgamates RS, GIS and GEE computational abilities to generate estimates of groundwater storage and subsequent computation of SGD. This integrated approach provides a more scalable and low latency framework for groundwater assessment in regions with complex terrain and scarce availability of field data. The proposed methodology is based on a water balance equation to compute changes in groundwater storage. The components of the water balance were computed using the Climate Hazards Center InfraRed Precipitation with Station Data (CHIRPS-Pentad) dataset, TerraClimate dataset, Soil Moisture Active Passive (SMAP L-4) dataset, Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) dataset, and Global Surface Water (GSW) dataset. Net groundwater inflows and out flows of the area is not considered as it was considered to be significantly small for the study area relative to the other components of the water balance. The SGD was computed using the proposed approach came out to be 12.12%, which according to the GEC falls under the safe category. Albeit the SGD in the study area was found to be quite low, uncontrolled use and mismanagement of groundwater resources coupled with climate change may lead to several adverse impacts on the overall environment and sustainability of the surrounding ecosystems. The study recommends multiple approach in addressing these challenges. Rainwater harvesting structures can be constructed to facilitate the groundwater recharge in valleys having high water demands. The collected water may be used directly or can be injected into the groundwater via injection well or infiltration basins. Small sized check dams and other water conservation practices can be implemented around the Industrial setups requiring large water demands. These dams may be constructed along the vast network of streams prevalent in the area to enhance the infiltration of surface water into the groundwater via stream bed seepages, but only after proper planning considering the factors spanning from soil parameters to logistical ones. Additionally, awareness campaigns and community engagement programs are emphasized for fostering sustainable water use practices at the base level. However, one must be mindful of the fact that remote sensing approach relies on pixel values to make inferences, which may fail to capture all the hydrogeological complexities and could be unrepresentative of the area under scrutiny, and estimates computed with remote sensing will almost always be less accurate compared to those obtained from ground observations.

This study implies that high-resolution remote sensing datasets aboard Google Earth Engine (GEE) can overcome data and computational limitations of traditional methodologies to a large extent. This study’s framework can be applied to similar mountainous terrains, and data scarce situations for guiding sustainable groundwater management. Furthermore, the research provides a foundation for future studies assessing the relationships between climate change and groundwater dynamics. This study can be further expanded/ modified to incorporate climate projections like precipitation, temperature, and evapotranspiration which allows for scenario-based planning, resilient and adaptive management strategies. With advancement in the field of remote sensing, and as the quality of the remote sensing datasets are continuously getting better, and accessibility is getting easier, the results using this approach are expected to improve over time. In conclusion, this study underlines the importance of advance remote sensing and GIS methodologies in addressing the complexities of groundwater resource assessment and management, especially in regions with complex terrains like Sikkim where conventional methodologies may be infeasible to provide adequate insights.

Keywords: *Groundwater management, remote sensing, GIS, Google Earth Engine, groundwater resource assessment, water balance, hydrology*

DIGITAL TWIN FOR SUSTAINABLE WATER MANAGEMENT FOR A VILLAGE IN INDIA

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Approximately 75% of rural households in India lack access to safe tap water, with extreme water stress predicted by 2050 due to over-extraction of groundwater. Groundwater is crucial for irrigation, especially in areas with low rainfall and for better livelihood and socio-economic development. This is counterproductive for the vision of Viksit Bharat 2047 and UN Sustainable Development Goal-6 (SDG-6) which aims to ensure everyone has access to safe and affordable drinking water. Among multiple reasons for the worsening groundwater situation in India, such as, access to cheap pumps, subsidised electricity, changing crop patterns and increasing population, lack of sound scientific understanding among stakeholders is also a major reason. Groundwater is not directly visible; hence, it is difficult for the local communities such as farmers, gram panchayat (GP), water user association, and other water stakeholders to visualize the complex hydrogeological aspects and estimate the volume of water available using equations, and modelling. There is a need for village communities to learn about groundwater science to make informed decisions and improve their management practices. This requires community members to take responsibility for gaining this knowledge and manage this scare resource sustainably. But this requires a technology-based method and system which is simple to understand and use considering the competencies of the village level stakeholders.

The digital twin (DT) concept is emerging as a helpful tool for water management. A digital twin network acts as a virtual model of a physical network, critical for analysing and managing elements or nodes of water resources in real-time. It can simulate water supply and demand, predict water quality, and detect possible contamination, thereby supporting a transparent and informed decision-making which is the need of the hour. Randullabad village in India, which has limited access to clean water for its population of 400 homes, exemplifies this issue. Hydrology of Randullabad covers key aspects of rainfall, groundwater, streams, and water management. Challenges include the hydrogeological complexity of basaltic aquifers, which have uneven recharge capacities, and the impact of climate change, leading to rainfall variability. Between 1-1.5°C increase in temperature over 30 years has raised evaporation rates, worsening water scarcity conditions. Annual rainfall in Randullabad ranges from 500-600 mm, primarily during the monsoon season from June to September. High runoff and low infiltration result in limited groundwater recharge. The area is characterized by basaltic aquifers with low permeability and poor storage capacity, where groundwater resides in fractures and weathered zones. The average annual rainfall has seen reductions, alongside a rise in drought occurrences, intensifying dependency on groundwater for irrigation, leading to over-extraction that harms groundwater quality. The village struggles with an inadequate water supply network, resulting in scarcity, competition, and poor water quality that threatens socio-economic growth, social conflicts, and public health, especially for children. The lack of real-time monitoring and data-driven decision-making worsens these problems. Currently, Randullabad's water management relies on sporadic manual data collection and a few sensors, making it hard to get a real-time understanding of water availability. This leads to slow responses and poor decisions, causing water wastage

and conflicts over resources. To overcome these challenges, a new, integrated approach is needed for sustainable water management.

This paper proposes using a digital twin for water management (DToWM) in Randullabad village to tackle existing shortcomings. The proposed architecture utilizes real-time data from sensors, IoT, satellite remote sensing, historical data, and machine learning to create a virtual model of the village's water supply network especially better understanding the recharge and storage potential of the aquifer. This can lead to the creation, maintenance, and monitoring the manage aquifer recharge interventions such as check dams, tanks, ponds. Implementing this approach could significantly improve water sustainability and public health in Randullabad. Groundwater contamination is another concern, stemming from agricultural runoff, geogenic sources, and improper wastewater disposal. High nitrate levels are found in many wells, primarily due to fertilizer use, and fluoride contamination poses health risks. Remediation strategies include improved agricultural practices, established treatment systems for waste, groundwater recharge initiatives, and community awareness projects for sustainable farming methods. DToWM can enhance Randullabad's participatory groundwater management for periodic groundwater assessment. Remote sensing and geophysical surveys can identify recharge zones and aquifer characteristics, while hadrochemical analysis and isotopic studies help track contaminant sources and flow patterns. Moreover, IoT-based monitoring systems can be used for real-time data collection on groundwater levels and quality and alerting the users. Recommendations for improvement involve using advanced modeling tools for better predictions and integrating traditional knowledge with modern practices for effective groundwater management. In conclusion, advanced techniques and community participation are vital in improving groundwater assessment and management in Randullabad, helping to address water scarcity and ensure sustainability in semi-arid regions.

Keywords: *Water management, digital twin, groundwater management, sustainable development goals*

MACHINE LEARNING-BASED GROUNDWATER LEVEL PREDICTION FOR SUSTAINABLE WATER RESOURCE MANAGEMENT IN AN INDUSTRIAL CATCHMENT

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Groundwater is a vital source of freshwater, playing a crucial role in agriculture and economic development. Accurate groundwater level (GWL) prediction is essential for sustainable water resource management. As soft computational data-driven technologies have advanced in recent years, numerous machine learning models have been created and are being used for GWL forecasting. ML models are more desirable than physically based and numerical methods because they can simulate and predict GWL without needing a thorough understanding of the underlying topographical and hydro-geophysical characteristics. An efficient substitute that does not call for precise and particular physical factors and attributes are machine learning (ML) techniques. Some of the widely used ML models in GWL Prediction are Support Vector Machine (SVM), Artificial Neural Networks (ANN), Extreme learning machine (ELM), Fuzzy logic, Adaptive Network-based Fuzzy Inference System (ANFIS). For many hydro-meteorological applications, hybrid machine learning and genetic models have been attempted and tested in numerous researches. The literature evaluation indicates that these hybrid machine learning models perform better in terms of prediction than many solo models. The ability of hybrid models to identify intricate mathematical nonlinear interactions between the independent and dependent parameters is one of its primary benefits. The objective of this study is to downscale Monthly GWL from quarterly GWL data using the Kalman Filter algorithm; To predict GWL using rainfall, evapotranspiration, mean temperature, and infiltration data using three ML methods – Decision tree, Random Forest and Bagged Tree; To compare and analyze the performance of the three models.

Talcher is one of the 4 sub-divisions of Angul district in the state of Odisha. The latitude and longitude of Talcher are N 20° 56' 57.372", E 85° 14' 0.744". It has a savanna climate which is known as tropical wet and dry climate with the Classification: Aw. The quantity of rainfall during summers surpasses that of winters. The area's yearly temperature is 30.53ºC (or) 86.95ºF and is 4.56% higher than India's average. Talcher typically receives about 131.22 mm of precipitation and has 134.21 rainy days annually that is36.77% of the time. Brahmani River flows through Talcher. The Brahmani River and its major tributaries such as Nandira Jhor, Singhara Jhor, Tikra Jhor, Samakoi, Nigra, Gambhira, etc. run through the Angul district. For the training stage the mean value of GWL is 3.90 m, with a maximum value of 7.45 m and minimum value of 0.22m. From the graphs and the performance metrics, it can be observed that for the training stage the Random Forest model is best among the three models used with r2= 0.82, RMSE = 0.62, MSE = 0.38 and NSE = 81.77. Decision tree models, with r2 around 0.68, has less accurate results than other models. Cross validation seems to not increase accuracy in prediction for the decision tree model during the training stage. The Bagged Tree model has an r2 value of 0.7, RMSE value of 0.85, MSE value of 0.76 and NSE value of 63.34. From the observed GWL versus predicted GWL graph of Bagged tree, it can be observed that around half of the values are over estimated and half of the values are underestimated. Smaller GWL values are over estimated and larger GWL are under estimated by the Bagged Tree model. The mean value of GWL for the testing stage is 3.94 m with maximal and minimal values of GWL for the testing stage being 8.83 m and 1.22 m, respectively. It can be observed that for the testing stage, from the graphs and the performance metrics, the Random Forest model is best among the three models used with r2= 0.80, RMSE = 0.61, MSE = 0.37 and NSE = 94.53. For decision tree, the cross validated models have shown an increase in accuracy. The 10-fold cross validated decision tree model has an r2 value of 0.70, RMSE value of 0.72, MSE value of 0.53 and NSE value of 73.70. The performance of Decision tree and Bagged tree models increased in the testing stage from the training stage. But the performance of Random Forest decreased slightly in the testing stage. Similar to the training stage values, the Bagged tree has overestimated smaller values of GWL and under estimated larger values of GWL. As in the training stage, here too the ensemble models have better performance than Decision tree.

In this study, multiple models were built for groundwater level prediction and compared to explore potential knowledge of GWL predictions. Forecasting of GWL is essential for sustainable management of ground water resources. GWL datasets from 2003 -2020 from the Talcher region, Odisha were collected and used to train and test three ML models for long-term prediction. Rainfall, temperature, calculated infiltration and calculated evapotranspiration values were used for the prediction of GWL. The Evapotranspiration values were calculated using the FAO-24 Radiation equation. Kalman filter was used to downscale GWL data. The performance of three machine learning models - Decision Tree, Random Forest and Bagged Tree in predicting GWL was evaluated. Each model is evaluated using the mean square error (MSE), root mean square error (RMSE), coefficient of determination (R^2), and Nash–Sutcliffe efficiency (NSE). The Random Forest model is seen to have best accuracy in both the training ($r^2 = 0.82$) and testing stages ($r^2 = 0.80$).

Keywords: *Decision tree, groundwater level, random forest, bagged trees, water resources management*

PARTICIPATORY GIS ANALYSIS AND MAPPING OF DRINKING WATER QUALITY CHALLENGES IN TANZANIA

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Increasing contamination and scarcity of critical water sources in arid and semi-arid regions of the globe are two challenges compromising the efforts to provide clean and safe water services for various purposes including drinking. This study investigated the practice of clean and safe water provision in Tanzania between 1960 and 2013. The study used community perspectives on the drinking water quality of critical water sources (around 65,000) captured during the national water point mapping in 2013. The critical water sources included both groundwater (Hand DTW, Machine DBH, SW, and Spring) and surface water (Dam, Lake, and River) resources. The methods used throughout the study combined classical statistics and Geographic Information Systems (GIS) tools to analyze trends in water supply services and critical water sources' quality in Tanzania. For the past five decades, groundwater resources contributed around 77% of the water demand while surface water resources contributed around 23%. However, the water users reported quality problems experienced during drinking and included, in ascending order, fluoride, milky, colour and salinity (salty). The salinity problem was reported across the country with Dar es Salam, Mara, Manyara, Dodoma, and Rukwa regions being the top five regions with severely affected critical water sources. In descending order, the most contaminated critical water sources in these regions were machine dug-boreholes (Machine DBH), shallow wells, and hand-dug tube wells (Hand DTW). Likewise, the colour and milky problems were reported across the country. The top five regions with severely affected critical water sources were Ruvuma, Mbeya, Kagera, Kigoma and Morogoro for colour problems and Shinyanga, Kigoma, Kagera, Lindi and Kilimanjaro for milky problems. The two drinking water problems were reported in all critical water sources except lakes. On the other hand, the fluoride problem was reported in fourteen (14) regions with the top five being, in descending order, Arusha, Mbeya, Manyara, Kilimanjaro, and Morogoro which are connected to the East African Rift Valley. Other regions where fluoride is a water quality problem included Kagera, Simiyu, Mtwara, Dar es Salaam, Mwanza, Mara, Pwani and Kigoma. The most affected critical water sources in these regions included rivers, hand-dug tube wells, machine-dug boreholes, shallow wells, and springs. The findings of this study highlight the quality of the critical water sources supporting the drinking water supply schemes across the country. The study further demonstrates the importance of participatory GIS in water supply services and management as it uses the feedback of the water users to map the water quality challenges at various critical water sources.

Keywords: *Critical water sources, water quality, exploratory data analysis, geospatial technology, GIS*

COMPARATIVE EVALUATION OF IMD AND NASA DATASETS FOR HYDROLOGICAL MODELLING

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Water is a critical resource with social, economic, and environmental values essential for sustainable development. Intricate hydrological processes characterize the watersheds in the Himalayan Glacier System (also referred to as the "Water Towers" of Asia), and the significance of glacial meltwater in the overall water budget of mountain rivers is not well-established. Streamflow modeling in snow-dominated catchments is of utmost importance as it helps to manage water resources, predict and mitigate floods, optimize hydropower generation, preserve ecosystems, monitor water quality, adapt to climate change, plan infrastructure, support agriculture, and facilitate recreational and tourism activities. SWAT is a physically based, semi-distributed hydrological model and a potential tool for rainfall-runoff modeling at a basin scale as well as for estimating how climate change will affect water supplies, irrigation management, estimation of evapotranspiration, sediment analysis, snowfall, and snowmelt estimation, integrated surface water groundwater modeling. The objective of this study was to compare the performance of the SWAT model for streamflow simulation using NASA and IMD datasets in the hilly catchment of Uttarakhand, India.

The Bhagirathi River Basin, situated in the Himalayan region of India was selected as a case study to evaluate the efficacy of IMD and NASA datasets for basin-scale hydrological modeling. This basin lies in the Uttarakhand state and covers an area of 4663.81 km^2. The DEM data with a resolution of 30 m × 30 m was sourced from USGS Earth Explorer, while soil maps at a 1:5000 k scale were obtained from the FAO DSMW database. Land Use/Land Cover (LULC) data, with a resolution of 100 m × 100 m, was acquired from the Copernicus Global Land Service. Climate data, including precipitation, wind speed, relative humidity, solar radiation, and temperature for the period 2000–2020, were retrieved from NASA's POWER Data Access Viewer. Daily streamflow data (2006–2014) were collected from the Central Water Commission (CWC), Uttarakhand. Additionally, precipitation and temperature data for the study area were extracted from the IMD website. These datasets provided the inputs for setting up the SWAT model and analyzing its performance for hydrological modeling. SWAT simulates the hydrologic cycle based on the water balance equation. Based on the literature review, 25 surface, subsurface, and snow parameters were selected, and pre-calibration sensitivity analysis was performed using the SUFI-2 algorithm to identify influential parameters. The ArcSWAT model was calibrated using daily streamflow data for the years 2006−2010 and 2011−2014 were used for validation at the watershed outlet.

The assessment of the SWAT model using IMD and NASA datasets indicates significant disparities in statistical metrics between the calibration (2006–2010) and validation (2011–2014) periods for daily and monthly streamflow simulations. The Nash-Sutcliffe Efficiency (NSE) for IMD data increases from 0.58 in the calibration phase to 0.69 in the validation phase for daily data and from 0.74 to 0.88 for monthly data. The Kling-Gupta Efficiency (KGE) values are consistent, measuring 0.78 and 0.76 for daily data and higher values of 0.87 and 0.88 for monthly data, reflecting superior model performance at the monthly scale. The Root Mean Square Error (RMSE) is much higher for daily simulations (87.11–87.39

m³/s) than for monthly simulations (62.62–47.06 m³/s), indicating the model's superior accuracy at aggregated temporal scales. Percent Bias (PBIAS) values show a slight rise from 2.82% to 7.49% (daily) and from 2.66% to 7.74% (monthly) during the calibration and validation period, respectively, indicating underestimation of streamflow based on IMD data. The correlation coefficient (r) increases from 0.79 to 0.84 for daily data and from 0.87 to 0.94 for monthly data, indicating enhanced concordance between observed and simulated values over broader scales. The model performance using NASA data is significantly superior, especially at the monthly scale. The NSE values surpass those of the IMD data, rising from 0.79 during calibration to 0.74 during validation for daily data and to 0.92 and 0.93, respectively, for monthly data. KGE values are consistently elevated, measuring 0.78 and 0.80 for daily data and 0.86 and 0.91 for monthly data, signifying strong model simulations utilizing NASA data. RMSE values are significantly lower than those of IMD data, ranging from 61.95 to 79.75 m³/s for daily data and 34.19 to 37.39 m³/s for monthly data, demonstrating superior prediction accuracy. PBIAS results are promising, with near-zero figures (0.96% and -5.58%) for daily data and 0.95 and -5.56% for monthly data during calibration and validation, respectively, indicating slight bias. The correlation coefficient (r) demonstrates robustness, increasing from 0.89 to 0.87 for daily data and from 0.96 to 0.97 for monthly data, indicating very good concordance. NASA data outperforms IMD data across most statistical metrics, particularly in terms of lower RMSE and higher NSE, KGE, and r values. Both datasets showed reliable performance, with better predictive accuracy at the monthly scale. Our results will promote the use of gridded data for simulating hydrological processes in ungauged catchments or catchments with very few gauging stations, for instance, hilly catchments. Combining insights from multiple datasets could potentially reduce uncertainties and improve the robustness of hydrological modeling in data-scarce regions. Future research should focus on integrating multiple datasets to address discrepancies and enhance the reliability of water balance predictions for sustainable water and land resource management.

Keywords: *Bhagirathi River Basin, SWAT, hilly catchment, streamflow simulation, climate change, water balance components*

ET-BASED IRRIGATION PERFORMANCE ASSESSMENT OF A COMMAND AREA USING GOOGLE EARTH ENGINE

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Effective utilization of water resources and ensuring food security have become pressing challenges due to increasing water demand and the simultaneous threats to water scarcity posed by climate change, pollution and overexploitation. Agriculture, as the largest consumer of global freshwater resources, plays a key role in this equation, with irrigation efficiency and water productivity emerging as the critical factors for optimizing water use and increasing crop yields. Multiple international organizations have adopted sustainable approaches with the aim of enhancing crop water productivity and have poured substantial amounts of investment into such ventures. With the advancements in remote sensing technologies and advent of various geospatial platforms, large-scale, rapid and cost-effective analyses of irrigation schemes have become a possibility. The primary determinants of water use efficiency include evapotranspiration (ET), which signifies crop water consumption (input) and the crop yield (output). A variety of earth observation datasets provide ET and biomass products at a global scale with varying spatial and temporal resolutions for assessment and incorporation into further analyses. However, these datasets only showcase the variability in water consumption and biomass generation and do not translate directly into any indicators of irrigation performance of a scheme.

In this study, eight indicators: 1) Cropping intensity, 2) Scheme utilization, 3) Less water-intensive crops, 4) Adequacy, 5) Equitable delivery, 6) Crop water productivity, 7) Reliability and, 8) Yield gap due to water stress were formulated to quantify the performance of an irrigation scheme incorporating data derived from remote sensing products. Each of these indicators are also associated with a set of critical and target values which aid in determining whether the performance based on a singular indicator is acceptable or not. The entire analysis was carried out using a tool developed in Google Earth Engine platform by the World Bank under the umbrella of Central Water Commission. The tool essentially consisted of two components viz., Cropmapper and Irrigation Performance Assessment indicators sheet. The Cropmapper was used to create a web-based application for the purpose of visualization of various geospatial layers such as the crops grown in the study area along with their seasonal distribution, ET-green, ET-blue, biomass generated and vegetation index map. The irrigation performance indicators sheet forms the crux of the tool output and contains the estimates of the aforementioned indicators as well as the relevant supporting information pertaining to the estimation such as season-wise and crop-wise rainfall, ET-green, ET-blue, volume of irrigation water requirement and total biomass generated. In order to evaluate the performance of irrigation schemes, the tool employs a score-based criterion which requires determination of scores for each indicator as per their individual performance computations and assignment of certain weights to each indicator based on their importance and influence upon the irrigation performance. Thus, the overall score represents a weighted score based on the performance scores of individual indicators. The major input datasets for the tool include the shapefile for the command area boundary, map for onset dates of monsoon from IMD, remote sensing layers viz., land cover maps from Sentinel-1 and Sentinel-2, actual

evapotranspiration and total biomass production maps from FAO as well as CHIRPS rainfall data. The overall methodology of the tool operation in Google Earth Engine can be sectioned into five parts – 1.) Data preprocessing, 2.) Crop type mapping, 3.) Irrigated area mapping, 4.) Creation of web application and, 5.) Generation of irrigation performance assessment indicators sheet, with each of these parts consisting of multiple subsequent steps.

In this study, the irrigation performance of a scheme implemented in command area of Ong catchment namely, Ong Diversion Weir Irrigation Project, was evaluated. All the remote sensing layers required as input for this study were acquired through the earth engine data catalog. The land cover layer was subjected to unsupervised classification to segregate the land cover into 10 classes and each of these classes were manually provided with labels belonging to a specific crop or crop rotation based on the agricultural statistics, cropping calendar and vegetation index information of the area. The tool also supports supervised classification using geo-tagged in-situ crop type samples obtained from field survey which can be digitized into the earth engine database as reference points. Separate crop maps were generated for the years from 2018 to 2022 using transfer learning, a deep learning technique, on the basis of an input labelled crop map for a single year, i.e., 2022. The irrigation performance of the canal for the entire agricultural year (June-May) of 2022 was evaluated based on the indicator sheet generated. The cropping intensity was found to be 87% which was less than the critical value thus, the indicator score was only 1. The irrigation utilization was 49% which was in between its critical and target values of 25% and 80%, respectively, thus, earning an indicator score of 5. Paddy was the major crop in the area which is a high water-intensive crop. The fraction of low water-intensive crops was only 37% resulting in an indicator score of 4. The adequacy and equity of the scheme were computed to be 0.2 and 0.04, respectively, both being within their critical and target values, with scores of 6 and 9, respectively. The water productivity for the paddy crop was found to be 1.1 kg/m^3 which was well beyond the target value of 1 kg/m^3 thus, earning a score of 10. The reliability and yield gap due to water stress were calculated to be 27% and 24% with scores of 4 and 5, respectively. The overall weighted average score for the irrigation scheme was 5.7 which was relatively low. The results of this irrigation performance assessment showcased that the irrigation scheme was not able to achieve optimal water use conditions due to discrepancies in some of the indicators especially cropping intensity. The indicators with low scores can act as waypoints to pinpoint the lacunae in irrigation management and may offer insights to address the detected inefficiencies. These findings highlight the potential of the tool to assess irrigation performance at larger scale and finer resolutions.

Keywords: *Google Earth Engine, irrigation performance assessment, irrigation efficiency, ET-green, ET-blue*

APPLICATION OF MACHINE LEARNING TECHNIQUES FOR THE PREDICTION OF GROUNDWATER LEVELS FOR NASHIK DISTRICT IN MAHARASHTRA, INDIA

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A severe groundwater crisis currently exists in India due to over-extraction and contamination of groundwater, which covers nearly 60% of all the districts in India and poses a threat to the drinking water security of the human population. Despite the national scenario that the availability of groundwater is favorable, there are pockets in certain areas of the country that face water scarcity because of non-uniform poor groundwater development, and over-exploitation leading to falling water levels. Therefore, understanding the response of groundwater levels (depths to water table) to climatic variables and pumping is necessary for sustainable groundwater management, specifically in meeting increasing groundwater demands in the agriculture sector. Since groundwater is a hidden water source with high spatio-temporal variability, quantifying its availability and the long-term impact of climate patterns on it is a highly complex task. To model the groundwater response to climate drivers, water demand, and surface water hydrology, it is necessary to find the relationship between them. There are conceptual and process-based modeling techniques to simulate the complex groundwater process, which requires a large number of hydrogeological data. Acquiring such enormous data is difficult and expensive. Consequently, it is desirable to explore data-driven and machine-learning techniques built on nonlinear interdependencies that could predict fluctuations in groundwater levels without an extensive understanding of the fundamental physical parameters. Among the several machine-learning algorithms available, artificial neural network (ANN) and support vector machine (SVM) were employed in this study. Nashik district of Maharashtra state was selected for the study, as groundwater has special significance for agricultural development, and groundwater development in some parts of the district has reached a critical stage.

In the study, components of groundwater recharge and groundwater discharge were estimated using input parameters such as recharge due to rainfall, recharge due to return flow of irrigation, recharge due to seepage from canals, draft due to irrigation use, industrial use, domestic use, and livestock use. Depths to water table for the period of 20 years, from 1998 to 2018, were used to develop four groundwater models using different combination sets of input variables. The data of 181 hydrograph stations were collected from GSDA, Nashik. Data of rainfall, canals, human population, livestock population, tanks and ponds, minor irrigation structures, and pumping wells were collected from the statistical department of the Nashik district.

While two models used annual data, the other two models used seasonal data as input variables to predict the pre-monsoon and post-monsoon depths of the water table. Several ANN structures were employed using the input variables of the models and different hyper-parameters were tuned in the case of SVM. The best combination of neurons/layers and activation function in the case of ANN and hyper-parameters in the case of SVM were selected based on the hit and trial method. Performance metrics such as correlation

coefficient (r), coefficient of determination (R^2), Nash-Sutcliff efficiency, mean absolute error, root mean square error, mean absolute percentage error, root mean square percentage error, and relative absolute error were used to compare the performance of the models. Based on the global ranking, out of four ANN and four SVM models, the best models were selected for the prediction of pre-post-monsoon depths to the water table. The performance of the ANN and SVM models were also compared.

Based on the global ranking, it was observed that that out of four models, annual data-based models performed better than seasonal data-based models for both ANN and SVM algorithms. Hence, only annual data-based models of ANN and SVM were selected for the comparison. Out of 181 nodes (hydrograph stations), 63 nodes were selected for 5 years; hence, 63×5 = 315 predicted depths to water table for both models were compared. On comparing the results, it was found that 167 (53.01%) predicted pre-monsoon depths were within 10 percent deviation for ANN models while it was 172 (54.60%) for the SVM model, which indicated that the SVM model performed better than the ANN to predict pre-monsoon depth. On the other hand, the ANN model with 68 depths (21.58%) out of 315 predicted depths performed better than the SVM model with 52 values (16.50%) in forecasting post-monsoon depths to the water table.

The study concludes that both the models, i.e., artificial neural network (ANN) and support vector machine (SVM), perform well in predicting pre- and post-depths to the water table. On comparing the performance of both the models, the SVM model performs better in predicting the pre-monsoon depths to the water table, whereas the ANN model performs well in predicting the post-monsoon depths to the water table. The predicted depths of water table from both ANN and SVM models follow the trend of the observed water table precisely and accurately in both seasons. The results reveal that the performance of annual data-based models is better than the performance of the seasonal data-based models, which implies that with the increase in number of input variables the performance of the models improves.

Keywords: *Groundwater level prediction, depth to water table, Nashik district, seasonal depth of groundwater, machine learning, artificial neural network, support vector machine*

A HYBRID APPROACH USING DEEP LEARNING AND HYDROLOGICAL MODELING TO IDENTIFY AQUIFER STRESS ZONES IN THE BARAKAR RIVER BASIN, JHARKHAND

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Aquifer stress assessment in semiarid hard rock terrains, such as the Barakar River Basin in Jharkhand, is crucial for managing the region's groundwater resources. In these areas, aquifers are often characterized by low porosity and limited recharge capacity, making them particularly vulnerable to over-extraction and climate variability. The harsh climatic conditions, coupled with irregular rainfall patterns, further exacerbate the risk of groundwater depletion. Therefore, a comprehensive assessment of aquifer stress, including factors like groundwater recharge, lateral flow, and base flow, is essential to monitor aquifer health and ensure sustainable water management. Understanding aquifer stress in these hard rock terrains is vital for developing strategies to mitigate water scarcity and support agricultural and domestic water needs in the region. This study presents a novel hybrid approach that integrates deep learning techniques, specifically Convolutional Neural Networks (CNN), with hydrological modeling using the Soil and Water Assessment Tool (SWAT) to assess and identify aquifer stress zones in the Barakar River Basin. The research aims to enhance the accuracy and efficiency of aquifer stress assessments by employing advanced machine learning models in conjunction with traditional hydrological models. This area remains underexplored in aquifer health studies.

The methodology of this study combines data-driven deep learning techniques with the SWAT model, leveraging 16 influential factors that encompass hydrological, physiographical, and socioeconomic variables. These factors include precipitation, land use, soil texture, slope, groundwater recharge, water extraction rates, and socioeconomic activities, collectively contributing to the aquifer system's stress. The deep learning component, based on CNNs, classifies the aquifer stress into four distinct categories: Minimal Stress, Moderate Stress, High Stress, and Critical Stress. These classifications are crucial for understanding the severity of the aquifer's stress and informing future management strategies. The integration of these datasets was critical in providing a holistic view of the factors contributing to aquifer stress.

The results of the study showed that approximately 32% of the Barakar River Basin was categorized as Minimal Stress, indicating areas where groundwater levels are stable, and recharge rates are adequate. On the other hand, Critical Stress zones, which accounted for 24% of the basin, were identified in areas with severe depletion of groundwater resources, where extraction rates exceed natural recharge, leading to significant stress on the aquifer system. These findings are consistent with observed groundwater depletion trends and highlight certain areas' vulnerability to long-term water scarcity. Integrating hydrological modeling through the SWAT model provided valuable insights into the hydrological budget components of the Barakar River Basin. By coupling the hydrological model's predictions of runoff and recharge potential with the CNN's ability to analyze spatial patterns in the data, the study offers a comprehensive and integrated framework for aquifer stress assessment. The use of SWAT enabled a deeper understanding of how climatic and physiographic factors influence groundwater availability. In contrast, the deep learning approach captured the complex spatial relationships that influence stress levels on the aquifer system. By providing an accurate and efficient method for aquifer stress assessment, the approach can be used by policymakers and water resource managers to identify vulnerable areas and prioritize intervention strategies. The integration of deep learning with traditional hydrological models represents a promising advancement in the field of aquifer stress assessment. It offers a scalable and adaptable solution for assessing aquifer stress in regions with limited data availability. Model validation demonstrated the robustness of the CNN model, with a precision score of 0.92, an AUC-ROC score of 0.91, and an F1 score of 0.84. This indicates that CNNs, with their ability to model complex, non-linear relationships in data, are well-suited for the task of aquifer stress classification, where the interplay of multiple environmental and socio-economic factors creates a highly intricate system. In conclusion, this research demonstrates the potential of hybrid deep learning and hydrological modeling for aquifer stress zone identification, providing a powerful tool for sustainable groundwater management. The successful application of CNNs in conjunction with the SWAT model in the Barakar River Basin serves as a benchmark for future studies and offers valuable insights for managing aquifer stress in hard rock terrains. This integrated approach improves the accuracy of aquifer stress assessments and provides a framework that can be adapted to other regions facing similar groundwater challenges. The study ultimately contributes to the global efforts in sustainable aquifer management, offering a pathway toward better resource allocation, conservation, and long-term water security.

Keywords: *Hybrid approach, SWAT, deep learning, hydrological modeling, aquifer stress*

CLEANER TECHNOLOGY FOR REDUCING FRESH WATER CONSUMPTION IN THE ELECTROPLATING SECTOR OF MORADABAD COUNTER CURRENT MECHANISM (CCM)

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The ecological integrity of rivers and sustainable use of water resources are critical for social and economic progress of human society. The continuous compounding of stress on groundwater is contributed by the agriculture, domestic and industrial sectors. The metalware cluster of Moradabad city is known across the world for brass art metalware and has carved a niche for itself in the handicraft industry. The city of Moradabad is the epicenter of metalware artwork and is popularly known as the brass city. There are about 1200 registered metalware industries in the city and thousands of unregistered household units. The metalware cluster is entirely dependent on groundwater. The status of groundwater table of Moradabad has a critical ecological context because the ‘River Ramganga’ is an aquifer-fed river in this region, therefore the flows in the river directly depend on the status of groundwater in the district. Technological improvements have been a key in the success story of Moradabad’s metalware sector. However, the consequence of this technological progress or the gaps in the current technologies on the environment in general and water use in particular has received relatively less attention. The metalware industry uses large volume of groundwater with very limited measures to reduce water use across industrial processes. The consumption of fresh water varies remarkably across big export units and household-level units. Fresh water is mainly consumed either during the rinsing of electroplated articles or after Ultrasonic Cleaning of articles before rinsing. Rinsing in the majority of units is still an inefficient system, which includes continuously and simultaneously operating multiple fresh water taps thus leading to extraordinary high use of fresh water. It is estimated that about seventy percent of the total freshwater used by the metalware industry is consumed in the rinsing process.

This paper documents the impact of WWF-India’s interventions from 2013 to 2024 around collective action industries, on the mainstreaming of cleaner technologies in Moradabad's metalware cluster. WWF-India in collaboration with Indian Institute of Technology (IIT), Kanpur initiated exploring cleaner technology interventions in 2013-14, which primarily consisted of investigating and field testing a technical solution to reduce fresh water use during the rinse process. However, it is critical to state that this journey of exploring a technological solution was weaved around the concept of ‘*multistakeholder approach*’. WWF-India and IIT-K methodically studied the uptake of technology by the metalware sector and later developed a technology solution to reduce fresh water consumption in the rinsing process. This partnership led to the development of a new manual rinsing mechanism known as the Counter Current Mechanism (CCM). This rinsing system essentially comprised of a composite iron tank, which had multiple partitions and discontinuation of all freshwater taps except one. This manual CCM was demonstrated in nine pilot industries during 2014-2016 and the impact of the manual CCM was studied in partnership with industries and academia. The stakeholders actively worked on improving the design of the manual CCM

and by 2017-18 a new design of the CCM was developed, which made the CCM as a completely automatic mechanism. An automatic CCM comprised of a composite Poly Propylene (PP) tank with three partitions and holes drilled on walls separating each chamber, which allowed water to flow from one partition to the other. A TDS controller mechanism is incorporated in the CCM to disconnect the flow of fresh water whenever the TDS is under the threshold (a pre-defined benchmark value). The consumption of water during rinsing at this particular CCM is measured by installing a dedicated water flow meter. The CCM is supplied with fresh water from one tap only unlike from two to three taps in the conventional rinsing system. There will be no supply of fresh water from the tap whenever until the TDS value in the most polluted chamber is below the threshold TDS as this would imply that the TDS of water is within range and fit for rinsing. However, the moment the TDS value of the most polluted chamber goes above the threshold TDS value the solenoid valve would be activated and that will lead to supply for fresh water from the tap. The supply of fresh water from the tap will stop the moment the TDS value in the polluted chamber falls below the threshold TDS value due to dilution.

The collective action by WWF-India and other stakeholders has led to the adoption of 162 automatic CCMs by forty industries during 2010 and till now. The cumulative share of these forty industries in the total export of metalware products is estimated to be in the range of 40 to 57 percent. Therefore, these forty industries are a good sample to capture the economic brevity of Moradabad's metalware cluster. The impact of automatic CCM on reduction of freshwater consumption in rinsing was studied by recording water consumption and number of articles rinsed in the CCM being studied on a daily-basis. A similar dataset was collected during the baseline study, i.e. before converting or replacing the traditional rinsing facility into an automatic CCM. It was estimated based on the data set that the average reduction in freshwater consumption was in the range of twenty-five percent to forty-seven percent after installation of automatic CCM. This sharp reduction in freshwater use further reduced the running cost of the Effluent Treatment Plants (ETP) thus enabling the industry to acquire double gain. The study based on stratified random sampling also estimated a total reduction of about 22 million liters from June 2020 to June 2024. The assessment methodology and the dataset used were also subjected to a creditable third-party auditor and the audit report validated WWF-India's methodology and its accuracy. This study has also assisted the district administration in encouraging the cluster for wider adoption of automatic CCM, which subsequently followed the formation of a working group and a letter issued by the district administration to representatives of the metalware sector. The stakeholders involved in the initiative equivocally recognize the necessary policy push that is needed to scale up the adoption of automatic CCM by the positive consequence of this technological solution.

Keywords: *Cleaner technologies, metalware sector, counter current mechanism, automatic, freshwater reduction*

DEVELOPMENT OF A SEDIMENTATION INFORMATION SYSTEM FOR RESERVOIRS IN THE KANDI REGION, PUNJAB, INDIA

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Reservoir sedimentation is a persistent issue in water resource management, particularly in regions with sediment-prone catchments such as the *Kandi* region of Punjab, India. To address the challenges posed by sediment accumulation and capacity loss, this study presents the development of a Reservoir Sedimentation Information System specifically tailored for reservoirs in the *Kandi* region, with a focus on the Chohal and Damsal reservoirs. Leveraging the capabilities of remote sensing and GIS, this research successfully estimates key metrics including water spread area, reservoir capacity, and sedimentation rates using data from Landsat 7&8 and Sentinel-2 satellite. The developed system integrates these metrics into a user-friendly platform, providing a powerful tool for policymakers, water resource managers, and local stakeholders to make informed decisions regarding reservoir management and sedimentation control. The primary objective of this study was to develop a reservoir sedimentation monitoring system that could offer insights into the sedimentation patterns of the key reservoirs in the *Kandi* region. This study captured sedimentation dynamics and their impact on water spread area and capacity. The results reveal that Chohal and Damsal reservoirs display a positive correlation between water spread area and increasing elevation, underscoring the precision of satellite-based monitoring in assessing reservoir capacity changes over time. In particular, the study's dual use of Landsat and Sentinel datasets allowed for a comparative analysis, highlighting the improved accuracy achieved with higher-resolution Sentinel-2 imagery in estimating reservoir metrics. For the Chohal Dam reservoir, analysis of Landsat data reveals a capacity loss of approximately 30.2% over a 36-year period, with an annual sedimentation rate of 0.84%. Comparatively, the Sentinel-2 data indicate a reduced capacity loss of about 25.2% over the same timeframe, corresponding to an annual sedimentation rate of 0.70%. These results suggest that the higher spatial resolution available from Sentinel-2 yields more accurate capacity estimates and highlights the variations in sedimentation rates based on the data source. Similarly, for the Damsal Dam reservoir, Landsat imagery indicates a capacity reduction of 33.6% over 34 years, with an annual sedimentation rate of 0.99%. Sentinel-2 data, on the other hand, show a capacity loss of approximately 27.8%, with an annual sedimentation rate of 0.82%, again illustrating the precision gained with higher-resolution satellite imagery. These findings validate the use of remote sensing in monitoring long-term changes in reservoir capacity and sedimentation rates, which are crucial for effective reservoir management. The development of the information system represents a significant advancement in reservoir sedimentation analysis by integrating spatial datasets, elevation-area-capacity curves, and sedimentation rates into a single GIS-based platform. This system was designed to offer an intuitive interface and interactive features that empower stakeholders to engage directly with the data. A key feature of this system is the development of volume calculators for both reservoirs. These calculators are built to utilize elevation-area-capacity relationships derived from satellite data and historical records. By incorporating both the original and updated elevation-area-capacity curves, the developed system enables users to observe capacity trends over time, enhancing

their ability to project future sedimentation impacts and capacity reductions. Beyond the capacity calculator, this system consolidates additional data on soil characteristics, water quality, and sediment composition, offering a comprehensive view of reservoir health. Soil characteristics within the catchment areas, for instance, provide insights into erosion sources and sediment quality, informing conservation strategies. Water quality data allows stakeholders to evaluate the ecological status of the reservoirs and assess potential impacts of sedimentation on water quality for downstream uses including agricultural irrigation. By encompassing these variables, the system supports an integrative approach to reservoir management. One of the key achievements is demonstrating the value of such systems for regions with limited access to ground-based survey data. In the *Kandi* region of Punjab, physical monitoring of reservoirs can be challenging due to rugged terrain and resource constraints. This system offers a practical, efficient alternative by capitalizing on remote sensing technology to deliver timely updates on reservoir status, allowing for proactive sedimentation management. Furthermore, by automating data analysis and providing user-friendly outputs, the system reduces reliance on specialized technical skills, enabling local officials, resource managers, and other stakeholders to interpret and utilize the data effectively. The outcomes of this study underscore the critical role of ongoing monitoring and adaptive management practices to ensure the resilience of water resources in sediment-prone areas. Reservoir sedimentation, if left unmanaged, can severely diminish storage capacity, affecting water availability for agriculture, drinking water, and industrial uses. By quantifying capacity losses and sedimentation rates, this system provides stakeholders with the knowledge needed to implement timely interventions, such as desilting operations, catchment area conservation, and sustainable water use strategies. Additionally, the system's ability to project future sedimentation trends facilitates long-term planning, helping policymakers make informed decisions to secure water resources for future generations.

This study establishes the developed system as a vital tool for the sustainable management of the Chohal and Damsal reservoirs in the *Kandi* region of Punjab. By incorporating Landsat and Sentinel-2 satellite data, the system provides accurate, real-time insights into sedimentation rates, reservoir capacity, and other essential metrics. This GIS-based platform not only improves the accuracy of sedimentation assessments but also offers a comprehensive decision-support system that integrates multiple dimensions of reservoir health. The findings highlight the significant potential of remote sensing and GIS in enhancing reservoir management practices, particularly in sediment-prone regions like the *Kandi* area, where traditional monitoring approaches are often impractical. This system also underscores the importance of satellite-based methodologies in adaptive water management and ecological conservation. As sedimentation continues to impact water bodies globally, such systems offer a scalable, replicable solution for monitoring and managing reservoir sedimentation in real time. By enabling proactive reservoir management and promoting sustainable resource utilization, the developed system aligns with broader goals of water security and environmental resilience in Punjab and similar regions facing sedimentation challenges. This study demonstrates the transformative potential of combining GIS and remote sensing to address complex environmental challenges and provides a foundation for future innovations in reservoir management systems.

Keywords: *Reservoir sedimentation, GIS, remote sensing, reservoir capacity, Kandi region*

ADVANCING GROUNDWATER LEVEL PREDICTION USING PHYSICS-INFORMED NEURAL NETWORKS AND MACHINE LEARNING FOR TRANSIENT HEAD VARIATION

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Groundwater (GW) level prediction is pivotal in sustainable water resource management, especially in regions vulnerable to water scarcity. Traditional prediction methods often struggle with the complexities of spatial and temporal variations in GW systems, necessitating advanced machine learning (ML) approaches. In this study, we investigated the effectiveness of the Kolmogorov-Arnold Network (KAN) in predicting GW levels and compare its performance with a standard Artificial Neural Network (ANN). KAN, known for its ability to explain, alongwith robust feature representation, integrates domain knowledge, potentially enhancing model interpretability and prediction accuracy. We assessed each model's accuracy and ability to capture GW fluctuations over time using a dataset generated from a hypothetical MODFLOW model simulating transient groundwater dynamics under varied conditions. Our findings suggest that KAN offers advantages over ANN regarding precision and insight, making it a promising tool for improved, transparent groundwater management.

In this study, we developed a GW model of the Ain River basin in France using MODFLOW 2005 to simulate spatial and temporal head variations. By repeatedly running the MODFLOW model under various boundary conditions and pumping scenarios, we generated a comprehensive dataset to capture the dynamic behavior of GW heads in the basin. Specifically, the inputs were the spatial coordinates (X, Y), time (t), external flow (W), hydraulic conductivity (Hk), and specific yield (S). We applied two machine learning models for GW-level prediction: the Kolmogorov-Arnold Network (KAN) and a conventional Artificial Neural Network (ANN). The ANN, widely used for GW modelling due to its flexibility and data-driven approach, captures patterns in the dataset but often lacks interpretability, making it challenging to connect predictions to underlying physical processes.

In contrast, KAN employs a structure that explicitly integrates knowledge of input-output relationships, enhancing interpretability by reflecting the underlying interactions within the data. This feature makes KAN particularly suitable for GW prediction, where understanding complex interactions is crucial for effective management decisions. The performance of both models was evaluated in terms of prediction accuracy and interpretability, highlighting KAN's potential as a more insightful tool for sustainable GW management. For spatial coordinates (X and Y), sharp changes in spline values might indicate areas with higher hydraulic gradients or more permeable subsurface structures, while smoother trends suggest uniform groundwater conditions. In time (t), periodic patterns in the spline could reflect seasonal groundwater fluctuations, while gradual trends may indicate long-term changes like groundwater depletion. Sudden changes might show responses to short-term events like rainfall or pumping variations.

The spline for K reflects the sensitivity of the groundwater head to aquifer permeability. Steep gradients suggest dynamic responses in areas of high permeability, while flatter trends indicate more stable conditions. Finally, the spline trend for S reveals the influence of specific yield on groundwater head. Steep changes suggest high sensitivity, often seen in unconfined aquifers, while flatter trends imply less impact, typical of unconfined or transmissive areas. These spline patterns in KAN provide interpretable insights into aquifer dynamics, enhancing understanding of groundwater behavior in the Ain River basin and aiding in data-driven resource management.

The results indicate distinct performance differences between the Kolmogorov-Arnold Network (KAN) and the Artificial Neural Network (ANN) predicting groundwater head. KAN achieved a training RMSE of 181.1 and a test RMSE of 212.3, showing a stable performance across training and testing. This suggests that KAN's in-built spline activation function effectively captures complex relationships between input variables and groundwater head, enhancing generalization to unseen data. The spline functions likely provide a better interpretive framework, allowing the model to capture non-linear trends in the dataset with reduced overfitting. In contrast, the ANN exhibited a much lower training RMSE of 109.7 but a significantly higher test RMSE of 652.3, indicating overfitting. The sharp discrepancy suggests that the ReLU activation function, while effective in minimizing the training error, struggles to generalize in this application, especially with only three neurons in the hidden layer. The ANN's poor test performance implies limited interpretability and an inability to accurately predict groundwater head outside the training data.

In conclusion, the KAN demonstrates superior generalization and interpretability over traditional ANNs for groundwater head prediction, particularly in the complex hydrogeological setting of the Ain River basin. While the ANN achieved a lower training RMSE, its high test RMSE indicates overfitting and limited robustness in predicting unseen data. The KAN, equipped with a spline-based activation function, provided more consistent results across training and testing, highlighting its capability to capture intricate non-linear relationships in groundwater dynamics. This stability and interpretability make KAN a promising tool for environmental modeling, where understanding variable interactions is crucial. Thus, KAN's performance in this study underscores its potential for enhancing groundwater management strategies through accurate and interpretable predictive modeling.

Keywords: *Groundwater modelling, artificial neural network, machine learning, MODFLOW, transient groundwater flow*

Theme 12

VADOSE ZONE HYDROLOGY AND AGRICULTURE WATER MANAGEMENT

SIGNIFICANCE OF SOIL MOISTURE PROBES IN CALIBRATING HYDROLOGICAL MODELS

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Soil Moisture in vadose zone plays a crucial role in a hydrological cycle and determines the water availability for vegetation especially for crop growth in rainfed agriculture areas. During the cropping period the soil moisture varies between the state of saturation to permanent wilting point depends on the crop stage and the effect of preceding rainfall events. Precise estimation of soil moisture helps to project the seasonal irrigation demand and optimize the water allocation at respective stages of crop growth. Hydrological models are often found as an effective tool for assessing the hydrological cycle and helps in partitioning the rainfall into surface and subsurface components. Calibrating the model parameters is considered as the important step for simulating the actual scenario which directly defines the performance of the model. Hence the objective of this study is to identify the sensitive parameters through calibrating the hydrological model with respect to the data obtained from permanent soil moisture station and understand the subsurface hydrology in a better way. This study is an attempt to make use of soil moisture data measured from soil moisture instruments installed at field for the model calibration and to identify the sensitive parameters of the model as well the local boundary conditions impact the soil sensor.

In this study, Variable Infiltration Capacity (VIC) hydrological model is chosen as it estimates the subsurface soil moisture values at user defined depths up to 1.5 m below the surface level. The data from permanent soil moisture station installed at GB Pant agricultural university is taken for calibration and for identifying the sensitive parameters in the model. The reason for point scale calibration and validation of Soil Moisture is to identify the field soil moisture response to local boundary conditions and to narrow down the specific parameters which are sensitive for model calibration. VIC model is a macroscale semi distributed hydrological model which simulates grid wise water balance components in terms of Evapotranspiration, Runoff, Root zone and Deep zone soil moistures. VIC model includes the grid wise input parameters in terms of meteorological data like Rainfall, Temperature (Min and Max), land class information like area of each land class in a grid, root fraction/root distribution, Leaf Area Index (LAI), Albedo, soil hydraulic properties like permeability, bulk density, saturation, field capacity and permanent wilting point. Here meteorological data (Rainfall, MinT and MaxT) from India Meteorological Department (IMD) is taken, National Bureau of Soil Survey and Land Use Planning (NBSSLUP) soil data is used, MODIS-MOD 15 LAI is used for defining monthly vegetation properties and further validated using secondary data and literatures. MODIS-MOD 43 is taken for monthly Albedo data. Secondary data were used for defining root fraction/root distribution beneath the surface of the selected crop. Single grid simulation approach is used, the grid resolution is considered as 3” (~5.5 Km) and a homogenous vegetation cover is defined for each crop stage for the entire grid as collected from field and the properties of the subsurface soil profile were defined in the model. The data from permanent soil moisture (PSM) instrument installed at G. B. Pant University of Agriculture and Technology by National Remote Sensing Centre (NRSC) is used for calibrating and assessing the performance of the VIC hydrological model. The soil moisture data was taken from *https://bhuvan.nrsc.gov.in/nhp/vic-soil-moisture-dashboard* for the Layer 1 from 0 - 15 cm and Layer 2 from 16 – 30 cm for a period between February 2022 to December 2022. The PSM was installed in the rainfed area. Two types of vegetation cover were observed during the study period namely Green Peas and Medium to Tall grass respectively. The model run was made during February 2022 to December 2022 using daily meteorological data, monthly LAI and root fraction distribution in the subsurface layers for the respective vegetation covers. The initial state of soil moisture and root fraction distribution was updated for each crop stage and the model was calibrated and validated for its best fit using statistical performance indicators.

The observed soil moisture obtained from PSM is compared with the VIC simulated soil moisture at the subsurface layers. The boundary conditions are updated at each crop stage and the calibration process was carried till its best fit. It is observed that root fraction definition in the model plays a significant role in subsurface soil moisture variation along with the antecedent moisture conditions which is influenced by local meteorological conditions. Since the vegetation cover in the selected site has a shallow root fraction distribution, the influence of variation is observed more in the layer I soil moisture i.e., up to 15 cm during initial stage. As the vegetation growth proceeds further in the season, the monthly LAI defined in the model along with the root fraction influences the variation of soil moisture in layer II i.e., up to 30 cm. It is observed in the results that the variation of subsurface soil moisture has a strong agreement with the Evapotranspiration as it is witnessed during the crop growth stage. The performance was assessed through the statistical indicators like R^2, Nash Sutcliffe Efficiency (NSE) and Kling Gupta Efficiency (KGE) yields an agreement between observed and simulated as 0.89, 0.69, 0.21 in Layer I and 0.81, 0.03, 0.23 in Layer II respectively. Hence the study concludes that soil moisture variation in the hydrological model is a function of root fraction distribution, LAI definition in the model and the meteorological conditions. Thus, the optimized root fraction distribution could be used for simulating the similar vegetation/crop types and soil type in the hydrological model. It is proven from this study that PSM instruments are significant in calibrating and validating the hydrological models at micro level and upscaling the same into macro framework for its application in various hydrological studies with similar crop and soil conditions.

Keywords: *Calibration, modeling, root zone, soil moisture, vadose zone*

ESTIMATING SOIL EROSION USING RUSLE MODEL TECHNIQUE IN AMBA RIVER BASIN, MAHARASHTRA, INDIA

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About 175 million hectares of land in India require soil and water conservation measures to address the increasing issue of soil erosion. Among the different types of erosion, sheet and rill erosion are the most significant, leading to substantial decline in agricultural productivity. Soil erosion in developing countries like India is primarily driven by raindrop spray energy and various human activities, which collectively trigger land degradation. Soil erosion is a three-phase process involving the detachment of soil particles, their transport by agents such as water or wind, and eventual deposition when the transporting energy diminishes. Factors contributing to soil erosion include intensive agricultural practices, soil degradation, and changing global climatic conditions. The consequences are profound and far-reaching including the loss of fertile topsoil, reduced soil fertility, soil compaction, eutrophication, groundwater contamination, and, adverse impacts on agriculture, water quality, ecosystems, and landscapes. Floods, in particular, intensify soil erosion. High water volume and velocity during floods dislodge and transport soil, stripping nutrient-rich topsoil essential for fertility and agricultural productivity. This eroded soil is often deposited downstream, resulting in sedimentation that alters landscapes and disrupts ecosystems. Predicting soil erosion is crucial to mitigate these challenges and implementing effective conservation strategies. This study focuses on estimating soil erosion in the Amba River Basin for 2018, a year marked by severe floods in the region. The research aims to evaluate the soil erosion using the Revised Universal Soil Loss Equation (RUSLE) model integrated with Geographic Information Systems (GIS) and remote sensing tools. The Amba River Basin, spans 929.75 km^2. The river originates in the Sahyadri ranges near the Khopoli-Khandala road at an elevation of approximately 554 meters. The region exhibits diverse geomorphological features, including mangrove vegetation in the lower basin, extensive agricultural zones along the riverbanks, and mudflats that support a rich variety of seabirds. The basin experiences a tropical climate, with an average annual rainfall of 3157 mm, 95% of which occurs during the southwest monsoon. The RUSLE model was employed to estimate the average annual soil loss in the basin. This model integrates five key factors: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), crop cover (C), and conservation practices (P). By combining these parameters, the RUSLE model provides a comprehensive understanding of the soil erosion processes and potential risks in the region. The R factor measures the erosive force of rainfall and was calculated using long-term rainfall data. In the Amba River Basin, R values ranged from 1266.35 to 1553.02 MJ mm/ha/h/year, with higher values observed in Sukeli and Karjat due to abundant rainfall. The K parameter depends on the physical and chemical properties of the topsoil. The K values in the region ranged from 0.018 to 0.021 t h ha/MJ/ha/mm, with lower values indicating reduced permeability and antecedent moisture content. LS factor reflects the influence of topography on erosion, with values increasing up to 645.98 as slope and flow accumulation rise. Using NDVI (Normalized Difference Vegetation Index), the C values ranged from 0.027 in dense forested areas to 0.053 in rocky terrains. Lower values indicate better soil protection due to vegetation cover. The P factor values ranged from 0.55 to 1, with higher values representing poorly managed areas more susceptible to erosion. The RUSLE model estimated that the average annual soil loss in the Amba River Basin is approximately 765.88 tons/year. Analysis of erosion severity maps revealed that 24% of the basin's area experiences high or very high erosion, underscoring the urgent need for targeted conservation measures. The study also identified a strong correlation between increased agricultural activity and high erosion risk, emphasizing the challenges posed by unsustainable agricultural practices. The findings highlight the importance of integrating empirical soil erosion models like RUSLE with GIS and remote sensing tools for effective resource management. This integration facilitates the creation of erosion severity maps, which are vital for regional planning and prioritizing conservation efforts. By identifying erosion-prone areas, policymakers and land managers can implement adaptive strategies tailored to mitigate the adverse impacts of soil erosion. Additionally, the study underscores the interplay between agricultural expansion and soil erosion risk, emphasizing the need for sustainable land management practices. Future research should focus on developing and evaluating adaptive conservation strategies that address the unique characteristics of the region's land use and topography. Such efforts will not only help mitigate soil erosion but also contribute to the long-term sustainability of the region's natural resources. In conclusion, the Amba River Basin study demonstrates the efficacy of using models like RUSLE in conjunction with GIS and remote sensing for assessing soil erosion. The insights gained from this study can inform soil conservation initiatives, promote sustainable land use practices, and guide future studies aimed at addressing soil erosion challenges.

Keywords: *Amba River Basin, GIS, NDVI, RUSLE, Soil erosion*

ROAD MAP FOR WATER EFFICIENT FARMING IN INDIAN HIMALAYA

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Water is core natural resource in farming, facing several challenges for the present and future including availability at source and sink. Age-old edict venerating the river systems *"Oum Gange cha Jamunechaive Godavari, Saraswati, Narmade Sindhu, Kaveri Jaleusminsannidhi Kuru"* highlights the cultural thrust on water in India. It contributes to Environment, Food, Livelihood security along with ensuring economic wellbeing and resilience to climate change. The Indian Himalaya is grouped under AER (Agro-Eco Region) 1: Western Himalaya Cold Arid Ecoregion, AER 14: Western Himalaya Warm sub-humid to humid with inclusion of per-humid eco-region, AER 16: Eastern Himalaya Warm sub-humid eco-region and AER 17: North eastern Hills Warm per-humid eco-region. Majority of small holding farmers in Himalaya practice farming under widely diverse agro-ecosystems. Hill farming has a major role in maximizing water efficiency and productivity. The knowledge and experiences gained in India over a century in soil conservation and watershed management have provided a strong base for water efficient farming. Summarizing the task and road map for future needs, a comprehensive management could well provide roadmap for future.

In mountain ecosystem, seasonal extremes and gaps in precipitation, vanishing vegetation cover, slopy terrains along with poor sink due to depth and gravels present major management issues. The criticality of water resource is well recognized. There is limited possibility of tube wells and canal irrigation, which may be compensated by conservation and harvesting of water. Availability of water for farm sector has to be on a time and volume specific. Major concerns for this sector are storage, efficient use of water sources, increasing wastage, pollution and degradation. The decisions and operations of farming have to be synchronized with the nature and availability of water resource. The pattern of receding water in the storage is an important tool. The inclusive research includes management of water, eco-system and meticulously scaled-up to farm holding to watershed to region, thereby targeting the regional and global opportunities. The watershed management approach is advocated for regions with lack of water conservation and storage, over exploitation of vegetation cover, water losses due to inefficient water conveyance and application aggravating the stress. Comprehensive and water centric management is needed under watershed approach.

Watershed is inclusive of ecosystem, natural resources, inhabitants, production systems along with on- and offsite implications. Degradation, loss of sink, fine particles, organic fraction, higher cost due to energy needs and applied resources severely affect productivity and viability of hill farming. Watershed management components include natural resources, their utilization, conservation and aggradation, humans and livestock and market and associated infrastructure, environment and climate. Development of water resources is another approach. Under this approach harnessing the available water into usable form on grid basis is adopted as inclusive approach. Conservation and ponding of rain water, diverting flowing water to farm fields and water bodies, surface and sub-surface water storage, along with appropriate conveyance and application systems forms the core management. The rainfall intensity moderated by vegetative cover, terrain and soil conditions, provides the balance available for crop growth. Integrated farming, protected cultivation and operational management is another option. Agro-Ecosystem approach is perceived as logical basis for optimum use and management of resources by several research workers. It involves management of an ecological unit, having similarities of natural resources, micro-climate, energy and production systems. Diversified hill cropping and Farming Systems Families is also an important approach. The primary aspects include production systems planning which involves demand, ecosystem potential, resources, skill and capacity based and policy links that are closely dependent on market intelligence. Agro-ecosystems are characterized and quantified. These include orientation to sun, landscape positioning, field slope, soil depth, texture and gravel content. Landscape forest cover whether up-stream or downstream is also included. Productivity is grouped under high, medium and low level. Emerging scenario-life-style purchasing capacity and consumers' awareness are the other factors that are considered along with farming practices.

Hill Terrain limits large scale use of canal or tube well irrigation. Whereas, small irrigation channels (Guls or Kuhls) face perpetual problem of repairs due to unstable terrains. Development of water harvesting ponds was appropriate. Protected cultivation is a suitable technology because of small holding size of around 0.4 to 0.6 ha/family. It has distinct advantage of 3 to 4 times higher production per year. It facilitates year-round cropping even during harsh winters. The physical damage to fruits and plants due to hail storm and excess rains are also prevented. It works as excellent tool for carbon sequestration. Apiary associated with poly house adds to the advantages. Grid based water harvesting ponds entail due emphasis to perennial vegetation, giving thrust to sustainable water resource development will. The improved vegetative cover will not only reduce splash erosion but also result in reduced tillage. This will positively influence soil erodibility. In turn will impart climate resilience to farming system. Inclusive advantage of Watershed management was highlighted by IPCC in improving the ecosystem resilience to climate change. Strategy consisted of runoff control, moisture conservation and vegetative cover as highlighted in the Hydrologic cycle.

To summarize, augmentation, conservation and multiple utilization of water resources, inclusive of entire cause and effect relationship has to be primary intervention towards water secured future. Water conservation in both non-arable and arable land, recycling in protected cultivation and harvested water fisheries are highly successful. The secondary interventions have to be water efficient farming and other sectors appropriately matching the defined objectives. The third intervention involves long term on-farm and on-station comprehensive, need based and problem-solving research, useable technology and skill development. Both these interventions were implemented on on-farm eco-systems, linked to market factors. The fourth equally crucial is enabling policies, investment both in human resources, infrastructure and realistic costing. The fifth important intervention has to be strong incentives and dis-incentives towards maximizing efficient use of water. Stage-wise involvement of stake holders was key to success. Wider adoption of the technologies is expected to contribute to Water Secured Future.

Keywords: *Water security, watershed management, water conservation, farming, hilly terrain*

ASSESSMENT OF AGRICULTURAL WATER AND LAND PRODUCTIVITY USING WATER ACCOUNTING PLUS FRAMEWORK FOR LUNI RIVER BASIN, INDIA

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In India, ensuring food security amidst limited water resources will become a growing concern in the coming decades. The agricultural sector is the major freshwater consumer in India, accounting for more than 80 percent. Besides, low water use efficiency and crop productivity are major challenges for developing countries like India. Furthermore, spatial and temporal information regarding water productivity and land productivity remains a significant challenge due to limitations in data availability. This study aims to address these critical gaps by analyzing water consumption patterns, Land Productivity (LP), and Water Productivity (WP) for both irrigated and rainfed crops in the Luni River basin, Rajasthan over an 18-year period, from 2001-02 to 2018-19.

The Luni River, the longest river in Rajasthan, originates in the Naga Hills (Nag Pahar) of the Aravalli Range in Ajmer district at an elevation of 550m (MSL) and traverses 495 kilometers in a south-westerly direction, ultimately disappears into the marshy land of Rann and Kutch region in Gujarat. It spans a geographical area of 72,000 km^2, traversing seven districts of Rajasthan: Ajmer, Nagaur, Jodhpur, Pali, Barmer, Jalore, and Sirohi. The geographical area of the basin spans arid to semi-arid conditions and encompasses three distinct agro-climatic zones: the northeastern upper part falls within the western dry region, the northwestern lower part lies in the central plateau and hills region, and the southernmost part extends into the Gujarat plains and hill region. The annual rainfall across the basin varies significantly, ranging from 1,048 mm in the western region to 221.5 mm in the southwestern area, with an average rainfall of 320 mm. Mostly 95% of the annual rainfall occurs during the monsoon months from July to September. The analysis is conducted using the Water Accounting Plus (WA+) framework, a Python-based tool that entirely relies on globally available remote sensing data. The study was focused on assessing the water and land productivity of a major cereal (Bajra), which is a key crop in the study area. WA+ framework is fully based on the remote sensing datasets, following geospatial datasets have been used in this study: Gridded rainfall from India Meteorological Department (IMD) with spatial resolution of 0.25°×0.25°, Actual Evapotranspiration (ET) from Simplified Surface Energy Balance (SSEBop), Leaf Area Index (LAI) from MODIS, Potential Evapotranspiration (PET) from Global Data Assimilation System (GDAS), Gross Primary Products (GPP) and Net Primary Products (NPP) from MODIS. These geospatial datasets were collected from the period 2000 to 2019 to assess the WP and LP for the Luni River basin. WA+ framework categorize the land use land cover into Protected Land Use (PLU) as designated for conservation and protection, where human activities are restricted, Modified Land Use (MLU) that have been significantly altered by human intervention for agricultural and other productive purposes, Utilized Land Use (ULU) engaged in various ecosystem services that typically exhibit limited human alteration, and Managed Water Use (MWU), where the natural water cycle has been artificially modified, particularly for agricultural and urban applications. These four major

land-use covers are further subdivided into 80 classes based on distinct open-source geospatial inputs. To prepare the WALU land use land covers for the study area, various geospatial datasets i.e., land use land cover from NRSC, Rainfed and irrigated crop area from MIRCA, Irrigated crop map from IWMI, Population from WorldPOP, Water bodies information from JRC-EU, protected areas information from WDPA, and ESA Globcover map have been used.

The results of the study were verified with field data, Crop Cutting experiments (CCE) were conducted to assess the yield and productivity of crops. In this study, CCEs were conducted at multiple locations across the basin to collect productivity data for major Kharif crops in the Luni basin, including guar, bajra, jowar, and groundnut. A 1 m × 1 m sampling frame was utilized for the CCEs, within which crops were harvested and their yields were precisely measured to determine the productivity of these major Kharif crops.

The analysis differentiated between rainfed and irrigated conditions, providing insights into how these different agricultural practices impact productivity. The result of the study reveals land productivity for the major cereal in the basin varies from 175 to 596 kg/ha/year from 2001-02 to 2018-19 under rainfed conditions, whereas, under irrigation, it varies from 201 to 900 kg/ha/year. The total land productivity of the basin varies from 482 to 1369 kg/ha/year with an average land productivity of 870.11 kg/ha/year. The spatio-temporal results of the study also reveal a significant increasing trend of land productivity under irrigation conditions. Similarly, the water productivity of the basin varies from 0.83 to 1.64 kg/m^3 with an average WP of 1.19 kg/m^3 during the study period. In conclusion, this study demonstrates the effective application of the Water Accounting Plus (WA+) framework in analyzing and mapping spatio-temporal water consumption patterns, Land Productivity (LP), and Water Productivity (WP) for irrigated and rainfed crops in the Luni River basin.

Keywords: *Irrigated and rainfed crops, land productivity, Luni River basin, water accounting plus, water productivity*

INTENSIVE IRRIGATION AFFECTING GROUNDWATER QUALITY: A CASE STUDY FROM PUNJAB, INDIA

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Agriculture in Punjab is heavily reliant on groundwater, with more than 70% of irrigation demands met through tube wells. The region's groundwater quality has become a major concern due to its direct linkage with extensive agricultural practices, especially in the context of intensive irrigation. Punjab’s agro-ecological landscape exhibits significant variations in groundwater quality, driven by diverse hydrogeological conditions. The very high evapotranspiration rate in Punjab accelerates sodium accumulation in soil which enhances sodicity of top soil and vadose zone soil. The natural rainfall recharge and irrigation return flows drag sodium from these sodic layers while infiltrating through top soil and leaching through vadose zone. The percolating water eventually joins the groundwater table in unconfined aquifers, imparting salinity known as inland salinity, which significantly contributes to Punjab's severe groundwater quality issues. The fine-textured soils prevalent in regions with shallow unconfined aquifers such as Malwa and parts of the Siwalik ranges in western, southwestern, and northern Punjab are especially prone to water-logging and high salinity issues due to excessive irrigation, which is further aggravated by long groundwater residence time and high evaporation rates. These regions are characterized by a thin vadose zone (<2mbgl). Presence of such a shallow water level often leads to a condition exacerbating issues of nitrate contamination, soil degradation through sodium accumulation (increasing Sodium Adsorption Ratio) and structural loss.

Conversely, regions like Majha, Doaba, and Sirhind in central and southeastern Punjab are characterized by sandy loam to loamy soils with semi-confined to confined aquifer systems and a thicker vadose zone reaching up to 70 mbgl. This geological setting makes these areas prone to secondary salinization and accelerated groundwater depletion, which significantly reduces agricultural productivity. The challenges stem from excessive irrigation and deep percolation, which enhance capillary rise and lead to salt accumulation in the root zone. Additionally, over-extraction of groundwater disrupts the hydrological balance, causing aquifer compaction and, in severe cases, land subsidence, further exacerbating the region’s agricultural and ecological vulnerabilities. This study examines the relationship between groundwater quality and irrigation practices, highlighting the impacts of varying vadose zone thickness on groundwater salinity, as well as variations in aquifer geometry, water table depth, soil composition, and rainfall, and their implications for agriculture. Additionally, it addresses the challenges posed by groundwater over-exploitation.

The methodology for this study includes a combination of hydrogeochemical analyses and vadose zone profiling. Groundwater analysis data such as Total Dissolved Solids (TDS) measurements and isotopic analysis provide a comprehensive overview of regional groundwater quality and its variations. TDS, a critical indicator of groundwater salinity, reveals high concentrations exceeding 2000mg/L in southwestern Punjab, marking the groundwater as unsuitable for both agricultural and domestic use. This is often associated with high Sodium Adsorption Ratio (SAR), which further deteriorates soil and groundwater quality. The poor water quality conditions, which vary spatially, can be attributed to factors

like irrigation return flows, inland salinity, water logging and excessive fertilizer use. The regions with thicker vadose zones, including central and southeastern Punjab, although exhibiting lower TDS values, are vulnerable to secondary salinization caused by excessive irrigation return flows. These return flows contribute to the accumulation of salts in the soil and groundwater, especially in areas where episodic recharge from rainfall or canal seepage is insufficient to flush the salts. The study also integrates groundwater isotopic analysis data (δ18O and δ2H) from published reports to trace recharge sources and mechanisms. Isotopic signatures suggest that precipitation contributes minimally to recharge in the water-logged regions of southwestern Punjab, where over-irrigation dominates. In contrast, the groundwater in central and southeastern Punjab reflects a significant contribution from canal seepage and irrigation return flows. The varying regional conditions present a complex hydrogeological landscape in Punjab, where both salinization and depletion are intertwined with the vadose zone's thickness and the intensity of irrigation practices. The study concludes that the depth to the water table, the thickness of the vadose zone, and the hydrogeological properties of the aquifer system play critical roles in determining groundwater quality. As a response to the dual challenges of salinization and depletion, this research recommends adopting a set of sustainable groundwater management practices. For the regions experiencing salinity due to water-logging, such as southwestern Punjab, measures such as subsurface drainage systems, alternate cropping patterns, and salt-tolerant crop varieties can be beneficial. Additionally, deficit and precision irrigation techniques should be promoted to optimize water use and minimize the adverse effects of excessive irrigation. Managed Aquifer Recharge (MAR) schemes, tailored to specific regional conditions, could play a pivotal role in enhancing groundwater recharge and mitigating the long-term salinity problem in over-exploited regions. The ideal vadose zone thickness of 10 to 50 mbgl provides balanced capillarity and drainage, facilitating optimal soil aeration, nutrient cycling, and water availability for sustainable agricultural production. Beyond this range, the soil's buffering capacity to manage salinity and retain moisture decreases, impacting crop yield and long-term soil health.

The study also emphasizes the importance of a comprehensive groundwater monitoring framework, integrating geophysical surveys, remote sensing, and GIS-based mapping. This framework will help in identifying vulnerable zones and tracking temporal changes in groundwater quality. The integration of groundwater modeling, calibrated with field data, can provide predictive insights into the potential impacts of various management strategies, facilitating better policy formulation. Furthermore, public awareness campaigns and policy interventions, aimed at regulating fertilizer use and encouraging water-use efficiency, are critical for ensuring sustainable groundwater management in Punjab. In conclusion, this study underscores the critical linkages between vadose zone characteristics, aquifer hydrogeology, and intensive irrigation practices in determining groundwater quality. By addressing these factors, and with the implementation of scientifically informed management practices, Punjab can work towards balancing agricultural productivity with the long-term health of its groundwater resources.

Keywords: *Vadose zone, salinity, sustainable groundwater management, water logging, groundwater extraction*

DETERMINATION OF SOIL HYDRAULIC PROPERTIES USING PEDOTRANSFER FUNCTIONS FROM SOIL TEXTURE PROPERTIES IN LUNI RIVER BASIN, INDIA

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Luni basin is the largest river basin in the northwest India, having arid to semi-arid climate. The region receives a very low rainfall of order 400 mm annually, major portion of which is received in the monsoon season. It is located in south-western part of Rajasthan. The Luni River basin is covered mainly by rocks belonging to the Pre-Cambrian rocks to Aeolian and Fluvial deposits of Recent to Sub-Recent age. The region has scarce surface water sources and brackish groundwater sources. Hence, management and utilization of available water resources becomes important. Soil hydraulic properties play important role in modelling and simulation of water movement process (infiltration, conductivity, storage and plant water relationships). Soil hydraulic properties are very much dependent on the textural composition of a soil, and can be predicted with the help of textural information along with other optional data. Texture of soil is an import information, which affects many soil characteristics such as: water holding capacity, aeration, erosion, soil workability, soil productivity and infiltration characteristics. Soil texture is a very stable characteristic which influences saturated hydraulic conductivity and other hydraulic parameters. Soils dominated by larger sand fractions tend to have higher porosity having higher K_{sat} values and have lower water retention content. Soils dominated by larger clay fractions tend to have relatively smaller pore spaces having lower K_{sat} values. Determination of hydraulic properties such as water retention characteristics and K_{sat} is rigorous and time taking exercise. Soil texture information, can aid in the determination of these properties using pedo-transfer functions (PTFs). PTFs are multiple linear regression equations relating the soil hydraulic properties to the texture, bulk density, retention water content at field capacity and retention water content at permanent wilting point. More the information is available closer are the predictions. There are several PTFs developed by various researchers for soils of different regions. Present analysis shows the prediction of K_{sat} and water retention parameter values using Rosetta PTFs with the textural properties of soil samples collected in the Luni River basin. The Rosetta PTFs are ANN based relations between the soil hydraulic functions and textural composition of soil samples.

A total of 54 disturbed soil samples were collected from different locations and depths varying from 10 to 100 cm, and were analysed for textural composition. Texture analysis was performed by Electromagnetic Sieve Shaker for coarse fractions (gravels and sand) and by Master Sizer (MICROTRAC S3500) for fine fractions (silt and clay). Finally, the entire distribution of soil particles is obtained by combining the results of both the analysis. The textural compositions for each soil sample so obtained are partitioned into clay, silt, sand and gravel compositions as per USDA soil texture classification. The compositions obtained are fed into PTFs, which yields the soil hydraulic parameters. The results of the electromagnetic sieving (coarse particles) and particle size analysis (fine particles) yields the particle size distribution of the soil samples analysed. The analyses yield the fractional presence of Gravels, sand, silt and clay particles in the soil sample. The result show that gravel

composition varies from 0 to 35.5 % with a mean value of 4.47 %, sand composition varies from 28.45 to 92.33 % with a mean value of 28.45 %, silt composition varies from 4.23 to 57.19 % with a mean value of 4.23 %, and clay composition varies from 0.07 to 9.55 % with a mean value of 1.84 %. The results show that samples collected vary texturally and comprises soil textures as: Sand, loamy sand, sandy loam, loam and silt loam as per the USDA soil classification, showing the predominance of sand followed by silt with trace presence of clay minerals.

The obtained fractional compositions of each sample analysed are fed to the Rosetta PTFs for the determination of K_{sat} and water retention parameters. The obtained value of K_{sat} varies from 28.13 cm/day for loamy soil to 839.35 cm/day for sandy soil with an average value of 12.75 cm/day which correspond to the loamy sand texture. The value of water retention parameters viz: θ_r, θ_s, α_v and n_v are also obtained which are important for modelling of flow process in the unsaturated zone. The variation in the textural composition along the river path show an increasing trend in sand and silt percentage, while clay shows a decreasing trend for a 10 and 20 cm depth of sampling. At 50 and 100 cm depth of sampling locations the sand % shows an increasing trend and silt shows a decreasing trend. The presence of sand along with silt fraction is predominant in surface soil. These estimates of hydraulic properties obtained by PTFs provide predictions of hydraulic conductivity and water retention parameters which are otherwise time taking and require rigorous lab and in-situ experiments. Spatial information of hydraulic properties is a valuable information in the determination of water retention characteristics and higher K_{sat} regions as potential recharge zones in the Luni basin.

Keywords: *Soil texture, hydraulic properties, pedo-transfer functions, saturated hydraulic conductivity, water retention parameters*

GRAVITY OPEN-CHANNEL IRRIGATION SYSTEMS IN HILL AREAS: A FIELD STUDY IN ANDHRA PRADESH, INDIA

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Natural springs and streams that originate on the hill tops and flow down the slope are the major sources of drinking water as well as irrigation in the hilly areas. A natural spring is defined as the water source which oozes out the groundwater onto the surface, typically at the point of sudden reduction of hill slope or in the foothill regions. On the contrary, a natural stream is fed by both upstream springs, often multiple of them, as well as the direct runoff from the rainfall. The eastern ghat areas in Alluri Sitarama Raju (ASR) district of Andhra Pradesh, India are replete with number of such natural springs and streams. While the yield of a spring is relatively low, such as 2-10 litres per second (lps), the streams comparatively carry larger flows, such as, 100 to 500 lps. Further the spring water is cleaner and free from dust and soil, unlike the surface water streams. Therefore, spring waters are protected, tapped and distributed for drinking purpose in the tribal habitations. On the other hand, the hill streams are abundant source of water for irrigation, particularly to cultivate crops like paddy and vegetables.

Gravity irrigation by diverting stream water from hill tops is a common practice in Dumbriguda and Hukumpeta *mandals* of ASR district. In a typical gravity open-channel irrigation system (GOIS), a check dam diverts the stream water into a cement-lined or earthen open channel and distribution channels finally carrying water to farmlands for irrigation. A reconnaissance study was done on 13 GOISs in association with the Water Resources Department, Government of Andhra Pradesh and three of them were taken up for the detailed study. The reconnaissance study of 13 GOISs found that: there is a general trend of reduction in the flow in the hill springs and streams. Some streams completely dry up during dry period. Shift to coffee cultivation by farmers on the hill slopes in recent years might have influenced the base flows in the streams. Depleted flows in the streams resulted in water shortage in the tail-end of the command areas, leading to failure of paddy crop in the GOISs. This problem is prominent in the GOISs which have predominantly earthen unlined main channels. The bed of the cement-lined main channel got eroded at locations with higher flow velocities. This particularly happened at the take-off location of main channel from the check dam and the segments of main channel with steeper bed slope. Water leakage from the bottom of concrete sidewalls is widespread in most of the GOISs. These leakages are resulting in water not reaching tail-end farmlands and in unequal distribution of water in the command area.

The detailed study was limited to three GOISs located in Ukurba, Panthalachintha and Podili villages in Hukumpeta *mandal*, ASR district. All these systems were about 8-10 years old. Since, Ukurba and Podili are neighbouring villages, there is some overlap in terms of villages benefited. However, these two GOISs provide water to mutually exclusive command areas. The detailed study was carried out using various methods such as groups discussions with farmers, transect walks to different channel locations and visit to the water diversion check dams on the hill tops. Information related to functioning of the systems for the past years, current water distribution and cropping practices, major problems faced by the systems were

gathered through discussions with farmer’s groups. The problems identified from the discussions were listed and field study of each of them was done by visiting those specific locations. Major functional problems in the three GOISs were enumerated broadly dividing them as source-related and distribution-related. Reduction of dry period flows or complete drying up of perennial streams were observed in all the three GOISs studied. Water leaks from the join between side walls and the bed is a wide-spread problem noticed across GOISs. These problems had ultimately resulted in water shortages and crop failures at the tail-end of the command areas. Bed erosion of cement-lined channels, due to higher flow velocities, were found to be common at the channel take-off from the diversion check dams and segments with steeper bed slopes.

Few of the solutions identified were prioritized for carrying out the renovation works. The renovation works are mainly of three types, viz., augmenting the water diversion from the source to the main channel, arresting the leakage of water from the main channel, and ensuring equitable distribution of water. There were also few works that are not directly related to the functional performance of the GOISs, such as, laying of deck slabs on the main channel at the road-crossing points to facilitate smoother vehicular movement. Further, a novel silt-water separation structure (SWSS) was designed and built in Podili reviving the silted-up pipeline, that is taking-off from the end of a cement-lined main channel. While LAYA, with grants from Ajim Premji Foundation (APF), spent financial resources for the renovation works, the authors provided technical support in designing and guidance in proper implementation of the identified improvement works. These interventions need to be observed for longer time to confirm their performance. Measures to augment base flow to the hill streams needs to be integrated for sustainability of gravity irrigation systems.

Keywords: *Gravity irrigation, open channel, silt separation, hill streams, base flow augmentation*

PERFORMANCE EVALUATION OF GLOBAL ET DATASETS USING THE GOOGLE EARTH ENGINE FOR GROUNDWATER AND WATER RESOURCES APPLICATIONS

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Groundwater is the largest freshwater resource, available globally. It is vital for supporting food production and population sustenance. However, groundwater levels are declining in many arid and semi-arid regions, and climate change is likely to exacerbate these declines by increasing evapotranspiration and reducing precipitation, further depleting soil moisture. Several studies highlight the strong link between evapotranspiration (ET) and groundwater recharge, particularly in water-scanty regions to explain how altering ET statistics can influence groundwater recharge in semi-arid climates. Accurate quantification of ET is essential, as groundwater recharge often hinges on the small difference between rainfall and ET. ET directly affects groundwater levels by influencing soil moisture and recharge rates, directly linking atmospheric conditions to groundwater fluctuations. Recent advances in satellite and reanalysis-based datasets have enabled unprecedented improvement in ET assessments at a finer spatial and temporal resolution, though achieving reliable ET estimates requires careful selection of appropriate datasets and methodology.

This study aims to focus on the utilization and accuracy assessment of global ET datasets, available on Google Earth Engine (GEE) through site-pixel evaluation with the conventional Penman-Monteith approach in the semi-arid environment of the northern part of India. Long-term daily historical records of various climatic parameters for 31 years (1990–2020) at the research farm of the Indian Agricultural Research Institute (IARI), New Delhi were used to estimate reference evapotranspiration (ET_0) using the Penman-Monteith equation to serve as ground observations. Many of the remote sensing and reanalysis-based datasets are offered by many global agencies and are useful in detecting spatial and temporal variability in meteorological variables at a finer scale. The global evapotranspiration products viz. Global Land Data Assimilation System (GLDAS) V2.2, Penman-Monteith–Leuning Evapotranspiration V2 (PML_V2), the Terra Moderate Resolution Imaging Spectroradiometer (MODIS, MOD16A2GF) V6.1, Famine Early Warning Systems NETwork (FEWS NET) Land Data Assimilation System (FLDAS) ET and TerraClim ET available on Google Earth Engine (GEE) platform were used for the analysis. Performance evaluation is facilitated through the application of five statistical performance evaluation indices viz., Root Mean Square Error (RMSE), Coefficient of Determination (R^2), Bias (PBIAS), Nash-Sutcliffe Efficiency (NSE) and Index of agreement (d).

The results of this study revealed significant variations in the performance of global evapotranspiration datasets when compared to Penman-Monteith-based estimates in the semi-arid context of central Delhi. Among the ET datasets assessed - GLDAS, PML_V2, MODIS, FLDAS, and TerraClim, statistical indices showed varying levels of accuracy. PML_V2 dataset demonstrated the highest consistency with ground observations, as reflected by higher R^2 values and lower RMSE, making it the most reliable ET product for this region. MODIS-ET estimates generally overestimated ET, particularly during the peak summer months when temperatures are highest. This overestimation suggests that MODIS-ET is less accurate in

extreme heat conditions, possibly due to its spatial resolution limitations and sensitivity to temperature changes. The TerraClim ET dataset performed reasonably well during non-monsoon months, but it showed some discrepancies in periods of high evapotranspiration, primarily due to temperature sensitivity and its limited ability to capture evapotranspiration peaks accurately. This indicates that TerraClim is less reliable during the summer or when ET is at its highest. The GLDAS ET estimates showed good overall performance with a moderate NSE score. However, it tended to underestimate ET during the monsoon period when evapotranspiration is influenced by both rainfall and temperature fluctuations. The GLDAS dataset is less sensitive to rapid changes in ET, which might be due to its reliance on modeled rather than observed data for certain atmospheric variables. The FLDAS-ET dataset also performed relatively well, showing good agreement with observed data during the non-monsoon period. However, the FLDAS dataset struggled during peak evapotranspiration periods, especially in late spring and early summer, where it consistently underestimated ET rates. This discrepancy could be attributed to FLDAS's model configuration, which might not fully apprehend the intensity of seasonal evapotranspiration variability.

The study highlights that while global ET datasets, PML_V2, MODIS, GLDAS, FLDAS, and TerraClim, provide valuable tools for estimating evapotranspiration in arid and semi-arid regions, their accuracy can vary significantly. The PML_V2 dataset emerged as the most reliable for the study area, followed by GLDAS, which performed well but showed few underestimations during monsoon periods. FLDAS and TerraClim also provided useful information but demonstrated limitations during extreme evapotranspiration phases. MODIS overestimated ET, particularly in the hot season, due to resolution limitations. The outcomes from the present study can serve as a guiding document for researchers and investigators in selecting appropriate datasets for various water resource-related applications, including groundwater fluctuation patterns, drought monitoring, hydrological modelling, agricultural water management, and other related studies in semi-arid climatic zones of India.

Keywords: *Global ET products, GEE, groundwater resources, Penman-Monteith Equation, GLDAS*

EVALUATION OF IMPACT OF SHIFTING SOWING DATE ON GROUNDWATER BEHAVIOR IN RICE-WHEAT PLAIN OF NORTH-WEST INDIA

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Groundwater is one of the important components of hydrologic cycle, which is stored in aquifers, rock formations, and beneath soil. Particularly in areas with limited surface water supplies, it is an essential resource for industrial, agricultural, and drinking water uses. Its availability is affected by increasing industrial water demand, a change in land use, and weather patterns. In the dominant agricultural regions such as North-western Indo-Gangetic Plain region, increasing irrigation water demand is a major cause of steady decline of groundwater. In the region, approximately 85% of the land is used for crop cultivation, mostly for rice and wheat production. To ensure groundwater availability for future, development of sustainable agriculture water management practices is crucial to prevent groundwater over-extraction. In this study, four major rice-wheat dominant districts (Karnal, Kaithal, Panipat, and Kurukshetra) of Haryana were selected to evaluate impact of different planting dates on groundwater resources. The study used meteorological data from the ICAR-Central Soil Salinity Research Institute, Karnal, and CCSHAU RRS Kaul weather observatories for the period 2013–2021. Digital elevation model was collected from BHUVAN, while groundwater level data was received from the Groundwater Cell, I&WRD, Panchkula. Cropping pattern information was taken from the Land Use/Land Cover (ERIS) dataset, while hydrogeological and lithological data were obtained from the Central Ground Water Board (CGWB). Three rice-wheat crop planting dates scenarios that correspond to different sowing periods throughout the *Rabi* and *Kharif* season were studied: SWD-1 (sowing from June 15 to November 5), SWD-2 (June 15 to November 15), and SWD-3 (June 15 to November 25). Impact of these crop planting dates scenarios were assessed in the four districts using the AquaCrop model and MODFLOW model. AquaCrop Model was used for estimating irrigation demand and deep percolation for rice-wheat system. The estimated rice-wheat growing season irrigation depth and deep percolation was considered groundwater draft from crop land. Whereas groundwater demand and groundwater recharge from other land uses (forests, residential areas, water bodies, and barren lands) was estimated using the standard methodology (GEC, 2009).

Total groundwater recharge and draft from all land uses were calculated by considering the entire study area as a single hydrological unit. The Visual MODFLOW 6.1 model, a 3D tool, was used to examine the impact of different sowing dates on groundwater dynamics in unconfined aquifer systems. The aquifer depth in the study region ranges from 90 to 180 m, with an average hydraulic conductivity of 22 m per day and a storativity of 0.12. Boundary conditions, including specified flux and head-dependent parameters (e.g., river borders), were integrated into the model. No-flux conditions were applied to the northern, southern, and western boundaries due to the absence of physical boundary features. The aquifer system spans a geographical area of 7,736.18 km², divided into 7,496 cells with a uniform cell size of

1 km × 1 km. Data from 205 observation wells, representing the entire study region, were used for model calibration (2013–2017) and validation (2018–2021). Model calibration, conducted using the PEST auto-calibration tool, involved defining hydraulic conductivity zones and adjusting specific yield values. The calibrated hydraulic conductivity ranged from 15.75 to 110.28 m/day across the region.

The model demonstrated strong agreement between simulated and observed hydraulic heads, with a coefficient of determination (R^2) of 0.97 and a root mean square error (RMSE) of 4.72 m during the calibration period. During the validation period, the model maintained strong performance, with $R^2 = 0.93$ and RMSE = 7.20 m. In 2013, the average water table depth was 23.5 m of the region, which decreased by 2.55 m, 3.88 m, and 5.58 m under crop planting scenarios SWD-1, SWD-2, and SWD-3, respectively, by 2021. Corresponding annual water table decline rates were 28.38 cm, 43.13 cm, and 62.05 cm. Among the scenarios, SWD-1 rice-wheat crop planting scenario (June 15 to November 5) proved to be the most effective in sustaining groundwater resources and agricultural productivity. The study concludes by underlining the importance of sustainable crop management to manage groundwater in agriculturally dominated regions. The findings provide a strong scientific basis for formulating crop management strategies and policies that ensure sustainable groundwater use while maintaining agricultural productivity.

Keywords: *Modflow, groundwater, variable sowing date, aqua crop*

EVALUATING METEOROLOGICAL AND GROUNDWATER DROUGHTS IN BIHAR STATE, INDIA

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The study examines the dynamics of drought and groundwater responses in ten cities of Bihar by employing meteorological and groundwater drought indices. Using the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI), drought conditions were analyzed for the historical period from 1981 to 2023. Future projections for 2025–2100 were explored under two Shared Socioeconomic Pathway (SSP) scenarios: SSP245, representing a moderate climate change trajectory, and SSP585, indicating a severe trajectory. To complement this analysis, the Standardized Groundwater Level Index (SGI) was derived from groundwater depth data collected from 15 observation wells, with data sourced from the Bihar State Groundwater Board and the Central Ground Water Board (CGWB). The study further investigates the relationship between meteorological drought indices and groundwater levels to understand how droughts influence groundwater resources across Bihar. The historical analysis reveals a clear increasing trend in drought severity, particularly after 2015, with notable changes observed on a 12-month time scale. Among the indices, SPEI consistently indicates more severe drought conditions compared to SPI across all studied locations. This difference is attributed to SPEI's ability to incorporate evapotranspiration, making it more sensitive to temperature-driven changes in drought severity. The findings show that the frequency and intensity of drought events have escalated in recent years, highlighting a growing vulnerability to drought in Bihar. Projections under the SSP scenarios provide valuable insights into the future evolution of drought conditions in the region. Under the severe SSP585 scenario, drying trends are dominant up to 2050, with several locations experiencing prolonged and intensified drought periods. However, a noticeable shift towards wetting trends is projected for the post-2050 period in some locations, with extreme wet conditions (SPI > 2) becoming increasingly prevalent towards the end of the study period. In contrast, SSP245 projects milder drought conditions throughout the future period, suggesting that moderate climate action could significantly mitigate the severity of drought impacts. Both SPI-12 and SPEI-12 indices suggest that most locations will face mild drought conditions in the near future (2023–2050), transitioning to prominently wet conditions in the far future (2051–2100). This shift in hydrological conditions underscores the importance of adapting water management strategies to cope with both drought and extreme wet events. Trend analysis, conducted using the Mann-Kendall test and Sen's slope estimator, confirms the observed changes in drought severity and frequency. These robust statistical tools provide reliable evidence of the increasing trend in drought conditions during the historical period and the complex patterns projected under future climate scenarios. The analysis emphasizes the need for proactive measures to address the impacts of these changing trends on water resources and agricultural systems in Bihar.

The spatial and temporal distribution of SGI highlights areas within Bihar that are particularly prone to critical groundwater drought conditions. These locations exhibit significant declines in groundwater levels, reflecting the combined impact of reduced

precipitation, increased evapotranspiration, and over-extraction of groundwater. Groundwater depletion in these areas poses a severe challenge to water security, particularly during prolonged drought periods when dependence on groundwater resources intensifies. The integration of SGI with meteorological drought indices enables a comprehensive understanding of the interaction between drought and groundwater resources, providing a valuable framework for monitoring and managing groundwater in drought-prone regions. Establishing the relationship between groundwater levels and meteorological drought indicators is a significant contribution of this study. By correlating SPI, SPEI, and SGI, the study demonstrates how readily available meteorological drought indices can be used to estimate groundwater levels during drought conditions. This relationship offers a practical tool for water managers and policymakers to anticipate groundwater stress based on drought forecasts, enabling timely interventions to mitigate the impacts of water scarcity. Moreover, the study highlights the critical role of groundwater level monitoring in understanding the broader implications of drought on water resources. The findings also address a critical gap in the current understanding of drought-groundwater interactions. While meteorological drought indices provide a broad overview of precipitation and evapotranspiration trends, their impact on groundwater resources is influenced by several region-specific factors, including aquifer characteristics, land use patterns, and water extraction practices. This study underscores the need for region-specific investigations to accurately capture the dynamics of groundwater response to drought. Such insights are essential for developing effective groundwater management strategies that are tailored to the unique conditions of each region. Additionally, the research emphasizes the importance of long-term monitoring of groundwater levels and the integration of hydrological data with climate projections. As climate change intensifies, the frequency and severity of extreme weather events, including droughts, are expected to increase, posing significant risks to water security. This study provides a framework for understanding how groundwater resources are likely to respond to these changes, offering valuable guidance for sustainable water management in Bihar and similar regions. In conclusion, this study provides a comprehensive assessment of drought dynamics and groundwater responses in Bihar State, integrating historical trends and future projections under different SSP scenarios. The findings reveal an alarming increase in drought severity in recent years and highlight the potential for extreme wet conditions in the future, particularly under SSP585. By linking meteorological drought indices with groundwater levels, the research offers practical tools for water resource management and underscores the need for region-specific strategies to address the complex challenges posed by climate change. The insights gained from this study can inform policies aimed at enhancing the resilience of water resources and agricultural systems in Bihar, contributing to sustainable development in the face of a changing climate.

Keywords: *Drought assessment, SPI, SPEI, groundwater dynamics, climate change*

EVALUATION OF SPATIO-TEMPORAL VARIABILITY OF GROUNDWATER QUALITY FOR IRRIGATIONAL SUITABILITY AND ITS RELATION WITH CLIMATOLOGICAL PARAMETERS IN PONDICHERRY REGION, INDIA

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Water is essential for all life on Earth, but only a tiny of portion about 2.5% of the world's total water supply is freshwater that can be used for drinking, agriculture, and industry. Many densely populated coastal regions worldwide struggle with freshwater shortages and are heavily dependent on groundwater. Climate change is worsening the pressure on these limited freshwater resources, leading to potential social conflicts as a result of erratic rainfall, rising demand, and overuse of scarce supplies. The current study centres on Pondicherry (293 sq.km), a Region that depends heavily on groundwater for drinking and agricultural needs and is increasingly exploiting deeper aquifers (over 60 meters below ground level). The primary objective is to assess the suitability of groundwater for irrigation by using graphical techniques and calculating index values. The study also graphically compares the past agricultural scenario of the Pondicherry region. The rainfall frequency and atmospheric temperature play a significant role in the present stage of development of the groundwater and its movement. This includes employing visual tools like Wilcox diagrams and US Salinity Laboratory diagrams to interpret water quality data, providing a comprehensive evaluation of its irrigation potential.

To evaluate the spatio-temporal variability of groundwater during the year 2022, a total of 62 samples were collected from various places that encompassed the entire study area with depth ranging from 2 to 104 mbgl. The pH, EC, and TDS values were determined by pH meter, EC meter and TDS meter respectively. Major cations (Ca, Mg, Na, K) were analysed using an ICP-mass spectrometer. The sulphate (SO_4) was analysed by spectrophotometric approach, nitrate (NO_3) ion chromatography, chloride (Cl) volumetric titration and carbonate (CO_3) were assessed using Portamess through titration techniques involving HCl, phenolphthalein, and methyl orange. The irrigation suitability was determined using Sodium Absorption Ratio (SAR), Percent Sodium (%Na), Residual Sodium Carbonate (RSC), Magnesium Ratio (MR) and Kelley's Index (KI). The temperature and rainfall data from 2010 to 2022 of Pondicherry Region was correlated with hydrochemistry of the ground water samples. The temperature and rainfall data were obtained from the Central Groundwater Board, South Eastern Coastal Region, Chennai.

Water and soil characteristics are crucial for plant growth. Using poor-quality water for irrigation can negatively impact crop yield. Intensive agricultural practices like the use of fertilizers, pesticides, and insecticides, can significantly affect groundwater quality. According to the USSL salinity diagram, most samples fell within the C3S1 (low SAR, high EC) and C2S1 (low SAR, medium EC) categories. Based on SAR classification, the majority of the water samples are considered excellent for irrigation. In the study area, 46.1% of samples (from Kariyamanikkam, Kalmandapam, and Kurumbapet) fall within good to acceptable levels for agricultural use based on % Na, while 30.2% are rated as exceptional (from Parikkalpattu, Kirumampakkam, and Kaduvanur). About 12.4% of samples from

Netaji Nagar, Thengaithittu, and Thuthipet are either unsuitable or questionable for agricultural practices, and 3.4% are entirely unsuitable (from Thirukkanur and Sellipet). As per Doneen's Permeability Index, most samples fall into Classes 1 and 2, indicating that the water is only marginally suitable for agricultural use. Most samples (98%) showed negative RSC values, suggesting a low risk of sodium accumulation. With a maximum MAR value of 38 meq/L, the water falls within the optimal range for irrigation. Regarding KI, 11.1% of samples are unsuitable for irrigation in the study area. Spatially, 35%, 50%, and 25% of the area is classified as good, moderate, and poor respectively. When comparing pre- and post-monsoon seasons (PRM and POM), about 52% of the area remains in the good category, with noticeable declines in the moderate (50-40%) and poor (15-8%) categories after the monsoon. Rainfall is the primary source of groundwater recharge in Pondicherry, with 63% of the rainfall contributing from the northeast monsoon (October to December) and 29% southwest monsoon (June to September). It is noticed that the maximum temperature (32°) experienced in PRM with minimum rainfall of 41mm. The maximum rainfall experienced during POM (1102.8mm) with a minimum temperature of 29°C. The higher rainfall and lower temperature cause groundwater dilution, making it more suitable for irrigation. The study also found a good correlation (correlation coefficient, r=0.93) between Cl^- and Na^+, particularly in the Muthialpet area, which covers about 8% of the total area, indicating the presence of marine water intrusion.

The study reveals that groundwater quality in the Pondicherry region is generally suitable for agricultural purposes, with most samples falling within good to acceptable ranges for irrigation. The majority of water samples, classified based on SAR and RSC, indicate minimal risk of sodium accumulation, and a significant area (46.1%) is ideal for agricultural purposes. The study also highlights spatial variability, with 35% of the area classified as good, though this improves during the POM. The PRM temperature peaks at 32°C with 41mm of rainfall, while the POM experiences 29°C with 1102.8mm of rain. The increased rainfall and lower temperature in the POM enhance groundwater dilution, making it better for irrigation. However, a notable concern is the marine water intrusion in the Muthialpet area, which affects approximately 8% of the region. Overall, the findings underscore the importance of managing groundwater resources to ensure their sustainability for agriculture, particularly in light of seasonal fluctuations and potential contamination. These results highlight the need for targeted management practices to address localised issues like high bicarbonate levels and saline water intrusion, to maintain the viability of groundwater for agricultural and potable purposes.

Keywords: *Deeper aquifer, irrigational suitability, climatological parameters, spatio-temporal variability, Puducherry*

A MULTI-INDICATOR RETROSPECTIVE ANALYSIS OF GROUNDWATER DROUGHT DYNAMICS IN CENTRAL INDIA

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Groundwater drought is an intricate phenomenon arising from the interplay of multiple factors, including climate variability, terrestrial water storage (TWS) anomalies, and land-use dynamics. Unlike surface water droughts, which are often visible and more immediate, groundwater droughts are subtle and can persist for years due to the slow response of aquifers to climatic and anthropogenic stresses. This complexity underscores the need for a nuanced understanding of groundwater dynamics, particularly in regions like central India, which are highly dependent on groundwater resources for agricultural, domestic, and industrial needs. The region is also characterized by semi-arid conditions and recurrent droughts, exacerbated by climate change, over-extraction, and unsustainable land-use practices. Central India's vulnerability to groundwater depletion and drought-related stress necessitates a robust assessment framework. Traditional methods of groundwater monitoring, such as well observations, often lack the spatial and temporal resolution needed for comprehensive analysis. The advent of satellite-based remote sensing techniques, such as those provided by the Gravity Recovery and Climate Experiment (GRACE) mission, offers unprecedented opportunities to monitor groundwater storage changes over large areas with high temporal resolution. GRACE measures changes in Earth's gravity field, enabling the estimation of TWS anomalies, which include groundwater, soil moisture, and surface water storage. However, isolating groundwater storage from TWS requires careful subtraction of other hydrological components, such as soil moisture and surface water.

This study employs GRACE-derived TWS data alongside ERA5 soil moisture datasets to develop a novel GRACE-based Groundwater Drought Index (GGDI) for central India. Covering the period from 2002 to 2022, the GGDI captures the temporal and spatial dynamics of groundwater drought, offering insights into the severity, duration, and recurrence of groundwater deficits. By incorporating ERA5 soil moisture data, which provides a high-resolution reanalysis of land surface hydrology, the study ensures a more accurate estimation of groundwater variability. The GGDI thus serves as a reliable indicator of groundwater drought, bridging gaps in traditional monitoring methods. Furthermore, the study examines the interrelationships between groundwater variability and climate-induced drought indices, such as the Standardized Precipitation-Evapotranspiration Index (SPEI). SPEI, calculated at multiple timescales, reflects the balance between precipitation and atmospheric demand for water (evapotranspiration), making it a valuable metric for assessing meteorological and agricultural droughts. By comparing SPEI with GGDI, the study aims to unravel the temporal lag between meteorological drought and its impact on groundwater. This lagged response is critical for understanding how prolonged dry periods and extreme weather events contribute to groundwater depletion over time.

In addition to climate-based indices, the study integrates vegetation indices—specifically the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI)—to

assess the ecological implications of groundwater drought. Vegetation indices derived from remote sensing reflect the health and productivity of plant cover, which is closely tied to water availability. The relationships between GGDI and vegetation indices provide valuable insights into how groundwater drought impacts ecosystem health, agricultural productivity, and land surface processes. This multi-faceted approach ensures a holistic view of hydrological drought attributes, encompassing groundwater, climate, and ecological dimensions. The GGDI reveals significant interannual variability in groundwater storage, with pronounced drought events in 2009, 2015, and 2018 coinciding with major meteorological droughts. A lagged response of 4–8 months between SPEI and GGDI underscores the delayed impact of climate variability on groundwater resources. The comparative analysis indicates moderate to strong correlations between GGDI and SPEI at longer timescales (9–12 months), highlighting the cumulative effect of prolonged dry spells on groundwater storage. NDVI and EVI exhibit seasonal fluctuations but show significant declines during severe groundwater drought periods. This relationship emphasizes the role of groundwater as a crucial determinant of vegetation health in semi-arid regions. The spatial analysis reveals hotspots of groundwater depletion in regions with intensive agriculture and over-reliance on irrigation, aligning with known areas of groundwater stress.

The results of this study have significant implications for water resource management and drought mitigation strategies in central India. By revealing spatial hotspots of groundwater drought and their temporal evolution, the GGDI offers a powerful tool for identifying areas at greatest risk. The comparative analysis with SPEI provides actionable insights into the interplay between climate and groundwater systems, highlighting the need for integrated management approaches that address both immediate and lagged impacts of drought. Additionally, the linkages with vegetation indices emphasize the broader ecological consequences of groundwater depletion, underscoring the need for sustainable groundwater use to support ecosystems and livelihoods. This research advances the understanding of groundwater drought dynamics in central India, contributing to the global discourse on sustainable water management. By leveraging satellite data, climate indices, and vegetation metrics, it bridges the gap between scientific analysis and practical applications, paving the way for more resilient and adaptive water resource policies. The comprehensive insights offered by the GGDI can inform decision-makers, researchers, and stakeholders in devising strategies to mitigate the impacts of drought and ensure the long-term sustainability of groundwater resources.

Keywords: *Groundwater drought, GRACE, Vegetation indices, SPEI, Central India*

APPROACHES TO EVAPOTRANSPIRATION PARTITIONING: INSIGHTS ON ISOTOPE BASED EVALUATION METHOD

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Evapotranspiration (ET) is a fundamental component of the hydrological cycle, representing the total water loss from a surface through both transpiration (T) by plants and evaporation (E) from the soil. Understanding how ET partitions into these components is crucial for efficient water resource management, particularly in agriculture, where it directly impacts crop water requirements and productivity. The T/ET ratio, indicating the proportion of water lost through transpiration relative to total ET, is an essential measure of water use efficiency (WUE) in plants. Transpiration supports photosynthesis and crop yield, while evaporation, which does not contribute to productivity, should be minimized for effective water conservation. Several methods have been developed to partition ET into its components. This paper reviews methodologies for partitioning evapotranspiration (ET) into crop transpiration (T) and soil evaporation (E), focusing on their role in eco-hydrology, crop water requirements, and sustainable agricultural practices. Various techniques have been developed to partition evapotranspiration (ET) into its components, with isotopic methods being one of the key approaches. These methods leverage stable water isotopes, particularly ^{18}O and ^{2}H, which exhibit different rates of fractionation during evaporation and transpiration, allowing differentiation between the two processes. Early studies laid the foundation for using isotopic signatures to partition ET, with significant advancements through the Keeling plot method, which enhanced measurement precision. Over time, tools like the Craig-Gordon model and laser-based analysers have further improved accuracy, achieving 10-20% precision in controlled conditions despite their high cost and complexity.

Isotopic methods exploit the distinct fractionation effects of evaporation and transpiration. Evaporation enriches the remaining water in heavier isotopes, while transpiration shows minimal fractionation as the water taken up by plants undergoes little isotopic change. This difference is quantified through mass balance equations, which estimate the contributions of each process to total ET. The method has evolved since its inception in the 1950s, with innovations like the Craig-Gordon model and Keeling plots providing frameworks for ET partitioning across ecosystems. Measurements of $\delta^{18}O$ and $\delta^{2}H$, along with d-excess and lc-excess, offer a more accurate partitioning by accounting for both kinetic and equilibrium fractionation effects. Distinct isotopic signatures of water vapor to partition ET, addressing isotopic fractionation, where lighter isotopes evaporate more readily, while transpiration exhibits minimal fractionation. The partitioning follows a mass balance equation: ET=E+T and $\delta ET = f_E \cdot \delta_E + f_T \cdot \delta_T$, where δET is the isotopic composition of total ET, f_E and f_T are the fractions of E and T, and δE and δT are their respective isotopic compositions. Global studies have enhanced our understanding of ET partitioning. For example, in China's Shiyang River Basin, T/ET ratios ranged from 71% to 96%, with an average of 87%, varying significantly with irrigation events. In India, isotopic analysis has revealed post-monsoon enrichment and moisture depletion during the monsoon, with delayed responses in deep-rooted plants. Similar insights from regions like Austria, Morocco, and the USA have highlighted the impact of irrigation and drought on soil and plant water uptake. Despite the use of advanced tools for ET assessments, research on ET partitioning in India remains limited. There is a significant gap in applying these advanced methods, necessitating multidisciplinary approaches tailored to local agricultural contexts. Translating research into actionable water management policies is crucial for enhancing India's contribution to global water resource management.

Global synthesis studies estimate that transpiration accounts for 61 ± 15% of total ET, challenging earlier assumptions about the dominance of evaporation. This ratio varies with vegetation type and climate, increasing from dry-land habitats (51%) to tropical rainforests (70%), emphasizing the role of vegetation in water dynamics. Technological advancements have improved isotopic analysis. Early methods like cold-trapping were labour-intensive and lacked temporal resolution. The development of laser spectroscopy in the 2000s enabled high-resolution, real-time measurements, allowing for continuous monitoring of ET components. CRDS has facilitated in situ, high-frequency measurements, enhancing isotopic data collection in field studies. Sampling for isotopic analysis involves the extraction of water from soil, plants, and atmospheric vapor. Soil water extraction uses vacuum distillation or cryogenic methods, while plant water is obtained through cryogenic vacuum distillation or by sealing leaves in bags. Atmospheric water vapor is captured using cold traps or ice cones. CRDS enables continuous monitoring of vapor isotopes, crucial for tracking diurnal and event-driven changes. Multiple sampling heights are required for Keeling plots.

This research aims to optimize irrigation practices using stable isotopes, with techniques like the Craig-Gordon model and Keeling plots being employed for detailed analysis. Studies are also underway to analyse groundwater, precipitation, and soil water, with a focus on understanding ET components and how drought conditions impact evaporation-transpiration (E/T) ratios. The approach combines field experiments with isotopic analysis to assess water balance in river basins and agricultural areas. Experiments are also being conducted to explore how different crop species and soil types affect the isotopic composition of water, influencing ET partitioning. These studies also consider the impact of land use changes on ET components, and isotopic composition of rainfall, groundwater, and plant water to understand ET dynamics in various climatic regions. Future directions include expanding the use of portable isotopic analysers for field studies across different Indian ecosystems, enhancing collaboration between institutions to pool resources and data for larger-scale studies, and applying isotopic data to water resource management, particularly in the context of climate change and agriculture. These research efforts contribute significantly to both local and global understandings of water cycle dynamics, showcasing South Asia's unique hydrological characteristics while reinforcing universal hydrological principles.

Keywords: *Evapotranspiration, water use efficiency, isotopic techniques, energy balance models, soil evaporation, plant transpiration*

CONJUNCTIVE USE PLANNING OF GROUNDWATER AND SURFACE WATER TO DETERMINE OPTIMAL CROPPING PATTERN

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Increasing population and its consequent demand for water is also increasing which poses a major issue in the context of adequacy of supply as per water demand. One of the major sectors facing the lack of supplies is the agricultural sector. Moreover, the changes observed in the climatic conditions in the recent years gave rise to a major decline in the availability of surface water and groundwater resources. In India, the availability of subsurface and surface water sources is 432 BCM and 690 BCM, respectively. While the annual water demand for the nation is predicted to be double by 2050 than the demand in 2000. According to the 2011 census, the availability of water per capita per year was 1614 m^3, while this number is predicted to reduce to a value of 1137 cubic meters by 2065. Different solutions to this problem are being investigated from decades and the most efficient way to deal with it has emerged as the conjunctive use of surface water and ground water. The coordinated and planned use of surface water and groundwater resources together is said to be conjunctive use. Several SWOT analyses (strength, weakness, opportunities, and Threats) have been conducted on the conjunctive use strategies and it has been found out that it is a very useful first predictive cum approximation tool which can further be used for analysing the problem more specifically and carrying out cost benefit analysis which help in making the decision-making ability more comprehensive. The study explores the use of genetic programming within a conjunctive water use framework in order to determine an optimal cropping pattern for culturable command area of 58750 ha located in the Tapi district of Gujarat, India. The majority of the area comes under the command of the Kakrapar Right bank main canal situated 30 km downstream of the Ukai dam constructed over the Tapi river. The primary objective of the model is to maximize the net benefits obtained from different crops while keeping constraints on land availability, water demands, and minimum cropping area allocated to each crop. This will further help to make a decision-support framework that will eventually enhance the water use efficiency for the agricultural system while minimizing the environmental impacts as well as inequalities due to socio-economic factors. The study in the initial stage involves assessment of the resources present in the region. This involves quantitative estimation of groundwater and surface water resources, existing agricultural patterns of the study area, suitability of the soil, current water demands etc. The data collection involves field measurements, satellite imageries and consultations by the stakeholders in order to get a holistic understanding of the area under consideration. The inputs to the model include water availabilities from different resources, meteorological data, crop data and economic data which includes market prices, pumping costs, cultivation costs etc. The methodological framework consists of generating an initial solution and evaluating its fitness, followed by selection of best solution, crossover, mutation and finding out the optimal solution. A 20% variation from previously allocated crop area is permitted in order to fulfil the minimum crop water requirements and a cost-benefit function is also formed for finding out the optimal results. While the use of CROPWAT 8.0 enables to account for the evapotranspiration needs considering threshold temperatures, humidity, rainfall, soil characteristics and crop coefficients for different crops for finding out the crop-water requirements which after defining the cropping pattern provides the net irrigation water requirements. The results obtained showed that opting the conjunctive use plan is both feasible and equitable for finding out an optimal cropping pattern. The net benefits thus obtained from the optimal allocation of land using the genetic algorithm increased by 35% at 100% water availability with no water stressed conditions compared to the initial allocation strategy. While, in the water stressed conditions the net benefits after optimal allocation of cultivable land increased by 28% and 24% at 90% and 75% water availability respectively. The majority of the land was allocated to sugarcane crop due to its high net returns followed by paddy and wheat. The cropping pattern was fractioned into five parts namely Kharif, Rabi, two-seasonal, hot-weather and perennial crops. The results also showed that in the months of June to September the acquisition of land from different crops was at peak covering almost all of the available cultivable area. The constraints were satisfied and the water demand for crops was always less than the available water for irrigation. The study's outcomes underlined the potential of conjunctive optimization models in addressing the challenges faced by the agricultural sector due to limited resource availability and sustainable management of water resources. The developed framework is a powerful tool for the policy making authorities and regulating bodies offering them the insights for designing sustainable water allocation strategies which focuses on environmental conservation objectives as well as fulfilling the economic development goals. The study also provides a notable contribution addressing the trade-offs between economic gains, environmental sustainability while ensuring the livelihoods of the farming communities.

Keywords: *Conjunctive use, genetic algorithm, optimal cropping pattern, irrigation water requirements*

ESTIMATION OF GROUNDWATER RECHARGE FOR SHALLOW AQUIFERS IN GANGA-YAMUNA DOAB REGION USING HYDRUS-1D AND IWTF METHOD

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Groundwater plays a key role in irrigation and domestic needs across the globe, specifically in areas with high agricultural activity and population density. Due to rapid urbanization and over-drafting for intensive agricultural activities and industrial use, groundwater is becoming increasingly limited in many regions worldwide, particularly in countries with arid and semi-arid climates. The excessive extraction of groundwater, primarily for irrigation, has resulted in significant depletion in groundwater levels. Therefore, sustainable groundwater practices, reclamation, and artificial groundwater recharge are very important to solve such problems. Knowledge of groundwater recharge is essential for the sustainable management of groundwater. However, the complexity of groundwater systems, along with the scarcity of observed data and challenges of selecting appropriate estimation methods, makes with task difficult. Traditional methods, like the Water Table Fluctuation (WTF) method, are often inadequate in regions with high variability in recharge due to irrigation, land use, and uneven monsoon patterns. To overcome these limitations, this study employs a combination of HYDRUS-1D simulation (HS) and an improved water table fluctuation method to estimate groundwater recharge in the Ganga-Yamuna Doab region. The Ganga-Yamuna Doab region has a total surface area of 57,467 km^2. It covers a total of 42 districts of Delhi, Uttar Pradesh, Haryana and Uttarakhand. The average annual rainfall of the study area is 654 mm. Silt and loam with low organic content are the dominating soil types in the region. Major aquifers in the region are older alluvium and younger alluvium. Firstly, HYDRUS-1D software is used to simulate the vertical movement of water in the soil column. Hydrus-1D is a free and open-source Windows-based modeling environment for analysis of water flow and solute transport in variably saturated porous media. It was developed by Jirka Šimůnek in 1990. This model applies Richard's equation, van Genuchten formula, and Feddes formula to simulate the vertical movement of water under varying boundary conditions. Soil and rainfall data were imported into the HYDRUS-1D model to construct a conceptual model that is a close representation of the field conditions. The model uses flexible time steps to simulate the movement of water through the soil column and generate bottom flux, which is the potential recharge infiltrating through the soil column. The bottom flux obtained from HS is used with the corresponding groundwater level to calculate specific yield. The improved WTF method was then applied to calculate groundwater recharge, which addresses the limitations of the traditional WTF methods. Particularly, the traditional WTF method is not efficient in estimating the groundwater recharge accurately when the groundwater table is stable or declining, as it hypothesizes no recharge under these conditions. The improved WTF method overcomes this limitation by taking into account the impact of factors like groundwater table fluctuations, lateral flow, and pumping. The application of HYDRUS-1D and the improved WTF method offers a comparative analysis of two different approaches. The output of this study highlights the major differences between the groundwater recharge estimate obtained using HS and the improved WTF method, highlighting the importance of incorporating advanced tools and correction for anthropogenic variability. The outcomes of this study emphasize the improved WTF method and its suitability for regions like Ganga-Yamuna Doab, where traditional approaches may fall short in capturing the dynamics of recharge processes. This study provides valuable insights into sustainable groundwater management. The methods and results can be extended to similar regions facing challenges in recharge assessment, enabling better planning and conservation of groundwater resources.

Keywords: *Groundwater, groundwater recharge, HYDRUS, water table, simulations*

Theme 13

PROTECTION OF GROUNDWATER DEPENDENT ECOSYSTEMS - RIVERS, WETLANDS, LAKES AND SPRINGS

A HOLISTIC APPROACH FOR IDENTIFYING ARTIFICIAL GROUNDWATER RECHARGE ZONES TO REJUVENATE UNGAUGED LAKES AFFECTED BY GROUNDWATER DROUGHT

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Surface water bodies such as lakes are vital sources of fresh water for many communities and are important for local ecology. Hence, it is necessary to identify whether they exhibit gaining or losing nature over time and become perennial or non-perennial, especially for ungauged lakes. It is crucial to determine natural and anthropogenic activities that enhance groundwater drought and cause changes in the lake's behaviour. Therefore, it is necessary to identify the causes that influence groundwater drought near lakes. If the groundwater storage anomaly occurred due to a precipitation, there exists a strong correlation between them. The correlation between the groundwater storage anomaly and precipitation is found to be weak due to anthropogenic activities. Artificial recharge structures (ARSs) play a vital role in managing groundwater reserves and rejuvenating lakes to reduce the vulnerability of groundwater drought caused by meteorological events. There are many studies related to prioritizing the zones suitable for ARS for managing groundwater resources. The novel aspect of this study is to identify the zones suitable for ARS to rejuvenate the lake during non-monsoon seasons by recharging water into the aquifer during monsoon season. The objectives of the study are (i) developing Satellite–Derived Bathymetry (SDB) models to estimate the depth of water at ungauged lakes, (ii) computation of the relationship between head difference (groundwater table (GWT) and water surface elevation (WSE) in lakes), standardized groundwater table index (SGWTI), and Standardized Precipitation Evapotranspiration Index (SPEI), (iii) identifying the suitable zones for ARSs for lake rejuvenation by integrating remote sensing, GIS, Multi Criteria Decision Analysis (MCDA) and hydrogeological techniques, (iv) proposing suitable methods in different types of ARSs for lake rejuvenation.

Optical-based SDB essentially relies on the principle that there is a statistical relationship between the amount of energy reflected from a water column that a sensor can detect and the depth of the water. The Landsat-5, 8 top-of-atmosphere (TOA) reflectance data at different time bands are initially employed to establish a correlation with the water column depth. The band values are extracted for multiple stream gauge stations operated by the CWC using the Google Earth Engine (GEE) platform. The temporal resolution of Landsat-5, 8 is 16 days, and a cloud filter of about 20% is applied while extracting pixel values between 2001 and 2018. The difference between the regular river WSE and the WSE at zero discharge (river bed elevation) helps to calculate the water depth (daily time series) in stream gauge stations located in the upper Godavari River stretch. For the present study, three stream gauge stations were chosen at Dhalegaon (76.3667E, 19.2037N), G.R. Bridge (76.7174E, 19.0191N), and Panchegaon (74.8786E, 19.5376N). The datasets are merged based on date, and splitting was performed to create training (75%) and testing (25%) datasets. Finally, various machine learning (ML) algorithms like decision trees, eXtreme gradient (XG) Boost, and Random Forest are applied to develop the relationship between the depth of water in the river (m) and

the reflectance values at various bands. The various evaluation metrics like coefficient of determination (R2), Mean Squared Error, Root Mean Square Error, and K–Fold Cross Validation (CV) are computed. Based on the evaluation metrics, the best performance model is identified. The best performance model is used to determine water depth in lakes.

For computation of SPEI, the daily precipitation ($0.25^{o}\times0.25^{o}$ resolution) and temperature data (1o×1o resolution) are downloaded for years 2008–2018 from the IMD website. The potential evapotranspiration is computed by the Hargreaves method. The daily disparity (in mm) is determined by taking the difference between daily precipitation and evapotranspiration. The daily disparity is then transformed to a 3-month disparity. The transformed disparity is fitted by using Pearson-3 distribution by using the Kolmogorov–Smirnov test (KS test) at 5% significance level. The parameters of the Pearson-3 distribution are estimated by using the maximum likelihood method. The SPEI is estimated by using the method proposed by. For computation of SGWTI, the groundwater levels for the years 2008–2018 (seasonal data) are obtained from the CGWB. The groundwater levels at various observation wells are fitted by using various continuous distributions like gamma, normal, Pearson-3, exponential, Gumbel, Pareto, and generalized extreme value distributions by using the Kolmogorov–Smirnov test (KS test) at 5% significance level. The parameters of the distributions are computed by using the method of moments. The SGWTI is computed by standardizing CDF obtained from the best-fitted distribution. Finally, the relationship between head difference, SPEI, and SGWTI is quantified by plotting the Pearson correlation matrix. A strong correlation between SPEI and SGWTI signifies that stronger influence of meteorological parameters (precipitation and temperature) on groundwater levels, and a weak correlation implies some anthropogenic influence. A strong correlation between SGWTI and head difference signifies that groundwater drought impacts the lake water level and vice versa for a low correlation. The suitable zones for ARS for lake rejuvenation are identified by using considering various factors such as runoff–rainfall ratio, frequency of groundwater drought, frequency of waterlogging, soil type, land use & land cover, geology, lineament density, distance from lakes, lake density, transmissivity, the thickness of the aquifer, depth of the aquifer, average groundwater fluctuation, elevation, and slope. The entropy method is used to determine the weightage of each attribute, and the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) is used to determine the rank for suitable zones. The highly suitable zones are validated with the lakes, which are highly influenced by groundwater drought. The results reveal that strong correlation is achieved between SPEI and SGWTI at different lakes in the river basin. It implies that the precipitation deficit and elevated temperatures led to a groundwater drought in the upper Godavari Basin. The suitable zones for artificial groundwater recharge were identified using hydrogeological, remote sensing, and climatic data analysis. By employing artificial recharge strategies, targeted regions experience an increase in groundwater levels, which will then positively influence lake water levels, helping to mitigate the effects of drought. The study shed light on the interaction between meteorological drought, groundwater drought, and their combined effects on lake sustainability, particularly in areas lacking direct monitoring. This research identifies effective groundwater recharge zones to restore ungauged lakes that have been impacted by drought. It provides a replicable model for enhancing lake sustainability and supporting strategic water management decisions under drought conditions.

Keywords: *Artificial groundwater recharge, groundwater drought, satellite–derived bathymetry, remote sensing, machine learning, lake rejuvenation*

IDENTIFICATION OF MORPHOMETRICAL PARAMETERS USING GEOSPATIAL TECHNIQUES OF TROPICAL RIVER BASIN, KERALA, INDIA

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Morphometry is characterized as the quantitative assessment and mathematical evaluation of the Earth's surface configuration, alongside the geometrical attributes and magnitudes of its landforms. Morphometric assessment of a river basin yields a quantitative representation of the hydrological network, which constitutes a critical element in the characterization of drainage basins. The evolution of a drainage system across both spatial and temporal dimensions is modulated by a multitude of factors, including the geological framework, structural elements, geomorphological characteristics, as well as the soil and vegetative cover of the region through which it traverses. The quantification of geomorphometric parameters, including but not limited to basin area, perimeter, length, stream order, bifurcation ratio, stream length, stream frequency, drainage density, elongation ratio, circularity ratio, form factor ratio, and texture ratio, of any given basin provides comprehensive insights into the geological, physiological, and hydrological dynamics inherent to that basin. Numerous researchers have conducted investigations into the morphometric characteristics of drainage basins, utilizing them as indicators of structural influences on the evolution of drainage systems and neotectonic processes. The utilization of remote sensing and Geographical Information System (GIS) methodologies has also gained prominence on a global scale. The Kuttiyadi River basin, located in the state of Kerala, has been selected for a comprehensive analysis for the purpose of formulating effective watershed management strategies. The study area constitutes a segment of the Precambrian granulite terrain located in southern India. The basin area is predominantly occupied by hornblende gneiss, which has undergone granulite-grade metamorphism. The presence of charnockite is extensively observed in the northeastern vicinity of the Kuttiyadi basin. The study was undertaken using Survey of India (SOI) topographical maps (1:50,000) and Arc GIS 10.8 software. Various thematic layers were prepared and estimation of morphometric parameters was done. The Kuttiyadi river basin has been classified into six distinct sub watersheds of 6^{th} order, and were subsequently digitized utilizing a topographic map. The computation of basin parameters essential for morphometric analysis, including ordering, lengths, area, and so forth, was conducted within a GIS platform. The morphometric variables that were computed have been systematically categorized into linear parameters, relief parameters, areal parameters. These computed parameters were subsequently used to derive additional metrics such as stream length ratio (RL), bifurcation ratio (Rb), drainage density (Dd), stream frequency (Fs), drainage texture (T), form factor (Ff), circularity ratio (Rc), elongation ratio (Re), constant of channel maintenance (C), length of overland flow (Lo), relief ratio (Rr), gradient ratio (Gr), and ruggedness number (Rn) for each of the five sub-watersheds. The first order has 1672 streams totalling 861.424 km, with a mean length of 0.5152 km. The bifurcation ratio (Rb) for this order is 5.5919, and the stream length ratio (RL) is 0.2315. As the stream order increases, the number of streams decreases, and their mean length increases. The sixth order has a single stream of 41.2420 km. The values of bifurcation ratio and stream length ratio indicate the hierarchical structure and scaling patterns of the stream network within the basin. The hydrological characteristics of the study area, as determined using Strahler’s method, reveal several key attributes that describe its drainage and stream network. The area of the basin is 664.584 km^2, with a perimeter of 153.2031 km and a basin length (Lb) of 42.78 km. The total stream length within the basin is 1341.5185 km, and there are 2081 streams of varying orders. The relief ratio (Rh) is 1900, indicating a steep and rugged landscape, reflected further by a ruggedness number (Rn) of 941.293. The drainage density (D) of the basin is 2.0185, suggesting a relatively high concentration of streams, while the stream frequency (Fs) is 3.1312, indicating the number of streams per unit area. The elongation ratio (Re) is 4.9474, and the form factor (Rf) is 15.5567, highlighting the shape of the basin and its tendency towards a more elongated form. The circularity ratio (Rc) is 0.3556, and the compactness coefficient (Cc) is 1.6758, both of which describe the basins compactness and its potential for efficient drainage. These parameters collectively provide a comprehensive overview of the basins hydrological and geomorphological features. In conclusion, the morphometric analysis of the Kuttiyadi River basin offers valuable insights into its hydrological and geomorphological characteristics. The study highlights the intricate relationship between stream network structure, basin shape, and landscape features. The high drainage density and steep relief indicate a dynamic and active drainage system, while the elongation and form factor suggest an elongated basin with potential for efficient water flow. The detailed parameters derived from this analysis provide essential information for effective watershed management and contribute to understanding the basin's response to both natural and anthropogenic influences.

Keywords: *Morphometry, geospatial techniques, Kuttiady, River basin*

TERRAIN MODELLING OF MANANTHAVADY RIVER BASIN, WAYANAD DISTRICT, KERALA, INDIA

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Morphometry, the quantitative study of landform shapes and dimensions, is a fundamental tool for understanding the geomorphological and hydrological characteristics of drainage basins. This field of study provides valuable insights into the structural and functional aspects of basins by analyzing parameters such as stream order, drainage density, stream frequency, basin elongation, and relief ratios. These metrics help evaluate the geometry of a basin, its runoff characteristics, flood susceptibility, erosion potential, and sediment transport dynamics. Such information is crucial for effective watershed management, land use planning, and environmental conservation. Morphometric analysis, conducted using Remote Sensing (RS) and GIS technologies reveals significant insights into the basin's geomorphological and hydrological behavior. Using Survey of India topo-sheets and ASTER GDEM data, the drainage network was delineated and analyzed based on Horton's stream ordering method. Morphometric parameters were calculated, including stream length, bifurcation ratio, drainage density, elongation ratio, circularity ratio, and form factor.

The Mananthavady River Basin (MRB), located in the northeastern part of Wayanad district, Kerala, is a tributary of the Kabani River and a significant component of the Western Ghats' hydrological network. Encompassing an area of 358.822 km², the basin lies within latitudes 11°40'00" N to 11°59'22" N and longitudes 75°46'38" E to 76°5'00" E, with elevations ranging from 720 m to 1860 m above mean sea level. The region features rugged terrain, including hill ranges, valleys, and alluvial plains, which provide a dynamic setting for studying drainage patterns and morphometric characteristics. The part of the MRB, originates near the Thondarmudi peak. The river merges with the Panamaram River at Koodalkadavu, where it becomes the Kabani River, eventually flowing into the Kaveri River in Karnataka. The stream order analysis of the MRB reveals a hierarchical distribution of streams, with the first-order streams dominating both in number and total length. There are 1051 first-order streams, totaling 366.34 km, with a mean length of 0.348 km. As the stream order increases, the number of streams decreases, while their mean length increases. Second-order streams number 523, spanning 173.23 km with an average length of 0.33 km. Higher-order streams, including the third (52 streams, 86.63 km), fourth (13 streams, 28.25 km), fifth (3 streams, 15.12 km), and sixth (1 stream, 27.11 km), show a progressive increase in stream length, reflecting the basin's typical fluvial hierarchy. The elongation ratio (0.325), circularity ratio (0.037), and form factor (0.293) suggest the basin has an elongated shape, leading to extended flow paths, slower peak discharges, and a reduced risk of flash floods. However, the high basin relief contributes to significant surface runoff and higher flow velocities during rainfall events, which can increase erosion risks. The ruggedness number, indicative of moderate erosion susceptibility, highlights the influence of steep slopes in shaping the basin's hydrology. Stream length is inversely proportional to stream order, indicating the homogeneity in geological and weathering processes. The basin is dominated by crystalline rocks, particularly those of the Wayanad Group and charnockites, which contribute to the predominance of lower-order streams and the dendritic drainage pattern. The mean bifurcation ratio (4.066) suggests minimal structural disturbances, reflecting a relatively

stable drainage network. Areal morphometric parameters like drainage density (1.941 km/km^2) emphasize the influence of impermeable crystalline rocks and steep slopes, resulting in efficient surface runoff but limited groundwater recharge. Relief morphometric parameters, including high basin relief and moderate ruggedness, further underscore the basin's susceptibility to erosion and high runoff potential. The MRB's geomorphology is largely defined by steep slopes, impermeable crystalline rocks, and a dense drainage network. These factors result in high surface runoff, limited groundwater recharge, and moderate susceptibility to soil erosion, particularly in steeper areas. Understanding these features is vital for developing sustainable water resource management practices and mitigating risks such as flooding and soil degradation. The MRB's hydrological characteristics shows moderate to high stream discharge and elongated flow paths. These features, coupled with its high drainage density and rugged topography, require targeted watershed management strategies. Recommendations include afforestation to enhance infiltration, constructing check dams to regulate water flow, and implementing soil conservation measures to minimize erosion in vulnerable areas. Sustainable land use planning and monitoring human activities, such as deforestation and unplanned land use changes, are critical for maintaining the basin's ecological balance. MRB exemplifies the interplay between geomorphology and hydrology in shaping drainage systems. Its elongated shape, dendritic drainage pattern, and high runoff potential emphasize the importance of morphometric analysis in guiding effective watershed management. By integrating geomorphological and hydrological insights with sustainable practices, this study offers valuable recommendations for preserving the basin's ecological and hydrological integrity.

Keywords: *Morphometry, GIS, Remote sensing, Kabani River, ASTER GDEM*

PERMANENT SOLUTION FOR FLOOD AND DROUGHT CONDITIONS – A NEW SCIENTIFIC AND NATURE BASED WATER NETWORKING PROTOCOL TO NEUTRALIZE THE GLOBAL THREATS AND ENSURE WATER SECURITY FOR THE FUTURE GENERATIONS BY FOCUSING ON GROUNDWATER

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Water is essential to all life. Human species use water directly for domestic needs, growing food, generating power and for industrial processes. Ensuring sufficient water for people for these purposes is an important ethical question. Population growth, lifestyle changes, development, and agricultural practices will contribute to an increasing demand for water during the next 20 years. Global water use is likely to increase by 20 to 50 percent above current levels by 2050, with industrial and domestic sectors growing at the fastest pace. Urbanization and climate change are together exacerbating water scarcity where water demand exceeds availability for the world's cities. Water and climate change are inextricably linked. Climate change is primarily a water crisis. We feel its impacts through worsening floods, rising sea levels, shrinking ice fields, wildfires and droughts. Drought and flood risks, and associated societal damages, are projected to further increase with every degree of global warming. By 2050, the number of people at risk of floods will increase from its current level of 1.2 billion to 1.6 billion. The impacts of disasters are exacerbated by urbanization and degradation of natural environments. Improving the resilience of water and sanitation services and protecting ecosystems will be key to surviving a climatically uncertain future.

India is highly vulnerable to floods. Out of the total geographical area of 329 million hectares (mha), more than 40 mha is flood prone. Floods are a recurrent phenomenon, which cause huge loss of lives and damage to livelihood systems, property, infrastructure and public utilities. It is a cause for concern that flood related damages show an increasing trend. This can be attributed to many reasons including a steep increase in population, rapid urbanization growing developmental and economic activities in flood plains coupled with global warming. Floods have also occurred in areas, which were earlier not considered flood prone. Continuing and large-scale loss of lives and damage to public and private property due to floods indicate that we are still to develop an effective response to floods. There has been an increasing trend of urban flood disasters in India over the past several years whereby major cities in India have been severely affected. The idea of a river as a living spiritual entity has no cognitive niche in Western materialism. By clarifying our values and ethical principles about water and nature, and about people and cultures, we will know better who we are, how we make sense of the world, and how our neighbours do the same. A robust field of water ethics, with room for divergent but ethically grounded views, can help us know ourselves and others more deeply, and find new and unexpected solutions to the challenges of the global water crisis.

The basics of groundwater was reviewed carefully and explained scientifically using few table-top experiments and technologies using few principles and techniques from biotechnology. Today on many newspapers, social media and networks, we can get the news that many volunteers had formed local groups and doing renovation activities of the available

water bodies to enhance the holdup volume and to minimize the water logging conditions in those areas which is a good sign of our community participation. This is one of the action plans of groundwater revolution mentioned in the earlier publication. The outcome of such community actions wherever happening throughout the globe is again an evidence-based proof for the New Hydrological basics for its acceptance and incorporation in the education system for our future generations. This temporary renovation actions alone are not enough to manage the flood and drought conditions. The Man-Made Mistakes happened in both the Surface visible water cycle and underground invisible water cycle needs to be rectified and corrected scientifically and technically by focusing on the Invisible Groundwater. The corrective measures will ensure water security for the future generations by neutralizing all the global water threats and scarcity projected for the next 30 years and provide a permanent solution for flood and drought conditions facing all these days throughout the globe.

Keywords: *Hydrological basics, water management, flood and drought, groundwater revolution, groundwater operation*

QUANTIFICATION OF FLOOD MITIGATION SERVICES BY GROUNDWATER-DEPENDENT WATER RESOURCES USING INVEST MODEL FOR THE WAINGANGA BASIN, INDIA

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Floods have been evident as a major point of concern globally, growing in frequency and intensity due to rapid urbanization, climate change and extreme weather events. Groundwater-Dependent Water Resources (GDWR) such as springs, lakes, wetlands, and peninsular rivers play a vital role in maintaining the ecological balance of urban watersheds by offering various ecosystem services (ES). Challenges such as growing population, rapid change in climatic conditions, unsustainable and uncontrollable human activities are disrupting the harmony and stability of these ES. Floods can drastically alter the river discharge, water level and quality of these resources, making them susceptible to pollution, erosion and decreased carrying capacity. The repercussions of floods extend beyond infrastructure damage and economic losses, affecting the daily lives of communities and essential ES provided by GDWR. However, the rapid transformation of urban landscapes, fuelled by increased development and advanced infrastructure, has led to impervious surfaces that interfere with deep percolation consequently increasing surface runoff and causing significant delay in the opportunity time for groundwater recharge. The benefits and services offered by the GDWR-based ecosystems need to be protected as they are crucial and very pertinent for the sustainable hydrological equilibrium of the environment and policymaking. The current study quantifies the urban flood mitigation (UFM) offered by the GDWR as an ecosystem service by the Wainganga Tributary of the Godavari Basin using the Urban Flood Risk Mitigation Module of the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model. The model estimates the amount of the runoff retained per pixel for the GDWRs and also projects the potential economic damage. The Wainganga River is one of the major tributaries of the Godavari River, often referred to as the lifeline of Central Peninsular India due to its significant ecological, economic and cultural importance. The river holds a length of 580 km with a coverage area of 51,000 km^2, encompassing a diverse range of landscapes, from dense forests and grasslands to agricultural fields and urban centres. The basic concept of this module is based on the popular SCS-CN based method which is preferred and eminent for measuring runoff in a given area. The input data requires various spatial maps of the Wainganga basin such as LULC, soil hydrologic group map, built infrastructure accounting map of building footprints, and also depth of rainfall, damage loss table including potential damage loss data for each building type, biophysical table considering table of curve number data values for each LULC class. The output addresses runoff retention volume and runoff (mm) for each LULC class. The model estimates the amount of the runoff retained per pixel for the GDWRs and also projects the potential economic damage. Conclusively, the model measures the amount of precipitation retained by the GDWR for the watershed pixel by pixel. The measured value can also serve as a guide for the management planning for the protection of the GDWR ecosystem. The measured contribution by the GDWR concerning changes in the urban landscape has been addressed and respective planning and management for the conservation of GDWR has been suggested. The present study emphasizes the critical role of GDWR in urban flood mitigation and underscores the need to prioritize their conservation in policy frameworks to ensure sustainable basin management and resilience against future flood risks.

Keywords: *Wainganga basin, ecosystem services, flood risk, groundwater-dependent water resources, InVEST*

FLOATING TREATMENT WETLAND (FTWS): INNOVATIVE TOOL FOR REVIVAL OF KHAM RIVER IN CHHATRAPATI SAMBHAJINAGAR, INDIA

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Rivers are one of the most productive natural ecosystems as they provide numerous environmental, economic, and social benefits. Cities situated on the bank of rivers or with rivers flowing through them are uniquely positioned to enjoy these benefits. To achieve these benefits, people need to establish a harmonious relationship with rivers, ensuring that they take care of them, and in return, rivers provide them with all the benefits. The Kham River is a seasonal river in the Marathwada region of the Maharashtra state of India. It is a tributary of the Godavari River, which flows through the city of Chhatrapati Sambhajinagar (formerly known as Aurangabad) having latitude 19°53' N and longitude is 75°20' E. In its upper reaches, it crosses a distance of 65 km up to a distance of 8.8 km from the historic city of Chhatrapati Sambhajinagar, where it finally merged with the Jayakwadi Dam of the Godavari River.

Floating Treatment Wetlands (FTWs), often referred to as floating islands, are an innovative method for treating domestic wastewater. These compact artificial surfaces enable aquatic plants to grow in the water that is too deep for them to progress**.** In the field of restoring lakes and rivers, FTWs present a promising approach by combining natural processes with technological advances. Floating treatment wetlands have a natural ability to degrade a variety of pollutants especially organic pollutants which are present in the water body. They depend on microbial transformation, plant uptake, and sediment aggregation. Bacteria in the rhizosphere (near the roots) and endophytes (inside the roots and shoots) contribute to the overall pollutant removal process. Rhizospheric bacteria focus on removing pollutants near the roots, while endophytes target pollutants within the plant tissues. In addition to pollutant removal, rhizospheric and endophytic bacterial communities provide other benefits, such as stress reduction, increased environmental tolerance, and regulation of plant growth through various mechanisms. Furthermore, deliberate inoculation of plant roots with specific bacterial strains can further enhance the pollutant removal efficiency of the system. Floating treatment wetlands utilize this natural capacity by establishing an ecosystem in which aquatic emergent plants flourish. The specific ecosystem absorbs nutrients and converts specific pollutants into non-toxic by-products, helping lakes and rivers. FTWs serve multiple purposes, such as improving water quality in stormwater run-off, controlling nutrients in watersheds, and providing a sustainable method for improving freshwater ecosystems and protecting natural water resources.

Urban water bodies in India are facing severe pollution problems that are slowly killing them. The current estimated population of Chhatrapati Sambhajinagar Municipal Corporation in 2024 is approximately 16,67,000. The Kham Basin generates 240.67 MLD of Sewerage. Disposal of sewage into water bodies has increased the load of organic contaminants. Research suggests that Floating wetland systems are more cost-effective and energy-efficient than effluent treatment plants or sewage treatment plants. Research shows that Floating Treatment Wetlands offer additional benefits to the river ecosystem in urban areas. To accomplish this, an integrated approach in between citizens and rivers need to engage in a coordinated effort, including cities and rivers that care for rivers that will provide many benefits to communities in the future.

To maintain healthy aquatic ecosystem; cities should maintain this mutually beneficial relationship with their rivers. The River Cities Alliance (RCA) was launched with 30 river communities in November 2021 and has now expanded to overall 145 cities. The National Institute of Urban Affairs (NIUA), a part of the Ministry of Housing and Urban Affairs, along with the National Mission for Clean Ganga (NMCG) under the Ministry of Jal Shakti, has now been entrusted with the responsibility of managing the RCA. The Kham River has become India's first seasonal river under this campaign. During the study we have also created a lab-based model of Floating Treatment Wetland (FTWs) and installed at S.B.E.S College of Science, Chhatrapati Sambhajinagar, Maharashtra. In this model the composite river water samples of Kham River were added. The findings of this model show good results. Plants absorbed the pollutants very well. The results of water quality parameters indicate that the FTW's will stands for an alternative treatment method. This is a very important factor in preparing an urban river management plan. If we adopt Floating Treatment Wetlands (FTWs) it is eco-friendly technology. FTWs will remain sustainable for the restoration of lakes and rivers in India in the future.

Keyword: *Eco-friendly technology, floating treatment wetland, pollutants, river cities alliance, river restoration*

REJUVENATING SMALL WATERBODIES: A CASE FOR SUSTAINABLE MANAGEMENT IN GAUTAM BUDDHA NAGAR, INDIA

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The systems of ponds, tanks and lakes are now increasingly under stress due to urbanization, inadequacies in the policy frameworks, and general apathy of the people. It centres on the initiatives of NbS carried out under the auspices of the HCL Foundation in Gautam Buddh Nagar District of Uttar Pradesh. This study evaluates the scope of NbS in saving water, assisting biodiversity generation, and thereby contributing to economic development. While it broadly focuses on NbS, the study still remains within its limitations to a certain extent, as it excludes mechanized water treatment systems and hydrological interventions. Besides this, it mainly concentrates on greywater-inflow ponds, while water bodies contaminated by industrial effluents and sewage are beyond the scope of its research. A mixed-method approach that integrates both quantitative and qualitative assessments has been adopted in order to evaluate the effectiveness of NbS in rejuvenation of ponds. The present research is based upon a stratified sampling. The four ponds have been selected for the study: Police Line Pond in Surajpur, Chauganpur Pond in Greater Noida, Milak Lachhi Pond in Greater Noida and Mahawad Pond in Dadri. The quality improvement of water was understood by measuring several vital parameters such as pH, TSS, BOD, DO and TDS. It is indicating that these aquatic environments are natural biodiversity hotspots that intrinsically have dynamic landscapes as a backdrop, thus interlacing human activities with natural functioning. Our strategies that have been implemented are holistic approaches to the management of water bodies, restoration of ecosystems, and promotion of biodiversity. The interventions selected at the site level fall under HCL Foundation's environment programme, ensuring sustainability. The water-quality assessments of all four ponds show trends as ecologically driven, thus indicating the positive effects of NbS interventions. Sedimentation and microbial decomposition up to replenishing oxygen are natural processes involving the ponds that enable improvement in water quality while encouraging biodiversity.

The results for these four ponds are presented as (i) Milak Lachhi Pond: pH ranges 7.02 to 8.67 signifies the water is generally neutral to slightly alkaline with support to aquatic life. TSS was significantly decreased from 391 mg/l at inlet to 23 mg/l inside the pond, which would be due to natural filtration that normally increases the clarity of water. Moderately high BOD levels -35.5–38.5 mg/l-suggest active microbial decomposition, which is the primary mechanism for nutrient cycling. In addition, the TDS level reduced from 402 mg/l to 304 mg/l, thereby indicating improved water quality favorable to aquatic organisms; (ii) Police Line Pond: pH value changed to a nearly neutral 7.2 in the pond with improved aquatic life conditions. TSS value reduced from inlet 104 mg/l to 44 mg/l, clarity improved, and photosynthesis occurred. BOD reduced from 38 mg/l to 17 mg/l, thereby resulting in less organic pollution. An elevation in dissolved oxygen levels from 3.8 mg/l to 5.1 mg/l results in more favorable conditions for aquatic organisms, while the reduction in total dissolved solids from 784 mg/l to 450 mg/l further denotes enhanced water quality; (iii) Chauganpur Pond: The broad stable pH range between 6.98 and 7.05 ensures aquatic stability. There is a marked TSS reduction from 100 mg/l to 30 mg/l, increasing light penetration, resulting in enhanced plant growth. Reduction of BOD from 70 mg/l to 25 mg/l indicates cleaner water.

The increase of DO from 2.6 mg/l to 4.5 mg/l would serve aquatic organisms, while the TDS values steady between 400–406 mg/l ensured a balanced mineral content; (iv) Mahawad Pond: The pH of water is found to be slightly alkaline (7.61). This supports biologically quite active. Low value of TSS -17 mg/l results in excellent transparency, which allows photosynthesis. Though a rather high BOD -65.5 mg/l exists, the decomposing action of microbes promotes nutrient cycle. DO level -3.5 mg/l is satisfactory for aquatic flora, and TDS -406 mg/l within the permissible range.

The matrix analysis revealed the ecosystem services of the ponds. The highest scores were achieved in the supporting services including habitat provision and biodiversity promotion, which stood at 64.09% indicating how the ponds support the ecosystem stability. The regulating services which include the improvement of water quality and climate regulation was scored to stand at 57.27%. Cultural services that include the recreation and aesthetic values of the sites were scored to stand at 35.76%, signifying the role the ponds played in facilitating conservation efforts. Livelihood support under socio-economic services secured 13.97%, while provisioning services-offerage of resources like food and water-scored the lowest at 10.77%, reflecting a shift in the community's interest from resource extraction toward obtaining ecological benefits. Community Perception was divided, however, when it came to concerns about pond maintenance in the community survey. Although 57.1% reported that no other agency had cleaned the ponds for over ten years, 98.5% recognized current efforts by outside organizations. In fact, 52.3% believed pond management should be the government's concern; 42%, the community's too, shared responsibility. It is worth mentioning that 76.1% participants were practicing cleanliness-related activities, a trend that indicates an increasing sense of community participation.

Gautam Buddh Nagar-based study shows pond water quality, biodiversity, and ecosystem resilience are significantly improved with NbS interventions, whereas sedimentation and the processes of microbial decomposition facilitate better clarity of water and ecological stability. Needless to say, supporting and regulating services are important to retain ecological balance; therefore, this matrix-based assessment emphasizes it is time to concentrate more on these components. Community engagement was an enabling tool to the achievements realised in pond rejuvenation, while shared responsibility among the stakeholders and government agencies becomes a necessity. Although provisioning services remain underutilized, their ecological and socio-economic benefits contribute to the value ponds hold in sustainable water management. To the end, it adds to the bulk of evidence proving NbS is a scalable and sustainable approach to water management. It therefore opens up the possibility of policymakers making decisions so much better informed by ecological resilience with community well-being. We acknowledge HCL Foundation's commitment to water conservation under their flagship environment program-Harit. The collaborative efforts of HCL Foundation in GBN have been instrumental in harvesting 34 billion liters of water through rejuvenation of 78 water bodies, spread over 214 acres, reviving local ecosystems. HCL Foundation increased its water retention capacity to 1,850 million litres in order to ensure water security for communities in Greater Noida. The local advantage of this lies in its ability to address the regional need for water conservation.

Keywords: *Biodiversity hotspots, climate resilience, groundwater extraction, nature-based solutions, water security*

ENCROACHING PLASTIC POLLUTION IN URBAN WETLANDS: A THREAT TO GROUNDWATER AND ECOSYSTEM HEALTH

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Urban lakes and wetlands are the blue spaces in urban ecosystems and they provide ecological, hydrological, and socio-economic benefits such as biodiversity conservation, flood regulation and water purification. However, these ecosystems are under severe stress due to urbanization and pollution. One significant but underexplored threat is, microplastics (MPs), i.e. plastic pollution which originates from the nearby landfills as leachate into wetlands, lakes, and adjacent groundwater systems. Our study focuses on Bhalswa Lake, an urban wetland in New Delhi, India, and its intricate connection to the nearby Bhalswa municipal solid waste landfill as well as the groundwater of the area. This work examines the potential of plastic pollution in creating a threat to the wetlands, especially the urban lakes, and their implications for environmental and groundwater health.

Landfills are part of urban waste management but have become major sources of pollution including microplastics. Microplastics in landfill leachate comes from the degradation of plastic waste and is a vector for toxic substances and antibiotic resistance genes. In regions like Delhi, where urban wetlands like Bhalswa Lake are in proximity to landfills, the risks of microplastic transport are amplified. These wetlands, intrinsically linked to their watersheds and surrounding groundwater systems, face compounded threats from leachate infiltration, urban runoff, and untreated sewage discharge. In our case study, the animal excreta from the nearby Bhalswa dairy, garbage dumping by local community, leachate from the nearby landfill and leftovers during gatherings cause the wetlands to engulf certain kinds of undesirable components injurious its health. Microplastic contamination in such systems poses a dual hazard. First, microplastics contribute to direct ecological disruptions by affecting aquatic biota and altering trophic interactions. Second, they act as carriers of pollutants, potentially contaminating groundwater. Despite these critical concerns, the interrelationship between landfill leachate, wetland pollution, and groundwater contamination remains inadequately studied.

Surface water samples from the lake were collected using a grab sampling approach, ensuring comprehensive representation of the lake's contamination profile. Approximately 30 liters of surface water were sampled and filtered in situ using stainless steel sieves (0.5 mm to 0.063 mm mesh). Residues were rinsed with distilled water into glass bottles and transported for laboratory analysis. Additionally, leachate samples from the landfill area were collected to investigate microplastics. Samples underwent wet peroxide oxidation (NOAA) to digest organic matter, followed by density separation using NaCl solution to isolate plastic debris. Filtered particles were analyzed using microscopy and FTIR spectroscopy for morphological characterization and polymer identification. Observations included microplastics of varying forms (fibers, fragments, films) and sizes, displaying diverse colors indicative of multiple sources and degradation stages (carbonyl index). FTIR analysis of microplastics from Bhalswa Lake revealed a dominance of polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), nylon, and high-density polyethylene (HDPE) and PTFE. Morphological examination identified fibers, fragments, films, and foam, suggesting mixed

sources such as plastic waste from the landfill, urban runoff, waste disposal, and recreational activities. The diverse color spectrum of microplastics further indicated varying weathering processes and polymer types. The carbonyl index shows that polyethylene (PE) has higher degree of oxidation and degradation compared to polypropylene (PP). The higher carbonyl index of PE compared to PP could be due to the different chemical structure and environmental stability of these polymers. PE degrades faster under oxidative conditions because of its less crystalline and more amorphous structure which is more prone to oxidation. PP has more crystalline structure and presence of tertiary carbon atoms which has different degradation mechanism and slower oxidation rate compared to PE.

Leachate samples from Bhalswa landfill showed high microplastic contamination, the landfill is a persistent source. These particles can be transported through surface runoff or leachate seepage to the lake. Groundwater samples although not included in this study are at risk of contamination. Urban lakes like Bhalswa are ecological refuges, supporting biodiversity including migratory birds and ecosystem services like carbon sequestration and recreational spaces. But microplastic contamination disrupts these roles by degrading water quality, threatening aquatic life and bioaccumulation of pollutants in the food web. Microplastics in landfill leachate which is loaded with heavy metals and persistent organic pollutants are long term risk to groundwater quality. This interplay of pollution across interconnected systems underscores the pressing need for comprehensive management strategies. The transport of microplastics from landfill leachate to Bhalswa Lake and potentially to groundwater represents a critical environmental challenge. Groundwater dependent ecosystems are most vulnerable to this contamination which can alter hydro chemical characteristics, reduce water quality, and compromise their ecological functions. The connection between landfill leachate, urban wetlands and groundwater systems is a critical part of urban ecosystem health. Bhalswa Lake is an example of the complexity of microplastic pollution where leachate from a nearby landfill is a major source of contamination. This study highlights the need for integrated management approach including improving waste management practices, upgrading leachate treatment facilities, and conserving urban wetlands. Addressing these challenges is key to protecting groundwater dependent ecosystems and urban blue spaces. Bhalswa Lake may have been affected but still its ecological significance is supporting migratory birds and urban biodiversity. With proper interventions the lake’s ecological integrity can be restored and reduce its vulnerability to microplastic pollution. This study highlights the broader implications of microplastic transport in connected systems and calls for collective action to mitigate its environmental impact.

Keywords: *Plastic pollution, urban wetlands, water quality, microplastics, landfill leachate*

SEDIMENT-WATER INTERACTION AND ITS IMPACT ON HYDRO-GEOCHEMISTRY IN THE SAJAMA NATIONAL PARK, VOLCANIC ZONE OF THE CENTRAL BOLIVIAN ALTIPLANO

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The Sajama National Park (SNP), surrounded by the Sajama, Parinacota, Pomerate, and Kunturiri glaciers, are important water reservoirs that provide ecosystem services and are highly sensitive to climate change. It is located in the central Bolivian Altiplano at an altitude of 3,860 to 4,184 m above mean sea level (amsl). The SNP is characterized by an average annual precipitation of approximately 320 mm. Previous geological studies carried out reveal that the area is completely covered by volcanic rocks of the dacitic-andesitic composition of Quaternary age (0.6 Ma) and remnants of rhyolitic pyroclastic flows of Pliocene age that cover the region, where these were eroded by past glacial activity and wind in the present, giving rise to fractured and eroded lava flows at the foot of the volcanoes and the sedimentation of sands and silts. This research focuses on evaluating the levels of natural contamination using contamination factors and geo-accumulation indexes and their impact on the hydrogeochemistry of groundwater and surface water systems within Sajama National Park, a volcanic zone in the Central Bolivian Altiplano.

A total of 59 samples were collected from various water sources (lakes, rivers, springs, thermal springs, wells) in the SNP, following Hydrochemistry laboratory protocols for water sampling. The geographic location of each sample point was recorded using a GARMIN portable global position system. Temperature (T), pH, Ox-Red Potential (ORP), electrical conductivity (EC), total dissolved solids (TDS) and dissolved oxygen (DO) were measured in the field using a HANNA multiparameter kit. Alkalinity was measured *in situ* by titration. Analyses of anions were carried out in the Environmental Chemistry laboratory of the Chemical Research Institute (IIQ), La Paz, Bolivia. The main anions, Cl^-, NO_3^-, and SO_4^{2-} were analyzed using a DIONEX model ICS 1100 ion chromatograph with an ion exchange column. The main cations, Na^+, K^+, Ca^{2+}, Mg^{2+}, total arsenic (As), and boron (B) were analyzed in the filtered acidified water samples using inductive coupled plasma emission spectrometry (ICP-OES) and mass spectroscopy methods (ICP-MS) at the University of Grenoble, France. A total of 30 sediment samples from rivers and profiles were digested with Suprapur HCl/HNO_3 solution, cold extractions were performed for 48 hours with constant agitation, and hot extractions were carried out using a Digiprep digester at 70°C for 24 hours. After cooling, the sample aliquots were diluted with 40 mL of ultrapure mQ H_2O, centrifuged for 20 minutes at 4000 rpm, and filtered using 0.45 µm filters into 15 mL Falcon tubes. Sediment extracts were analyzed with an ICP-OES, at the University of Grenoble, France.

The water sources within the Sajama National Park (SNP) exhibit considerable variability in their hydrochemical properties. Temperatures range from 5.1 to 31.5°C, with pH levels spanning from slightly acidic to alkaline (5.9–9.4). Salinity varies between 56 and 2330 µS/cm, with diverse redox conditions observed. Surface waters are predominantly of the Na-

Cl-HCO_3 type, while groundwaters are mainly Na-Ca-Mg-HCO_3 type, and hot springs display a Na-Mg-HCO_3-Cl composition. These water types are influenced by the dissolution of Na and Ca silicate minerals, dolomite, and calcite. The concentrations of dissolved elements in natural water sources show wide variation: arsenic (As) from 0.004 to 1900 µg/L, boron (B) from 28 to 11,792 µg/L, and lithium (Li) from 0.019 to 2810 µg/L. Along the Sajama River, where the Milluri, Junthuma, Taipypuchuni, and Taypyjawira rivers converge, there is notable accumulation of As, B, Li, and Fe. In river sediments, As ranges from 6.7 to 2006.6 mg/kg, B from 21.1 to 419.2 mg/kg, Li from 0.002 to 37 mg/kg, and Fe from 13,997 to 369,997 mg/kg. Lagoon sediments exhibit lower concentrations: As from 14.7 to 19.8 mg/kg, B from 27.2 to 33.5 mg/kg, Li from 5.1 to 6.1 mg/kg, and Fe from 11,759 to 29,353 mg/kg. Geothermal rocks contain As from 18 to 73.6 mg/kg and Fe from 1,885 to 137,667 mg/kg. High enrichment and geo-accumulation of As and B in river sediments along the Sajama River are primarily attributed to geothermal sources, with additional contributions from sedimentary and volcanic rocks and decomposing organic matter. Li and Fe concentrations in river sediments show low to moderate enrichment, with the highest accumulation in the Junthuma River, also linked to geothermal sources. The hydrogeochemistry of the Sajama National Park system reflects a complex interplay of geothermal activity, sediment interactions, and geological processes. Variations in volcanic rock composition, ranging from dacitic to rhyolitic and ignimbritic, significantly influence water chemistry by affecting mineral solubility. Enrichment and accumulation of As and B in river sediments within the Sajama basin appear to result from continuous input from geothermal waters. Additionally, fine-grained sediments and deposited organic matter contribute to this accumulation, underscoring the dynamic geochemical environment of the region.

Keywords: *Sajama National Park, hydrogeochemistry, sediment, enrichment factor, geo-accumulation index*

ECOSYSTEM HEALTH ASSESSMENT OF KOL WETLANDS, A RAMSAR SITE: TOWARDS ENVIRONMENTAL SUSTAINABILITY

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The Kol Wetlands, recognized as a Ramsar site in Kerala, India, are a distinctive and ecologically significant habitat. This research explores the ecological dynamics of the Kol Wetlands, with a particular focus on the ecological contributions of fish, birds, and mangrove species. Biodiversity assessments, based on the Shannon-Weiner Index (H') conducted to evaluate species richness. Findings reveal ecosystem stress in the Kol wetlands, marked by declining avifaunal diversity, low fish diversity, increasing invasive plant species, and mangrove degradation due to urbanization and land-use changes. Wetlands are “lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water”. The study has been carried out in Kol wetlands of Thrissur district, a Ramsar site in Kerala. The district includes an estimated wetland area of 13,285 ha, comprising 271 small wetlands that fall below the minimum size threshold. According to Kol Wetlands were also declared as a Ramsar Site in 2002 and form part of the Central Asian Flyway of migratory birds. The word "Kol," which is from the Malayalam language, translates to "bumper yield", this term is associated with an exceptional cultivation process performed within the backwaters during December to April. Kol Wetlands lie between 10°20' to 10°40' N latitude and 75°58' to 76°11' E longitude, these low-lying tracts, situated from 0.5 to 1 meter above mean sea level (amsl), are submerged for nearly six months in a year. The main objective of this study is to analyze the impact of changes in biodiversity (birds, fish, mangroves, and plants) on the functionality of the Kol wetland ecosystem.

Birds have vital significance in ecological processes such as pollination, control of pests, cycling of nutrients, and seed dispersal. Through their planktivorous diet, fish help maintain balance in phytoplankton populations, preventing harmful algal blooms that compromise water quality. Mangroves themselves provide essential ecosystem services, such as carbon sequestration, stabilize shorelines, thereby reducing erosion and shielding inland areas from floods. The H' is a diversity index used to assess species diversity of birds, fish, mangroves, and wetland plants in the Kol Wetlands, Ramsar site ecosystem taking into account species richness. Relative abundance (pi) was calculated for each species, which will help to identify trends and shifts in biodiversity. Total of 182 bird species were identified, spanning over 16 orders and 47 families. Among these, 24 species are newly recorded in this area, while 44 were transcontinental migrants. Habitat classification revealed that 24.86% of the birds relied on aquatic habitats, 21.55% were waders, and 53.59% were terrestrial, indicating that the Kol wetlands also support a significant number of passerine species. Shannon diversity of 3.11 for the whole wetland also indicates the high diversity of birds. According to (Jayson, 2018) total of 155 species of birds belonging to 15 Orders and 49 Families were recorded from the area. Among the 15 Orders, Passeriformes, Charadriiformes and Pelecaniformes dominated with 46, 30 and 25 species, respectively. The H' for the given bird population data is 2.13, indicating a moderate level of biodiversity among the species. As per the study it is observed that there is a reduction in Index value which denotes the pressure on avifauna in this region.

The study area recorded a total of 55 fish species distributed into 44 genera, 23 families and 10 orders. The most abundant species identified were *Amblypharyngodon melettinus* (2171 individuals) and *Systomus subnasutus*(1622 individuals). The estimated H′ for the two abundant *Amblypharyngodon melettinus* and *Systomus subna* species is 0.683 whereas the H′ calculated order-wise is 1.767. As per the estimated index, it is observed the aquafauna exhibit very low diversity. The Kol wetlands, Ramsar site host a total of 140 species, distributed across 23 families of dicotyledons, 11 families of monocotyledons, and 5 families of water ferns. The vegetation is characteristically unique with only aquatic and marshy varieties such as Hydrilla, Eichhornia, water ferns, and algae but also various types of small trees along the bunds that may endure long-term waterlogging. Recently *Cabomba furcata*, commonly known as Pink bloom has emerged as new threat to the Kol fields, along water hyacinth and *Salvinia molesta.* According to commonly found mangrove species are *Rhizophora mucronata* and *Excoecaria agallocha* similarly, rarely found mangrove species are *Avicennia officinalis, Bruguiera cylindrica, Aegiceras corniculatum.* Soil samples obtained from the Chettuva mangroves indicate that organic carbon content varies between 1.06% and 2.35%. The carbon stocks in these regions were 2,089.33 t CO_2 per hectare, with the mangroves mainly consisting of *Rhizophora mucronata* and *Bruguiera cylindrica*. According to the Shannon diversity corresponding to Kol wetlands is 3.309. The study noted that the Kol wetlands, Ramsar site are under significant pressure from habitat alteration, infestation of aquatic weeds, and changes in land use patterns. The Kol lands are being converted to coconut, areca nut, banana plantations and other cash crops at an alarming rate. However, mangrove destruction is underway, with ecotourism being one of the cited reasons for degradation in Chettuva, and real estate activities have already cleared out vast mangrove patches in Pulloot, Kodungallur. The evidence implies that human-induced reduction of mangrove cover could reduce these carbon sinks, making climate change even worse. Additionally, tourism activities were identified as potential hindrances to migratory birds, also reduction of mangrove cover could reduce these carbon sinks , suggesting a need for better management practices within Ramsar Sites.

Keywords: *Ramsar site, Kol wetland, Shannon-Weiner Index, Biodiversity, Ecosystem services*

ASSESSMENT OF RESERVOIR SEDIMENTATION USING GEOSPATIAL TECHNIQUE: A CASE STUDY OF SALERAN RESERVOIR IN SHIVALIK FOOT-HILLS OF NORTH-WEST INDIA

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Dams and reservoirs are important infrastructures to conserve soil and water, and saving downstream areas from floods and droughts. However, reservoir sedimentation has become an important issue all over the world as it reduces storage capacity and shorten the useful life. Soil erosion and reservoir sedimentation are interconnected processes that significantly affect the storage capacity and functionality of reservoirs. Runoff from sloped catchments carries eroded sediments into reservoirs, where the flow velocity decreases, leading to sediment deposition. This accumulation reduces the reservoir's storage capacity, shortens its lifespan, and negatively impacts downstream ecosystems, dam equipment, and water availability. Globally, reservoirs lose 0.1-1% of their capacity annually due to sedimentation, with India experiencing a slightly higher rate of 0.1-1.5% per year in north-wester parts of Shivalik hills locally known as the Kandi region. Sedimentation also distorts the elevation-area-capacity curve, leading to inaccurate water availability estimates. Conventional methods for estimating sedimentation, such as bathymetric surveys and stream flow analysis, are labour-intensive, costly, and time-consuming. In contrast, geospatial techniques using Remote Sensing and GIS offer a more efficient, cost-effective solution. These technologies allow for accurate calculation of reservoirs' water spread area and volume, aiding better reservoir management and planning. One such earthen dam was constructed at the outlet of Saleran watershed which is located between the coordinates of 31º 35' 58.56"N, 75º 59' 14.54" E and 31º 37'58.21" N, 76º 01' 47.87" E in Shivalik foot-hills in the year 1995. The reservoir of the dam is facing the problem of high siltation rate that is causing reduction in its storage capacity at a very fast rate. Hence, this study was planned with the specific objectives of determining capacity loss rate of the Saleran reservoir due to sedimentation and to update the elevation-area-capacity curve of the reservoir using geospatial technique. The Survey of India (SOI) toposheets have been used for preparing the reservoir catchment area. The digitization and georeferencing of traced area was carried out using ArcGIS software. The Landsat 8 OLI satellite sensor imageries with 30 m spatial resolution data was used in the present study. Satellite imageries of Saleran reservoir on different 18 dates, for the years 2016-2020 were downloaded from USGS Earth Explorer web portals. The layer stacking and image registration of downloaded satellite images were used to create subsets of the Area of Interest (AOI) using ERDAS Imagine 14.0 software. Modified Normalised Difference Water Index (MNDWI) was used to extract the water spread areas of the reservoir on different dates during the years 2016-2020 at different water elevations. The standard False Color Composition (FCC) of images were used for verifying the water pixels. Water spread areas of the Saleran reservoir at different water elevations between Full Reservoir Level (FRL) to Minimum Dead Level (MDL) on different months of the years 2016-2020 were used as an input in Prismoidal formula to calculate the reservoir incremental capacity. Field data collection and ground verification of Saleran reservoir features was conducted after geo-referencing of satellite imageries. The computed storage capacity and water surface areas (Geospatial 2020) and (Bathymetric 2021) have been compared with design storage capacity data and water surface area of the year 1995 of reservoir to analyze the reduction in the water surface area and the loss of reservoir storage capacity due to sedimentation and to update elevation-area-capacity curve. The loss in storage capacity-2020 estimated using geospatial technique and 2021 using bathymetric technique are compared to the design storage capacity of the Saleran reservoir in the year 1995 at different water elevations the loss in the storage capacity (2020) varies from 2.54 ha-m (93.27%) to 36.09 ha-m (18.03%) at the observed minimum and maximum reservoir water elevation of 389.67 m and 402.01 m, respectively in a period of 25 years (1995-2020). The total storage capacity of the Saleran reservoir was estimated to be 164.03 ha-m in the year 2020, against the design capacity of 200.12 ha-m at the highest elevation of 402 m in the year 1995. There was a loss of 36.09 ha-m of storage capacity due to deposition of sediments in 25 years (1995-2020). That means 18.03% of the storage capacity decreased by the year 2020. The results indicate that Saleran reservoir is losing its capacity at a rate of 0.721%, annually. As per bathymetric survey evident the loss in the storage capacity (2021) varies from 1.77 ha-m (65.00%) to 24.22 ha-m (12.10%) at the observed minimum and maximum reservoir water elevation of 389.50 m and 402.01 m, respectively in a period of 26 years (1995-2021). The total storage capacity of the Saleran reservoir was estimated 175.90 ha-m in the year 2021, against the design capacity of 200.12 ha-m at the higher elevation of 402.01 in the year of 1995. There was a loss of 24.22 ha-m of storage capacity due to deposition of sediments in 26 years (1995-2021). That means 12.10% of storage capacity decreased by the year 2021. As per bathymetric survey results indicate that Saleran reservoir is losing its capacity at a rate of 0.45% annually. There is an upward shift in the updated elevation-capacity curve compared to the design elevation-capacity curve-1995 indicating decrease in storage capacity of Saleran reservoir at different elevations and hence updated curve should be used for estimating water stored in the reservoir.

Keywords: *Reservoir, Sedimentation, Bathymetric, Remote Sensing and GIS, MNDWI*

SYSTEM DYNAMICS AND MODELING OF MICRO-WATERSHEDS

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Climate change has led to frequent and intensifying weather patterns that led farmers sought to groundwater resource for irrigation which substantially accelerated the decline of water tables in India. Sustainable management of water resources at micro-watersheds is critical for addressing long-term water security, particularly in regions reliant on groundwater for agriculture. Various government initiatives such as MGNREGA, Watershed Development under Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) and Atal Bhujal Yojana (Atal Jal) have emphasized the development of surface water storage structures. However, understanding the intricate dynamics of climatic, hydrological, physiological, and socio-economic factors at the micro-watershed level presents a complex challenge for the rural communities to adopt and construct surface water storage structures. In this study, we leverage remote sensing data to model and analyze the dynamics of micro-watersheds, using which "what if" scenarios can be constructed to evaluate the impacts of various interventions like the creation of water bodies or the building of MGNREGA structures. These interventions aim to reduce groundwater stress and facilitate a transition toward rainwater-fed irrigation systems. Our simulations incorporate various climate-induced scenarios to assess the influence of prospective interventions on water availability and system sustainability. The simulations can help CSOs engage rural communities in exploring effective rainwater harvesting structures to support rain-fed agricultural systems and build community resilience against climate change.

We used different data sources for modelling the systems dynamics at micro-watershed level. These include Rainfall (GSMaP Operational: Global Satellite Mapping of Precipitation), Runoff, Temperature (from ECMWF ERA5-Hourly), Monsoon onset using CHIRPS Daily, Surface water bodies, cropping area, Area under different stream orders, Mild, moderate and severe weeks of drought based on Manual for Drought Management 2016 by Ministry of Agriculture and Farmers Welfare, Government of India, NREGA structures, Crop health, Stage of Groundwater Extraction using CGWB data and supplemental groundwater irrigation using evapotranspiration and soil moisture. The choice of remote sensing datasets was governed by their spatial coverage, spatial resolution, temporal resolution and whether they are operational. Using a socio-hydrological lens, we developed a systems model to model the dynamics at micro-watershed level. A micro-watershed is influenced by climatic factors that influence the supply-side of irrigation such as rainfall, temperature, drought and onset of monsoon. Depending upon the capacity of prevailing water bodies and MGNREGA water structures that harvest the generated runoff, total surface water storage of the micro-watershed is determined. Based on the field observations, the surface water storage in water bodies and MGNREGA structures are directly used for irrigation through horizontal siphoning (low impact zone of 200 m around the water body). The seepage from surface water bodies and MGNREGA structures has been observed to increase the soil moisture levels in surrounding farmlands, extending up to 1.5 km away (low impact zone). To irrigate farmlands within the low-impact zone and areas beyond both the low- and high-impact zones, farmers supplement irrigation by abstracting groundwater. Groundwater abstraction in a year

depends on the state of groundwater in the micro-watershed due to long-term abstraction along with the state of groundwater in the block, estimated annually by CGWB.

We intend to perform year on year projection of agricultural outcomes such as cropping area and crop health with continuous and discrete interventions of large surface water bodies and MGNREGA-funded water structures in the micro-watershed under various climate scenarios. The projection framework can be also used as simulation framework for what-if scenarios to maximize the climate resilience of the micro-watershed. What-if scenarios are hypothetical simulations used to predict outcomes of various interventions, for example, building ten check-dams and two ponds in the micro-watershed. What-if scenarios are essential to identify the most appropriate combination of interventions that are contextual and specific to the agro-ecology of the micro-watershed. The projection and simulation framework can provide critical evidence toward creating surface water storage structures through rainwater harvesting, ultimately reducing dependence on groundwater for irrigation. By demonstrating the potential benefits of these storage structures, CSOs can strengthen community engagement and mobilize local action in adopting rainwater harvesting methods that are sustainable and in line with national water conservation goals. The framework will provide evidence on the impact of increasing surface water storage using simulations enhancing cropping area, cropping intensity and crop health during drought years, demonstrating the farmer adaptation to groundwater scarcity by notable reduction in groundwater abstraction observed due to available surface water storage for a sustainable approach to alleviate groundwater dependence. Furthermore, we intend to identify the “tipping point” in groundwater usage, beyond which continued abstraction would lead to a sudden and unsustainable drop in groundwater levels, effectively eliminating access for many small farmers.

The projection and simulation framework aims to provide CSOs with evidence to initiate community discussions on the importance of supply-side and micro-watershed-based interventions for sustainable water management in irrigation. By demonstrating the positive impact of increased surface water storage and therefore reduced groundwater dependence to improve cropping area and crop health, the framework can help CSOs engage rural communities in exploring effective rainwater harvesting structures to support rain-fed agricultural systems and build community resilience against climate change. A key outcome of the above socio-hydrological systems approach is to model the complex feedback loops on demand side which are between natural and human systems, particularly illustrating how farmers’ crop choices prompted by increased water availability from surface water bodies for irrigation can amplify groundwater stress. For example, an increase in surface water availability has led farmers to transition from less water-intensive to more water-intensive crops in the past, thereby elevating groundwater demand. Another aspect to model within this framework is the equitable distribution of water bodies and MGNREGS structures among different social groups within the micro-watershed, ensuring fair access and promoting sustainable water management across diverse communities.

Keywords: *Climate change adaptation, groundwater stress, MGNREGA water structures, tipping point in groundwater usage, equitable irrigation*

VALIDATION OF CRAIG GORDON MODEL FOR EVAPORATION ESTIMATION IN THE GANGA YAMUNA DOAB REGION

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The research examines the application of stable water isotopes to assess evaporation (Craig-Gordon Model), illustrating isotopic enrichment along a running water body. A large number of studies has demonstrated isotopic enrichment as a component of evaporation from stagnant water bodies. However, there is a lack of knowledge regarding the evaporation and isotopic signature of ground level vapor (GLV) fluxes above running water bodies. The estimation of the water budget and the determination of vapor loss, particularly in natural river systems, can be challenging due to uncertainties in the monitoring of water flow. Nevertheless, it is somewhat simpler in canals/reservoirs where the inlet and outlet are fixed. The Upper Ganga Canal (UGC) evaporation characteristics are evaluated from September 2021 to August 2022, leaving out the wet season (June to July). Applying the model for evaporation investigations on running water bodies is made possible by the canal's controlled hydraulic environment. The UGC originates from the Ganga River at Bhimghoda Barrage in Haridwar, built in response to a severe famine in the Ganga-Yamuna Doab region of India caused by a lengthy monsoonal failure. The canal system has a principal canal extending 290 kilometers from the Bhimgoda barrage, Haridwar to Nanao, Aligarh, Uttar Pradesh. The canal discharges 300 m^3/sec of water, facilitating irrigation for the most densely populated areas of Uttar Pradesh and Uttarakhand, encompassing a fertile area of 9,000 km^2. Haridwar's climate is characterized by an average of 4.48 mm of precipitation per day and a maximum annual temperature range of 46.35°C to 1.83°C. Nanao exhibits a broader temperature range, spanning from 48.71°C to -1.03°C, and a reduced average annual precipitation of 0.26 mm/day.

Canal surface water and GLV samples were collected and analyzed for stable isotopic composition. GLV was collected utilizing a Cryogenic Trap where atmospheric air is constantly circulated at a flow rate of 250 ml/min by an air pump linked to a custom-built moisture trap submerged in -80º C ethanol-liquid nitrogen sludge. Moisture in the air is condensed in the trap, which is subsequently melted (Precautions are taken as the melting of the condensed phase may lead to fractionation) once a significant quantity of moisture has accumulated at ambient temperature. The results of canal surface water indicate distinct isotopic enrichments from the headwaters to the canal's terminus. There is a seasonal shift in the isotopic enrichment levels; higher enrichment is observed during the pre-monsoon season, intermediate enrichment values during the post-monsoon season, and lower enrichment during the winter season. The surface water evaporation in transit from Haridwar to Nanao is estimated using the revised Craig Gordon model. The seasonal variation in the evaporation by inflow (E/I) reveals less evaporative loss in the winter season (5.41 ±1.86%, standard error 0.93%), while the seasonal variation in the E/I indicate 15.49% ± 5.12% with standard error of 2.29% in the pre-monsoon season and intermediate values for the post-monsoon season (12.06% ± 1.43%, standard error 0.64%). The E/I ratio in the Upper Ganga Canal is inversely proportional to the slope of d-excess, meaning that a negative slope results in an intense evaporation while a slope that approaches zero results in a moderate evaporation. Prior studies suggest that the appropriateness of an estimation method for a

specific area can be assessed by examining the key climatic factors influencing evaporation in that region. Three climate zones are identified in the Ganga-Yamuna doab region according to the data collected using Normalized difference in vegetation index (NDVI), Standardized precipitation index (SPI), and Evaporative Stress Index (ESI), viz. The Northern humid zone, the Transition semi-humid zone, and the Southern semi-humid to semi-arid zone. The Craig-Gordon model evaporation estimates respond in a progressive order from the humid to the semi-arid climatic zone. For instance, the northern zone accounts for 20 ± 7% (standard error ~ 2%), the transition zone for 33 ± 5% (standard error ~ 1%), and the southern zone for 50 ± 10% (standard error ~ 3%). The sensitivity analysis highlights that relative humidity is the primary climatic variable in the Ganga-Yamuna doab region, surpassing temperature and ground-level vapor isotopes in its capacity to influence evaporation. An effort has been made to reduce the uncertainty in the evaporation estimation in comparison to previous studies by carefully designing year-long sampling, using canal surface water temperature, using GLV isotopic values and avoiding rainfall effects. Nevertheless, the estimated result could be improved by taking into account the flow velocity and turbulent mixing of water at check dams.

Keywords: *Stable water isotopes, ground level vapor, evaporation, Craig Gordon model, evaporative stress index*

APPLICABILITY OF KUMARASWAMY DISTRIBUTION TO DERIVE GEOMORPHOLOGICAL INSTANTANEOUS UNIT HYDROGRAPH (GIUH)

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Prediction of floods in ephemeral streams is very challenging due to the highly variable rainfall patterns and a lack of the historical time series data**.** Many of the researchers have utilized the Geomorphological Instantaneous Unit Hydrograph (GIUH) model to predict the discharge in un-gauged basins and the results were encouraging. The GIUH is a probabilistic model that is based on the drop's travel time distributions in the catchment. To determine the runoff from the catchment, various paths that a randomly selected raindrop would take in reaching the outlet known as the trapping state are calculated. The path probability functions are then convoluted to represent the unit hydrograph. The GIUH generated is the probability distribution function (PDF) of the travel times to the outlet. However, determining the probabilities for each path and convolution of various PDFs become very difficult. It is found that using PDFs to represent the GIUH can be a substitute for the conventional GIUH. An alternate proposal is to couple the GIUH with other models. Since the GIUH is represented using PDFs, it would be fitting to examine the suitability of various statistical distribution approaches to derive the GIUH. Over the years many PDFs have been employed with GIUH to produce reasonable runoff estimates. Some PDFs include gamma distribution, logistic distribution, Weibull distribution, and Nakagami-m distribution. In this study, an attempt has been made to derive a GIUH using the Kumaraswamy distribution. Keeping in mind the effectiveness of statistical distribution approaches, the present study aims to utilize the Kumaraswamy distribution to derive the GIUH and analyze its effectiveness in predicting floods in ephemeral streams. Simultaneously the effectiveness of existing GIUH models such as Nash-based model and travel time probability distribution model is also analyzed. Using the SRTM 1-arc-second data obtained from the USGS Earth Explorer, delineation of the channel network and basin is carried out in the QGIS 3.28.2 which is open-source software. The geomorphological characteristics are extracted and the GIUH models are developed in the Python programming language. Five events of heavy precipitation are selected to check the applicability. The results obtained from the simulation are compared with the observed data at the monitoring sites. Here, an approach has been made to utilize Kumaraswamy distribution to generate the GIUH from the known peak discharge and time to peak values. To generate the GIUH various geomorphological characteristics of the basin are required. The geomorphological features of various sub-basins of Banas River are extracted using the freely available SRTM Digital Elevation Models (DEMs) with the aid of open-source software QGIS. The channel network characteristics such as order of the basin, bifurcation ratio, stream length ratio, and stream area ratio are calculated from the extracted feature. These ratios are used to determine peak discharge values and time to peak. The parameters of the distribution are calculated using a heuristic search algorithm such as Harmony Search Algorithm. The validation of the proposed model is done by comparing it with the already published data. On comparison with other distribution approaches such as the Logistic, Gamma, Weibull distribution, and Nakagami- m distribution, it has been found that the

Kumaraswamy distribution outperforms other distribution approaches for the Myntdu-Leska catchment, while it significantly fails to regenerate the GIUH for Burhner catchment. However, beyond the peak discharge value, the shape of the GIUH is recaptured. It can be said that for catchments that require a longer time to attain. On comparison, the Root Mean Squared Error (RMSE) values for Logistic, Gamma, Weibull, Nakagami-m, and Kumaraswamy distributions come out to be 2.9, 1.5, 1.8, 1.7, and 1.3 respectively for Myntdu- Leska catchment and 15.8, 5.6, 4.3, 4.9 and 10.8 respectively for Burhner catchment. The R^2 error for the Kumaraswamy distribution for the Myntdu- Leska and Burhner catchment are 0.917 and 0.797 respectively. The RMSE values show that the Kumaraswamy distribution performs better for the Myntdu- Leska watershed than the other two approaches. After the peak discharge value, the Kumaraswamy distribution fits better than the other approaches while it fails to match the observed values in the rising limb part. It can be concluded that for rainfall events that produce peak discharge in a relatively shorter duration, the Kumaraswamy distribution can be a useful prospect for generating the shape of the hydrograph. This may be the case of the flash flood events when the high-intensity rainfall produces a quick runoff in a relatively short time. The validation with published data shows that Kumaraswamy distribution can be utilized as a PDF to produce the GIUH. The proposed approach has been extended to apply it to the Banas River basin which is a partially gauged basin of Rajasthan state of India. Various GIUHs have been developed for the sub-basins of the Banas River, which can be useful in predicting the flash flood events and in proposing the mitigation schemes.

Keywords: *GIUH, ungauged basins, Kumaraswamy distribution, probability distribution functions, flash floods*

WATER QUALITY AND GEOCHEMICAL ASSESSMENT OF TERRACOTTA DUG WELLS: AN IMPLICATION IN RESTORATION AND CONSERVATION OF ANCIENT CIVILIZATION

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The dug wells have been the source of drinking, domestic, and irrigation water since the inception of human civilization. We studied the geochemistry of fifteen dug wells constructed from the Stone Age to the Medieval period in the Mohani River basin with special reference to their archaeological significance and live status in delivering ecosystem services. These dug wells were located in the two ancient villages, Mangarh and Daihar, in the Chouparan Block of the Hazaribagh district in the Jharkhand State. Both villages are apostles of the ancient civilization that witnessed the evolution of Vedic culture in the form of Bhadrakali, Kamala Mata, and Maa Samohar Temples. The land use practices significantly impaired the archaeological evidence, including the density of ring-shaped dug wells in the Mangarh and Daihar villages. Ring wells were so named because of the lining with terracotta rings, which can be distinguished from other types of wells. The archaeological records classified the construction of such dug well as old as 2500 years ago. The shape, circumference, diameter, water table, and depth of all fifteen dug wells were almost identical in our study area. All were 1.9 meters in diameter with 35-40 ft depth. The base ring of the terracotta dug wells comprises the woods of the *Eugenia jambolana*, vernacularly known as Jamun, Jambul, or Java Plum. The Jamun wood does not degrade in water for a longer period. When placed in the dug wells, it prevents the formation of algal blooms in the water. It helps in the adsorption of organic pollutants, dyes, heavy metals, parasites, and toxins and minimizes the frequency of dug well cleaning.

The study area experiences three distinct seasons, namely summer (March-May), Monsoon (June-October), and winter (November –February), with annual average rainfall of 1347 mm. During peak summer, the maximum temperature goes up to 46 ^{0}C, and the minimum temperature drops to 4 ^{0}C. Geologically, the area is underlain by Chotanagpur granite gneiss and unconformably overlain by lower Gondwana formations consisting of sandstone, shales, and coal seams. Groundwater mainly occurs under water table conditions in weathered residuum and semi-confined conditions in deeper fractures. Granite rocks show maximum thickness of weathered mantle in favorable topographic and drainage conditions. The filed inventory of dug wells was carried out using handheld GPS and drone mapping in the monsoon month of September (2024). The water samples of the dug wells were collected by adopting standard protocols. Filed and laboratory analyses of the physicochemical parameters were carried out using standard methods. The results of dug well water quality data were analyzed to determine the geogenic and anthropogenic sources of the dissolved ions, decipher weathering patterns, and identify geochemical signatures of the groundwater.

The ionic balances were generally within ± 5-10 %. The pH, EC, TDS, and salinity varied from 7.29-8.80, 441-4080 µS/cm, 313-2890 mg/l, and 173-1730 mg/l, respectively. Dominating cations were of the following order: $Ca^{2+} > K^{+} > Na^{+} > Mg^{2+}$, and the dominating anions were of the order $HCO_3^{-} > Cl^{-} > NO_3 > {}^{-}SO_4^{2-} > F^{-} > PO_4^{3-}$. The Pearson correlation

showed a strong pairing between cations and anions, indicating their common sources in the dug well waters. However, the high dissolved concentration of K^+, NO_3^-, and Cl^- indicates a long history of farming practices and sewage disposal responsible for their enrichment. The PCA analysis revealed four principal components with 86.94 % of total variance having Eigen value > 1. The Gibbs' diagram suggests that rock weathering and dissolution of evaporites are the dominant mechanisms controlling the water chemistry of dug wells. Piper plot showed that the dug well water types are mostly characterized by Ca-Cl, Ca-HCO_3, Na-HCO3, and Na-Cl facies. The effective CO_2 pressure ($\log P_{CO2}$) varied from -1.80 to -3.4, greater than the atmospheric value of -3.5. The dug well waters were supersaturated with calcite while saturated to supersaturated with aragonite. The high to very high salinity hazard can impact crop yield and land degradation. Interestingly, the low SAR (< 10) recorded in our study indicates water percolates through the soil more easily. The systematic and comprehensive geochemical assessment of the ancient fifteen terracotta dug wells indicates high concentrations of dissolved ions that make groundwater non potable. The total hardness of more than 50 % of dug well water samples exceeded the drinking water standard (IS10500). From the study, it is found that the restoration and conservation of historically important civilization pieces of evidence should be carried out and must be protected.

Keywords: *Ancient civilization, terracotta dug wells, geochemical assessment, ecosystem services, restoration and conservation*

MAPPING SPATIAL AND TEMPORAL DYNAMICS OF LAKES OF BELAGAVI TALUK, KANRATAKA USING GEO SPATIAL TECHNOLOGY

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Water bodies are vital to sustaining both human and ecological systems. They play an integral role in maintaining the balance of local and regional climates, providing water resources for agricultural, industrial, and domestic purposes, and supporting biodiversity. Identifying and monitoring changes in the extent and condition of water bodies is essential for effective water resource management and environmental protection. Remote sensing data has proven to be an invaluable tool for analyzing the spatial and temporal variations of lakes, helping to monitor hydrological changes and to study the impacts of urbanization, climate change, and land use on water bodies. One such study was conducted in Belagavi taluk, focusing on the long-term changes in the hydrological response of lakes in the region.

The study primarily utilized satellite data from various sources, including CartoSAT-1. Of 5.6m resolution and Corona space imagery, to evaluate changes in the number, size, and drainage networks of lakes in Belagavi taluk over a period of several decades. The study compared three significant time points: 1920, 1973, and 2017, using cadastral maps from 1920, Corona satellite data from 1973, and fused satellite imagery from CartoSAT and LISS IV from 2017. this study conducting analysis only for 1920, 1963 and 2017 as are identifying water bodies changes for century. Through these datasets, the study delineated the boundaries of lakes and drainage systems and assessed how these have transformed over the years, particularly focusing on urban expansion and its impact on water bodies.

The analysis showed that between 1920 and 1973, the number of lakes in Belagavi taluk declined by approximately 30.30%. However, there was a notable increase in newly formed lakes during the same period, with the number of lakes growing by 27.86%. This expansion could be attributed to changing land use patterns, possibly due to increased agricultural activities or natural processes such as flooding or changes in the region’s hydrology. In terms of surface area, the lakes in 1973 had expanded by 50%, reaching an area of 849.27 acres, compared to 563.18 acres in 1920. The average rate of expansion for the lakes during this period was about 5.63 acres per year, highlighting a gradual increase in their size.

However, the period from 1973 to 2017 witnessed a significant degradation of lakes in Belagavi taluk. During this time, a total of 49 lakes disappeared or were severely degraded, largely due to uncontrolled urban expansion, industrialization, and the impacts of climate change. Human activities, including the construction of buildings and infrastructure, resulted in the conversion of many lakes into built-up areas or other land uses. Other lakes that survived the urbanization process have experienced a reduction in size, and their water quality has deteriorated due to pollution, often becoming filled with algae and waste.

The study used remote sensing data to identify and measure these changes in a systematic manner. The satellite images from 1973 and 2017 provided a clear picture of the transformation of the region. In 1973, there were 160 lakes, while by 2017, only 124 lakes remained. Despite this decline in the number of lakes, the period from 1973 to 2017 saw the creation of 31 new lakes, although this number was significantly lower compared to the earlier period. This suggests that while new lakes were formed, their creation could not offset the losses experienced due to human interventions and environmental changes.

Urban growth was another critical factor contributing to the reduction in the number of lakes and their degradation. The study mapped urban expansion in the region by analyzing satellite images from 1973 and 2017. In 1973, the urban area was around 22 square kilometers. However, by 2017, this area had grown dramatically to 92.10 square kilometers, marking an increase of more than four times. This rapid urbanization resulted in the conversion of agricultural land, open spaces, and wetlands into residential, commercial, and industrial zones, significantly reducing the available space for lakes and drainage systems.

The consequences of this urban expansion are evident in the disappearance and degradation of lakes. A total of 49 lakes were either entirely filled in or converted into built-up areas or open land with scrub. The remaining lakes saw a reduction in their size and a decline in water quality due to pollution and the encroachment of urban developments. The shrinking of lakes and their pollution pose a significant threat to the local ecosystem, as these water bodies are crucial for maintaining biodiversity, supporting agriculture, and providing clean water.

The findings of this study emphasize the importance of monitoring and managing water bodies through advanced techniques such as remote sensing and geographic information systems (GIS). By conducting a systematic inventory and spatio-temporal analysis of lakes and drainage systems, it is possible to identify the factors contributing to the degradation of lakes and prioritize conservation efforts. The results of the study highlight that human activities, such as urban expansion, land use changes, and pollution, have had a profound impact on the health of lakes in Belagavi taluk. If these trends continue, the environmental consequences could be severe, leading to the loss of vital water resources and ecological functions.

The study concludes that effective lake conservation planning is essential for maintaining a healthy and sustainable environment. Through the use of scientific techniques and satellite data, authorities can identify critical lakes that require protection and develop strategies to safeguard these water bodies from further degradation. This could include implementing policies to control urban sprawl, reduce pollution, and restore damaged lakes. Furthermore, public awareness and community involvement in conservation efforts are crucial for ensuring the long-term preservation of lakes and their surrounding ecosystems.

In summary, the study on the lakes in Belagavi taluk demonstrates the significant changes in the number, size, and condition of lakes over a span of nearly a century. The combination of urban growth, land use changes, and environmental factors such as climate change has led to the loss of many lakes and the degradation of others. Through the use of remote sensing and GIS technologies, it is possible to track these changes, prioritize conservation efforts, and develop strategies to protect and restore the remaining lakes in the region.

Keywords: *Lakes, satio-temporal changes, drainage pattern, dynamics of lakes, Belagavi taluk, and remote sensing*

MORPHOMETRIC COMPARISON OF RIVER BASINS IN BARAMATI TEHSIL, MAHARASHTRA, INDIA

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A comparative investigation of areal, linear, and relief factors revealed that the Karha river basin is more developed than the Nira and Bhima basins. Watersheds, also known as drainage basins, are hydrological units defined by geographical characteristics that impact the flow and distribution of water. Morphology refers to the study of the size, shape, and organization of landforms. Morphometric analysis of watershed involves quantitative examination of land surface properties such as the dimensions, shape, and scale of landforms. Modern tools enable detailed analysis of the basin characteristics. Morphometric analysis is critical for the efficient use and management of natural resources within a watershed. Planners can find development prospects by analysing a basin's linear, areal, and relief parameters. Soil, vegetation, geology, and structure all have a role in shaping drainage networks, which contribute to landscape change.

Geospatial technologies have significantly enhanced the precision and ease of computing morphometric indicators, allowing for more accurate assessments of a basin's geometry, including aspects like geomorphology, geology, slope, and other structural constraints. Significant advances to geomorphology, particularly after 1945, have focused on the link between a drainage system's morphological features and hydrological factors. Initially it is necessary to investigate the relationship between stream order and numerous basin metrics, such as average stream length and drainage area. Geospatial techniques, aid in better understanding of these linkages and their implications in watershed management. The goal of this research is to improve knowledge of selected river basins' hydrological and geomorphological behaviour, laying the groundwork for long term and informed watershed management. Under this study morphometric analysis of the Nira, Karha, and Bhima River basins was conducted using topographic maps (1:50,000 scale, Survey of India, 47 J Series) and SRTMDEM data at a resolution of 30 meters. These river basins, which originate in western Maharashtra's Sahyadri highlands, are located in Baramati Tehsil, Pune District, Maharashtra, India.

Using ArcGIS 10.4 and the Arc Hydro tool, essential morphometric characteristics such stream lengths, watershed areas, and stream orders were calculated using Strahler's approach. The investigation also looked at areal, linear, and relief features with established formulae. The stream and basin networks were mapped in a regional coordinate system (WGS1984, UTM Zone 43N) to ensure uniformity and accuracy. The investigations yielded a number of notable results that help to better understand the region's hydrological and geomorphological aspects. The river basins were identified as 5^{th} to 7^{th} order streams. The investigation found that the Nira, Karha, and Bhima basins had 1603, 2543, and 750 streams, respectively, with total lengths of 1071.98 km, 1892.83 km, and 535.36 km. All the three basins are derived from the Deccan Traps, a volcanic plateau that has a considerable impact on the region's morphology and drainage patterns. These river basins feed left bank tributaries of the upper Krishna River, which is an important regional water system. Among the three basins, the

Karha River Basin is the longest and most developed, with evidence of considerable erosional processes shaping its current. form.

Each of the three river basins, has a dendritic drainage pattern, which is typical of locations where rivers follow the natural contours of the environment with no structural intervention. This pattern demonstrates that river systems have developed throughout time to accommodate the underlying Deccan Traps rock formations, which are usually homogenous and allow for unrestricted flow of water. However, the Karha basin has better developed characteristics than the other two. The Karha basin's areal, linear, and relief features, which include a bigger basin size, more convoluted stream networks, and steeper terrain, indicate that it is in the advanced phases of erosion. The use of GIS based morphometric analysis considerably improved the study's efficiency and accuracy when compared to traditional field methodologies. With tools like ArcGIS and ArcHydro, it was feasible to precisely map the basin borders, compute stream orders, and quantify numerous morphometric factors. This method sheds light on the hydrological, geological, topographical, and pedological interactions within basins, illustrating how these elements work together to determine river system behaviour. Previous research has shown that GIS based morphometric analysis is critical for successful watershed management and planning, especially for soil and water conservation initiatives. The findings of this study also emphasize the necessity of knowing these basins' hydrological, geomorphological, and hydrogeological properties in order to effectively manage watersheds and conserve natural resources. The findings of this study, in particular, highlight the importance of focused management in the Karha river basin, where erosion processes and geomorphic features require immediate attention to ensure long term environmental sustainability as the well-being of local communities depends on the river resources. The investigators suggest that planners may use GIS technology to make educated judgments on resource conservation, sustainable management techniques, and future development plans.

Keywords: *Areal aspect, linear aspect, relief aspect, GIS, GPS, morphometric analysis*

A MULTI-FACETED APPROACH FOR ASSESSING GROUNDWATER RECHARGE POTENTIAL IN THE BEGURU SUB-WATERSHED, KARNATAKA, INDIA

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The Beguru sub-watershed of Karnataka deals with severe groundwater decline that intensifies during prolonged years beyond drought seasons. Agricultural activities in the sub-watershed encompass paddy cultivation along with maize and are canut farms and additional field crops which demand efficient water management for agricultural sustainability and local living. The World Bank-assisted Rejuvenating Watersheds for Agricultural Resilience through Innovative Development (REWARD) program 1 implements contemporary watershed management approaches to build agricultural value chains and increase farmer resistance. The REWARD project uses a diverse assessment methodology to evaluate groundwater recharge capabilities throughout the sub-watershed. Effective science-based water management requires complete knowledge about how hydrogeology, land use activities particularly farming practices relate to water availability. This research combines evaluation of hydrogeological patterns together with geophysical techniques and examination of groundwater resources in detail. Hydrogeological data containing rainfall data (2015-2022) acquired from the Karnataka State Natural Disaster Monitoring Centre and LULC, soil, lithology, and geomorphology maps were provided by the Karnataka State Remote Sensing Applications Centre alongside groundwater level information. The LULC clearly mapped agricultural land distributions including diverse crop and plantation areas for evaluating their effects on water resource dynamics. The IISc established methodologies provided the basis to calculate Actual evapotranspiration (AET) from meteorological data. The groundwater potential zone map was generated using weighted overlay analysis of these thematic layers by integrating factors such as lithology, lineament density, soil type, LULC, drainage density, slope and geomorphology. ERT method was employed at 17 survey sites from GP1 to 17 as part of geophysical investigation for mapping sub-surface geological features and locating groundwater recharge areas. The ERT technology detects electrical conductivity variations beneath the surface that respond to the properties of geological materials along with their porosity and fluid content. Groundwater resource assessment was done to estimate the water balance (draft/excess) by considering the existing recharge and extraction of water from aquifer. The key properties of groundwater flow and storage were measured through pumping tests performed in four representative locations which determined both transmissivity and storativity values of the aquifer.

The hydrogeological study showed that the sub-watershed includes 57% of its land area used for agricultural production. Arecanut plantations take up a significant 8.16% share of the net cultivable land and stretch across the three regions of southern western and central parts of the sub-watershed as the irrigation demand is constantly throughout the year. A large concentration of this farming activity shapes the regional water flow patterns in ground waters. Rainfall analysis revealed an average annual rainfall of 917.7 mm with substantial inter-annual unevenness and the incidence of drought years, which pose significant challenges for primarily rain-fed agricultural practices. The regions with denser arecanut

plantation in northwest and southwest sub-watershed showed lower groundwater levels was a result of continuous groundwater based irrigation. The weighted overlay analysis method generated a groundwater potential zone map that showed specific areas with maximum groundwater recharge abilities. The evaluation of subsurface characteristics at the 17 locations was conducted through geophysical investigations. A model based on geophysical measurements showed zones that possess resistivity signatures indicating saturated water-bearing zones and fractured units in the prevalent geologic formations. The geophysical survey at GP1 revealed low resistivity areas from shallow zones and from deeper zones which pointed toward potential recharge possibilities at various hydrology levels. The resultant high chargeability values in these zones further support the interpretation of water saturation. The other survey sites revealed alike spatial patterns with dissimilar depths and sizes which reflected the natural heterogeneity throughout the subsurface region. The geological areas detected during observations mark important zones for artificial recharge shaft deployment.

The estimated groundwater draft/excess amount stands at +2.07 MCM per year together with 1.87 MCM of yearly non-committed monsoon runoff establishes ample opportunities to develop artificial recharge systems for agricultural water needs. Four borehole tests across different locations showed variable transmissivity ranging from 11.97 to 97.61 m^2/day and storativity outcomes ranging between 3.37×10^{-9} and 0.0108. The low recovery rate in Pumping Test 1 indicated strong groundwater recharge potential within that area. The high transmissivity value measured during pumping test 2 confirmed that the aquifer possessed excellent connectivity properties. A total of 16 optimal recharge shafts were proposed based on the integrated analysis and their design parameters were set at depths between 20 and 35 m beneath ground level. The proposed shafts should allow for an annual recharge amount of 1.03 MCM. Hydrological analyses of the geophysical surveys alongside pumping tests produced a superior approach for location selection that prioritized appropriate areas for recharge shaft placement. This study successfully integrated multiple dataset types to accomplish complete groundwater recharge evaluation in the sub-watershed. This approach provides detailed solutions to address the critical water management requirements during heavy agricultural use. Through the integrated analysis of hydrogeological parameters and data from geophysical surveys and land use assessment, enabled the identification of precise locations with optimal characteristics for artificial recharge. Geophysical surveys delivered necessary knowledge about subsurface layers and their hydrological conditions to optimize the placement of recharge shafts. The conducted pumping tests produced vital aquifer characteristics that serve as essential inputs for designing the proposed recharge structures. This study yields essential data to establish sustainable groundwater management practices by showing how artificial recharge facilities should be situated to increase water accessibility for domestic and agricultural needs. Artificial recharge implementation will result in a significant contribution to water security durability while sustaining community livelihoods. Water resources from monsoon season can successfully be collected for artificial recharge purposes to support irrigation requirements during the essential and dry period between January-April when crops require immediate and crucial water support. The proposed recharge shaft network presents a sustainable approach to increase groundwater availability which results in enhanced water security and enables reliable agricultural practices in the study region.

Keywords: *Groundwater recharge, ERT, hydrogeology, artificial recharge*

Theme 14

ISOTOPIC TECHNIQUES IN GROUNDWATER INVESTIGATIONS AND MANAGEMENT

INTEGRATING HYDROGEOCHEMISTRY AND STABLE ISOTOPES TO UNDERSTAND THE GROUNDWATER SALINIZATION IN A COASTAL AQUIFERS OF ODISHA

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Coastal aquifers are important sources of freshwater for many communities, but they face increasing stress of seawater intrusion due to various factors like over-extraction of groundwater, influence of tidal activities, rising sea levels, etc. Seawater intrusion poses a significant effect on freshwater resources, leading to increased salinity and potential degradation of water quality, which can have considerable impacts on agriculture, human consumption, and the coastal ecosystem. The hydrological and geochemical processes that govern groundwater chemistry in coastal aquifers are very complex. Hence, there should be a proper understanding of how different mechanisms affect groundwater chemistry. This study utilizes a combined approach, integrating major ion chemistry, minor elements such as bromide (Br-) and lithium (Li+), and stable isotopes (^{18}O and ^{2}H) to delineate the extent of seawater intrusion and understand the hydrogeochemical processes along the coastal aquifer. Br- is conservative and often remains unchanged during various geochemical processes, making it an important indicator of seawater mixing. Li+, on the other hand, provides insights into water-rock interactions and the extent of seawater influence. Stable isotopes of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) are key tools in hydrological studies, as they provide insights into the recharge processes in aquifers. Seawater is typically enriched in heavy isotopes, making $\delta^{18}O$ and δ^2H useful indicators for identifying the presence of marine-origin water in a freshwater aquifer. This study aims to contribute valuable insights into these coastal salinization dynamics for better management and safeguarding of freshwater resources.

The study was carried out for the coastal regions of Puri district, in the Odisha state, in the eastern part of India. The study area is about 490 km^2 and covers coastal parts of the Astarang, Kakatpur, and Gop blocks of the Puri district. The area is densely populated and local people mainly depend on groundwater for drinking purposes and agricultural activities. For the present study, a total of 90 nos. of samples were collected during the post-monsoon period in December 2021 from the shallow tube well, surface water and seawater samples from within 10-12 km from the coast. pH, EC and TDS were analysed using a Hanna Portable meter. Groundwater samples were analyzed for major elements using Flame Photometer for Na+, K+, Spectrophotometer for SO_4^{2-}, NO_{3-} and by Titration method for Ca^{2+}, Mg^{2+}, Cl-, HCO_{3-} and minor elements, Bromine (Br-) and Lithium (Li+), using Ion Chromatography. Stable isotope ratios of δ^2H and $\delta^{18}O$ were measured using isotope ratio mass spectrometry (IRMS). Stable isotopes $\delta^{18}O$ and δ^2H were interpreted by comparing groundwater samples with the global meteoric water line (GMWL) and the local meteoric water line (LMWL).

Groundwater chemistry data revealed significant variations in major ion concentrations across the study area. pH varies from 5.9 to 8.5 and TDS varies from 45mg/l to 5278mg/l with an average value of 820mg/l. The concentration of major cations Na^+, Ca^{2+}, Mg^{2+} varies from 6.5 mg/l to 1482 mg/l, 4 mg/l to 132 mg/l, 1 to 112 mg/l respectively and concentration of major anions such as Cl^-, HCO^{3-}, SO_4^{2-} varies from 14 to 2638 mg/l, 12mg/l to 503 mg/l, 3 mg/l to 297 mg/l respectively. Samples collected closer to the coastline in the Northeastern parts exhibited elevated levels of Na^+ and Cl^- as well as in the central part of the southeast part suggesting the influence of seawater mixing. However, the rest of the wells show relatively lower concentrations of these ions, indicating these zones are not affected or a lesser degree of seawater influence. The spatial distribution of major ions highlighted the region that is highly saline zone from lower saline zones. The concentration Br- varies from 0 µg/l (Below Detection limit) to 8.87 mg/l with a mean of 1.15 mg/l. Bromide concentrations were notably higher in the wells that showed higher chloride content, which is an important indicator of seawater mixing. The conservative nature of Br- allowed for a clear distinction between seawater-affected groundwater from the unaffected region. Lithium concentrations vary from 0 µg/l (Below Detection limit) to 2664 µg/l with a mean of 153 mg/l which also showed a similar pattern, with higher levels in wells with higher Br^- and Cl^-. The variability in Li+ concentrations provided insights into the rock-water interactions within the aquifer. When saline water stays for a prolonged period in the aquifer matrix then there will be an exchange between Na^+ in water and Li^+ in the aquifer which increases the Li+ in groundwater. The combined analysis of Br^- and Li^+ offered a detailed picture of the intrusion dynamics, revealing areas of mixing and interaction that might be difficult to understand through major ion analysis alone. Stable isotope analysis further supported the findings from major ion and minor element chemistry. The $\delta^{18}O$ and δD ranges from -2.21 to -7.03 ‰ with an average value of -4.95‰ and the Deuterium (δ^2H) varies from -14.41 to -48.82 ‰ with an average value of -32.20 ‰. It is found that the $\delta^{18}O$ and δ^2H values exhibited enrichment in the well having higher TDS and higher chloride, indicating mixing between freshwater and seawater and are plotted close to the seawater value. The Global Meteoric Water Line (GMWL) ($\delta D = 8*\delta^{18}O + 10$, Craig 1964) and Local Meteoric Water Line (LMWL) ($\delta D = 7.86 * \delta^{18}O + 8.81$) plotted almost parallel and overlapping on each other with similar slope. The scatter plot of $\delta^{18}O$ vs δD shows samples are distributed along the GMWL and LMWL lines indicating samples are derived from precipitation sources. However, most of the samples are shifted to the right of both lines which suggests that the samples have undergone some degree of evaporation which shifted them rightward. This study identifies seawater mixing, rock-water interactions, and evaporation processes as the key factors controlling groundwater salinization in the region. However, the groundwater particularly in the northeastern coastal and central-southeast regions showing elevated Na^+, Cl^-, Br^-, and Li^+ concentrations and covers around 20% of the study region has been affected by seawater mixing. It is suggested that further research using geophysical techniques to additional support to current understanding and develop better mitigation strategies.

Keywords: *Coastal aquifer, hydrogeo-chemistry, bromide, lithium, stable isotopes, seawater mixing*

STABLE WATER ISOTOPE IS AN INDICATOR OF SURFACE WATER AND GROUNDWATER INTERACTION IN SHALLOW AQUIFERS OF THE BRAHMAPUTRA RIVER SYSTEM, INDIA

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The interaction between surface water and groundwater is a fundamental aspect influencing the hydrogeological and ecological dynamics of shallow aquifers, particularly within widespread river systems. This work investigates the use of stable water isotopes ($\delta^{18}O$ and δD) as tracers to clarify the relationship between groundwater and surface water in the Brahmaputra River system. By examining the temporal isotopic compositions of precipitation (n = 187), river water (n = 151), and shallow aquifers (n = 151), the differences spotted emphasise the mixing and recharging processes. The study covered precipitation from October 2022 to 2024, while river water and shallow aquifer from Guwahati from April 2023 to October 2024. Meanwhile, spatial sampling of the shallow aquifer (n = 48) for the stretch of 800 km in the centre of Assam valley of the Brahmaputra River system. The results show a significant isotopic overlap between groundwater and surface water in some areas, suggesting a robust hydrological connection impacted by monsoonal inputs and seasonal flow patterns. The Isotopic ranges for precipitation is $\delta^{18}O$: –20.96 ‰ to 4.09 ‰ and δD: –154.92 ‰ to 40.91 ‰, for river water is $\delta^{18}O$: –11.87 ‰ to –6.54 ‰ and δD: –78.99 ‰ to –32.65 ‰, and for shallow aquifer temporally is $\delta^{18}O$: –6.32 ‰ to –4.31‰ and δD: –39.41‰ to –29.38 ‰. In regions that depend on interdependent water supplies, this study provides an overview for sustainable groundwater management and emphasises the importance of stable isotope studies in deepening our understanding of hydrological processes.

This study analyses the shallow aquifers spatially and temporally. For temporal observation, a daily dataset of stable isotopes from a shallow aquifer at Guwahati is observed. The spatial extent of groundwater samples was also gathered on the Sadiya - Dhubri stretch of 800 km in July 2022 along the Brahmaputra River's channel at the centre of Assam Valley. The stable isotope analysis was carried out using the liquid triple isotopic water analyser of LGR in accordance with the analytical protocol of laser-based, off-axis integrated cavity output spectroscopy (ICOS). A dual $\delta^{18}O$ and δD isotope space was used to analyse the isotope values, and empirical relationships were shown against the Global Meteoric Water Line (GMWL). In contrast to the GMWL, the Local Meteoric Water Line (LMWL: $\delta D = 8.137\ \delta^{18}O + 10.664$) had a different slope and intercept, indicating the isotopic makeup of the precipitation in the studied area. Since evaporation was shown to be the predominant process in this situation, the Local Evaporation Line (LEL: $\delta D = 6.05\ \delta^{18}O – 6.14$) was established. At our sampling locations, the relationship between the Local evaporation line (LEL) and the Local Meteoric Water Line (LMWL) is essential for determining the water sources and comprehending the evaporation and mixing processes. The isotopic composition of the water that is entering may be clearly defined at the point where the LEL and LMWL intersect, providing important information about its properties and source. The line-conditioned excess (lc-excess) has been computed for precipitation in order to efficiently normalise the evaporation signal in data because the precipitation station is situated in the centre of the basin. This calculation is represented by the following formula: lc-excess = $[\delta D – a\times\delta^{18}O – b]$

/ S, where the a and b correspond to the slope and intercept of the local meteoric water line and S shows the measurement uncertainty during the analysis of hydrogen and oxygen isotope.

The results of the isotope analysis indicate an amplified input of total annual precipitation during the monsoon, which signifies a notable nature of rock water interaction within the aquifer. The nature of rock-water interaction is shown by variation in oxygen isotope more than the variation in hydrogen isotope, which shows rocks carrying rock forming with oxides fractionate with recharged water. The geochemistry of stream water and groundwater in the basin area is largely influenced by the interaction between water and rock. According to the Gibbs diagram, the majority of samples are situated within the rock dominance area, indicating the significant impact of rock on the chemical composition of the water. Both stream water and groundwater exhibit similar hydrochemical evolution processes; however, groundwater, with its longer residence time in the subsurface, experiences more prolonged and intense water-rock interactions. This leads to considerably higher concentrations of solutes in groundwater compared to stream water. In contrast, stable isotopes are primarily affected by processes such as evaporation and the introduction of new water. Due to these influences, stable isotopes are regarded as more effective for tracing the interaction between surface water and groundwater. The influence of evaporation on isotope fractionation is profound, especially in the context of stream water. The process of isotopic fractionation, as water transitions from a closed system (groundwater) to an open system (stream water), leads to a notable enrichment of isotopic compositions. The isotopes of water in streams are affected by intensified evaporation, which causes them to differ from those in groundwater. This leads to underestimations of groundwater discharge ratios when using isotope tracers.

The importance of stable water isotopes ($\delta^{18}O$ and δD) as useful markers for analysing surface-groundwater interactions in the shallow aquifers of the Brahmaputra River system is emphasised by this study. A significant connection is shown by the isotopic analysis, which is impacted by fundamentals including river flow dynamics and seasonal monsoonal recharge. Different levels of interaction are revealed by spatial variations in isotopic fingerprints throughout the research region; certain zones exhibit a higher level of mixing because of particular hydrological and geomorphological conditions. These results demonstrate the significance of incorporating isotope-based research into water resource management and provide insightful information about the hydrological processes operating in the area. This study's main limitation is that the method for assessing indicator uncertainty primarily relied on the variation coefficients of groundwater discharge at each specific sampling site.

Keywords: *Lower Brahmaputra basin, stream water-groundwater interaction, stable water isotopes, seasonal variation, shallow aquifer*

UNRAVELLING GROUNDWATER FLOW PATHS AND CONTRIBUTIONS TO AQUIFERS EMPLOYING NATURAL TRACERS AND END MEMBER MIXING ANALYSIS IN THE SOUTH-WESTERN GHATS, INDIA

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Mountainous regions play a crucial role in global hydrological systems, functioning as "water towers" that supply freshwater to lowland areas. They support groundwater systems and rivulets, serving as vital sources of water for agricultural, industrial, and domestic purposes. This role is particularly significant in tropical regions, where seasonal variations heavily influence water availability. Understanding recharge processes in mountain Critical Zones (CZs) is therefore essential. The Southern Western Ghats of India exemplifies this dynamic, supplying water to the semi-arid lowlands on the eastern side of western Ghats through intricate groundwater flow paths. Despite their importance, research on hydrogeological processes in mountain ecosystems, particularly in tropical climates, remains limited. This study, conducted in the Munnar Critical Zone Observatory (CZO) in the Southern Western Ghats, investigates groundwater flow patterns and their seasonal variations. By utilizing natural tracers to analyse recharge dynamics, the study offers valuable insights for sustainable water resource management and landslide risk mitigation in the region.

To understand groundwater (GW) flow paths, 12 GW samples (7 borewells and 5 open wells) and 15 rivulet stream water samples were collected across different elevations of the mountain during pre-monsoon (PRM), southwest monsoon (SWM), and northeast monsoon (NEM) seasons, allowing for a seasonal analysis of recharge patterns. The samples were analysed for stable isotopes ($\delta^{18}O$, $\delta^{2}H$), tritium (^{3}H), chloride (Cl^{-} as a conservative tracer), and other major solute concentrations. These tracers provided critical insights into recharge sources and flow paths, as isotopic values serve as reliable indicators of water origin and dynamics. The isotopic values, along with elevation patterns, revealed the altitude effect, with groundwater samples displaying a clear depletion gradient indicative of recharge processes. Rainwater samples were also collected seasonally and spatially along varying elevations in the study area, enabling the construction of a Local Meteoric Water Line (LMWL). Based on the findings, $\delta^{18}O$ and $\delta^{2}H$ boxplots for groundwater and rivulets were generated, along with a ternary diagram plotting $\delta^{18}O$ (‰) against Cl^{-} concentrations (mg/L) on the Y-axis. These analyses revealed three distinct groups of groundwater sources characterized by unique tracer concentrations. Tritium (^{3}H) levels further differentiated the groups, confirming the presence of three major groundwater flow paths: Mountain Front Recharge (MFR), Mountain Block Recharge (MBR), and Front-Slope Recharge (FSR), each with distinct recharge mechanisms and dynamics. MFR, observed at lower elevations (<1500 m amsl), exhibited low $\delta^{18}O$ and Cl^{-} values and is influenced by rivulet flow losses and irrigation channels, indicating faster recharge processes. MBR, found at higher elevations (>2000 m amsl), displayed intermediate $\delta^{18}O$ values, elevated Cl^{-} concentrations, and low ^{3}H levels, suggesting longer residence times due to deeper infiltration within the mountain blocks. In contrast, FSR, located at mid-elevations (1500–2000 m amsl), showed high $\delta^{18}O$ and low Cl^{-} values, coupled with high ^{3}H levels, reflecting shorter residence times and recharge predominantly through direct precipitation on mountain slopes. These findings highlight the distinct recharge mechanisms operating in mountainous regions. The spatial arrangement of recharge zones aligns with elevation gradients and local hydrological dynamics, while the combined use of isotopic and solute tracers effectively delineates groundwater flow paths.

The study employed End Member Mixing Analysis (EMMA) to quantify contributions from distinct groundwater flow paths-MFR, MBR, and FSR-using extreme values of natural tracers $\delta^{18}O$ and Cl^- as end members to determine the contributing fractions both spatially and temporally. Error propagation analysis was applied to account for uncertainties in the estimated percentage fractions, with variations in end-member concentrations considered to enhance result accuracy. The EMMA analysis revealed that FSR contributed an annual average of 47.2% to groundwater recharge, followed by MBR at 28.8% and MFR at 23.9%, emphasizing the critical role of FSR in maintaining regional water resources. Seasonal analysis indicated notable variability in recharge contributions. During the PRM season, elevated temperatures enhanced soil permeability, making FSR the dominant recharge process, particularly at higher elevations. In the SWM season, abundant rainfall and active surface water flow resulted in a more balanced contribution from MFR, MBR, and FSR. Conversely, the northeast monsoon (NEM) season, characterized by intermittent rainfall and reduced surface runoff, once again favoured FSR as direct infiltration became the primary recharge process, sustaining groundwater resources. These seasonal patterns underscore the complex interplay between climatic conditions and topographical features in shaping recharge mechanisms in the Munnar CZO. The study highlights that recharge mechanisms are closely tied to altitude and topography, which influence groundwater flow pathways. In mountainous terrains like the Munnar CZO, the interaction between groundwater and surface water is strongly influenced by steep slopes and ephemeral streams. These streams serve as natural conduits, particularly in lowland areas, where they significantly contribute to recharge through MFR processes. Additionally, the region's deep-cut streams and V-shaped valleys channel water into specific recharge zones, playing a pivotal role in shaping MBR and FSR dynamics.

These findings offer valuable insights into groundwater-surface water interactions and underscore the importance of understanding recharge mechanisms for sustainable water resource management in mountainous ecosystems. These results offer direct implications for sustainable groundwater management, providing insights that can guide groundwater extraction practices to ensure aquifer levels remain sufficient to support agriculture, local ecosystems, and community needs. Furthermore, the identification of FSR as the dominant recharge source in high-risk landslide zones holds significant potential for disaster management. However, the study acknowledges certain limitations, particularly the small number of sampled groundwater sources, which constrains the ability to assess broader spatial variability. To address this, future research could expand sampling networks, incorporate additional tracers, and employ continuous monitoring techniques to better capture temporal variations and enhance accuracy.

Keywords: *Mountain block recharge, groundwater, stable isotopes, end member mixing analysis, critical zone, western Ghats*

HYDROLOGICAL INVESTIGATIONS OF CHAMASARI SPRINGS USING STABLE ISOTOPES AS NATURAL TRACERS

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Environmental isotopes, oxygen and hydrogen, in particular, have been extensively used to study various environments of different climate extremities. Springs, the main source of fresh water for rural populations in the Himalayas, are drying up and eventually dying. The present study aims at using stable isotopes in Chamasari, Uttarakhand, India, to understand the nature of springs and if possible, find plausible ways to revive them. Samples from springs and precipitation were collected and analysed using the Isotope Ratio Mass Spectrometer (IRMS) instrument. The results thus obtained indicate that the Local Meteoric Water Line (LMWL) of the present study region deviates from the Global Meteoric Water Line (GMWL), with a slope lower than that of GMWL. Water samples show a variation in $\delta^{18}O$ values of about -0.28 per mil per 100 m elevation. Electrical conductivity (EC), spring discharge, temperature and other parameters measured on the field show a general decreasing trend of EC with an increasing discharge and altitude, with little deviations in some places. Based on the data and results, it can be concluded that spring water may have suffered evaporation or undergone mixing with some evaporated water and that $\delta^{18}O$ and δD isotopes of precipitation show an altitude effect. The deviation of EC from its general trend for the area may indicate an involvement of natural and possibly some anthropogenic factors, such as the interaction of water with the local geology of the area or the developmental activities of the rural population.

Keywords: *Stable isotopes, Springs, Chamasari, IRMS, Himalayas*

A δ^2H AND δ^{18}O ISOSCAPE OF GROUNDWATER IN THE EAST KHASI HILLS DISTRICT, MEGHALAYA, INDIA

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Groundwater is one of the preferred sources of water supply, sustaining drinking water supplies, irrigation for agriculture, and industrial processes. It serves as the primary source of freshwater, particularly in areas where surface water is scarce, and is used for drinking purposes by one-third of the global population. Consequently, in the present times, groundwater resources are under stress due to overexploitation, and pollution from different sources like agricultural runoffs, industrial effluents, and domestic waste, often rendering groundwater unfit for human use, and ecological health. The stress on groundwater resources necessitates long-term management approaches such as controlled extraction, pollution control, and efficient recharge systems. Stable isotopes of water (δ^2H and δ^{18}O) serve as important tracers and have been widely used to decipher the interactions among all compartments of the hydrological cycle. Integrating stable isotopes analyses will provide better insight into existing water sources and their recharge mechanisms and contamination pathways, thus enabling more precise modeling of management practices so as to ensure the long-term availability and retention of the quality of this essential resource.

The present study is the first attempt to assess the δ^2H and δ^{18}O distribution in the groundwater of the East Khasi Hills District, Meghalaya, India. The results from the study will help in understanding recharge mechanisms and help in defining better management practices ensuring long-term availability of this essential resource. The study was conducted in the East Khasi Hills District of Meghalaya, India. The study area's climate ranges from temperate humid in the northern region to subtropical humid in the southern region, with temperatures varying between 1.7°C and 24°C. This district is renowned as the wettest region on Earth, home to Mawsynram and Cherrapunjee, which receive an average annual rainfall of approximately 12,270 mm and 11,600 mm, respectively. The dominant rock types in the district comprise basement Precambrian granitic gneisses, overlain by Mesozoic quartzites, followed by the tertiary sequence. The major aquifer representing the water table occurs in the quartzites. This group of aquifer systems in the study area provides moderate groundwater potential. Water table occurs in the weathered quartzite under unconfined conditions and under the semi-confined conditions in the fractured and jointed rocks. The wells drilled at hydro-geologically suitable sites to depths of approximately 80–150 meters below ground level (bgl) yield moderately 5-15 m^3/hr, and are located in the weathered Pre-Cambrian rocks.

Seventeen (17) sampling locations across the district were selected for the collection of water samples. Freshly pumped groundwater samples from the borewells from different sampling locations were collected during April 2023. Electrical conductivity (EC) and total dissolved solids (TDS) measurements were taken using the Eutech CyberScan PCD 650 (pre-calibrated and set to automatic temperature compensation) on-site. For stable isotopes analysis, the samples were filtered through a 0.45µm syringe filter (Merck Millipore) in a dry, pre-washed and 10% nitric acid-rinsed 15 ml polypropylene bottle (Tarson) on-site. For chloride analysis, samples were collected in dry, pre-washed and 10% nitric acid-rinsed 125 ml polypropylene bottles (Tarson). All samples were stored at 4°C until analysis.

Hydrogen (^{1}H,^{2}H) and oxygen (^{16}O,^{18}O) stable isotope analyses were conducted using a continuous flow isotope ratio mass spectrometer (Isoprime, UK) at the Nuclear Hydrology Laboratory, National Institute of Hydrology (NIH), Roorkee (India). The results are expressed in delta notation (δ) as per mil (‰) relative to VSMOW (Vienna Standard Mean Ocean Water), with a laboratory precision of ≤1.0 ‰ (1σ) for $\delta^{2}H$ and ≤0.05 ‰ (1σ) for $\delta^{18}O$. Deuterium excess (d-excess, ‰) was calculated following the standard equation. Chloride concentrations were determined using Ion Chromatography (Dionex ICS-5000, Thermo Fisher, USA) following standard procedures at the Nuclear Hydrology Laboratory, National Institute of Hydrology (NIH), Roorkee (India). The results are reported as mean (n=3). The $\delta^{2}H$ values in groundwater ranged between -51.60 ‰ and -29.60 ‰, with a mean of -42.28 ‰ (V- SMOW). The $\delta^{18}O$ values in groundwater ranged between -8.11 ‰ and -5.57 ‰, with a mean of -6.89 ‰ (V- SMOW). The d-excess values ranged between 10.10 ‰ and 14.93 ‰, with a mean of 12.86 ‰. The EC ranged between 28.02 and 464.30 µS/cm, with a mean of 149.56 µS/cm. The TDS ranged between 19.72 and 306.80 mg/L, with a mean of 102.61 mg/L. The chloride concentration ranged between 1 and 34.30 mg/L, with a mean of 8.98 mg/L.

The $\delta^{18}O$ and $\delta^{2}H$ values in groundwater showed a linear relationship ($\delta^{2}H = 8.8202 * \delta^{18}O + 18.517$) with R^2= 0.98. The majority of the groundwater samples fall above the Global Meteoric Water Line (GMWL), with one sample close to it, indicating a minimal influence of evaporation. The $\delta^{18}O$ and d-excess showed irregular distribution, confirming negligeable evaporation. The higher d-excess values indicate that the rainfall in this region is from low clouds, which has undergone less sub-cloud evaporation and quick recharge in a humid environment. The relationship between $\delta^{18}O$ and TDS indicates mineral dissolution. The findings of the study will enhance the understanding of recharge processes and support the development of improved long-term strategies for safeguarding groundwater resources in the district.

Keywords: *Groundwater, isoscape, East Khasi Hills, Meghalaya, stable isotopes*

RADON LEVEL MEASUREMENTS IN GROUNDWATER SAMPLES OF DOON VALLEY OF UTTARAKHAND, INDIA

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Radon is formed as part of the Uranium-Thorium decay chain. It has an atomic number of 86 and a half-life of 3.82 days. According to the World Health Organization (WHO), breathing radon gas (^{222}Rn) ranks as the second cause of lung cancer after smoking cigarettes. More uranium in nearby rocks leads to higher radon levels in groundwater. Various factors like geological features, presence of shear zones, degree of metamorphism, soil porosity, and mineralization influence how much radon ends up in the water. This study utilized the Durridge RAD-7 to measure Radon (^{222}Rn) concentration in samples collected from 27 well locations from Haridwar and Dehradun districts of Uttarakhand state in India, during monsoon (July, 2021), pre-monsoon (May, 2022), and post-monsoon (November, 2022) seasons to track the radon variations effectively. Haridwar is a significant pilgrimage spot, drawing millions of devotees annually. Dehradun is a bustling tourist hub, welcoming diverse visitors seeking its natural beauty and cultural attractions. The wells were purged by pumping for 15 minutes to ensure sample quality. Specialized glass bottles with a 250 mL capacity were used to collect water samples to effectively measure radon in-water activity. A hand-held pH meter and EC meter recorded pH and EC values, respectively. Within 12 hours of sample collection, radon measurements were carried out using RAD-7. The detector was attached to a bubbling kit, which released radon from water into the air in a closed loop for measurement purposes. The Wat-250 procedure was utilized for both the 250 mL capacity vial on the RAD-7 and water sampling, ensuring an extraction efficiency of 94%. The RAD-7 provided a summary at the end of the measurement run. Pearson correlation was used to examine the relationship of radon with the EC and pH. A p-value test verified if the correlation observed was statistically significant or not. The background sample utilized in this study was millipore water from the National Institute of Hydrology, Roorkee with the mean value of radon as 1.897 Bq L^{-1}.

Results indicated that ^{222}Rn activity peaked during the monsoon season (July 2021) while it was lowest in post-monsoon season (November, 2022). During the monsoon season (July, 2021), samples revealed elevated radon concentrations. Out of 27 samples, 26 samples (i.e. about 96%) exceeded the Maximum Contaminant Limit (MCL) of 11.1 Bq L^{-1}set by the US EPA. The ^{222}Rn activity ranged from 10.15 ± 2.27 Bq L^{-1} to 42.42 ± 4.46 Bq L^{-1}, with an average value of 24.87 ± 3.33 Bq L^{-1}. The EC range at sampling sites varied from 40 to 1310 µS cm^{-1}, averaging 482.22 µS cm^{-1}. The pH range at sampling sites was between 7 and 8.7, with an average of 7.80. Radon values were scrutinized alongside EC and pH levels. Enhanced infiltration of rainwater through faults and fractures could mobilize radon-rich groundwater, slightly elevating EC levels due to the dissolution of minerals along the flow paths. Pearson correlation revealed a positive relation, although weak relation, between EC and radon levels. However, this correlation is statistically insignificant as per the p-value. This is likely to be due to the dilution from extensive rainwater influx, which reduces the overall ionic strength of the water. A moderate negative correlation was observed between pH and radon levels, signifying statistical significance with a p-value of 0.0140. The observed significant negative correlation might be attributed to the acid-neutralizing interactions of rainwater (typically slightly acidic) with carbonate-rich lithologies. From samples during the pre-monsoon season (May, 2022), six sample sites surpassed the MCL. The ^{222}Rn activity ranged from 0.12 ± 0.5 Bq L^{-1} to 17.37 ± 2.89 Bq L^{-1}, averaging at 7.52 ± 1.83 Bq L^{-1}, being within the permissible limits according to EPA standards. The EC observed at sampling sites varied from 50 to 1140 µS cm^{-1}, averaging at 415.19 µS cm^{-1}, while pH levels ranged from 6.9 to 7.8 with an average of 7.40. The correlation between radon levels and EC remained weakly positive, and a p-value of 0.0093 was observed, signifying statistical significance. The weakly positive correlation may be due to the limited recharge which concentrates dissolved ions and radon in groundwater. Uranium-rich lithologies, such as granites in the Lesser Himalayas, contribute to elevated radon and ion levels, while faults and fractures facilitate deeper circulation, enhancing the co-occurrence of radon and dissolved solids. The correlation between radon levels and pH was weakly negative and statistically insignificant. This may be due to the buffering effect of carbonate-rich lithologies, which stabilize pH despite radon release. During post-monsoon season (November, 2022), 7 out of the 27 sampling sites surpassed the MCL. The activity of ^{222}Rn ranged from 0.10 ± 0.49 Bq L^{-1} to 18.13 ± 2.95 Bq L^{-1}, averaging at 6.20 ± 1.60 Bq L^{-1}. The EC ranged from 90 to 1110 µS cm^{-1} across the sampling sites, averaging 469.63 µS cm^{-1}. The pH levels ranged from 7.1 to 8.3, averaging 7.68. The radon values exhibited correlations with EC and pH. Both indicated a very weak negative correlation and were statistically insignificant. Post-monsoon groundwater systems often reflect a transitional state. Radon may still be mobilized from lithologies influenced by recharge, but dilution from the residual rainwater and aquifer mixing weakens the relationship between EC and pH.

The lithology of the Siwaliks and Lesser Himalayas, dominated by sedimentary and metamorphic rocks with uranium-bearing sandstone and granites, serves as a natural source for radon. It is observed that the Himalayan river systems in the N-W Himalayas, namely the Kulu, Kangra, Garhwal, and Dehradun areas, is conspicuous by its high dissolved uranium concentration. The Indian Department of Atomic Energy has reported uranium mineralization associated with the sandstone of the Middle Siwalik. Uranium has been reported from the fault and shear zones and Siwalik sandstone. The Siwaliks, rich in sandstones and clays, may exhibit limited radon emanation compared to the Lesser Himalayas. Faults and fractures act as conduits for groundwater flow. The decay of uranium isotopes within these rocks leads to radon enrichment in groundwater, especially in regions with significant aquifer-rock interactions. Higher radon concentrations are observed during the Monsoon season. So, precautions must be taken by the people to use the groundwater especially during the monsoon season. Radon concentrations in each site are determined by geology and groundwater dynamics. Allowing groundwater to stand before consumption, using aeration systems to release radon gas by bubbling water, and using GAC filters to trap radon are some radon mitigation strategies that can be followed.

Keywords: *Radon, RAD-7, groundwater, Haridwar, Dehradun*

ISOTOPIC CHARACTERIZATION OF SPRINGS OF LESSER HIMALAYA - A CASE STUDY OF KALSI REGION, UTTARAKHAND, INDIA

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Springs are the natural emergence of groundwater. Springs are created when a saturated aquifer zone intersects with the surface, causing the water to emerge as springs from rock pores, fractures, or depressions. These natural water sources serve as a primary source for drinking, domestic, and agricultural purposes for people in hilly regions. Additionally, springs play a crucial role in maintaining the base flow of rivers during the lean season. Despite its importance, a global decline in spring discharge has been observed due to climatic and anthropogenic reasons. The problem of drying springs and decline in discharge have also been reported from the Himalayan region. According to a study, nearly half the number of perennial springs in the Himalayan region have dried up or become seasonal. In addition to this, the seasonal springs in the Himalayan region are receding much more rapidly than perennial springs. The Kalsi region in the Lesser Himalayan region faces the same fate, with an increasing number of springs drying daily. So, the springs in the Himalayan region need a more comprehensive understanding of recharge source and processes, flow mechanisms, and their sustainability during the non-monsoonal season. The study has been carried out in the Kalsi region of the Lesser Himalayan region as a model pilot study to understand the hydrology of springs in the Himalayan region. The sustainability of springs depends on the recharging process, predominantly controlled by the rainfall patterns (monsoonal characteristics) and recharge time. Identifying the source and origin of springs is most important for systematically planning water conservation measures to sustain future development and needs. So, the artificial recharge process using rainwater harvesting is widely practiced for augmenting and managing the groundwater and spring resources. Many researchers have used different techniques to address the problem of drying springs. The environmental isotopic techniques have proven to be the most effective tools for solving critical hydrological issues. Environmental isotopes (stable and radioactive) have the distinct advantage of larger spatial and temporal resolutions for hydrological investigations. The use of the isotopic values in the present study will enhance the understanding of Himalayan springs.

The elevation range in the study area varies between 376 m to 2228 m whereas the elevation range of sampling sites lies between 949m to 2034 m. Springwater samples for stable isotopes were collected from 118 springs during the pre-monsoon and post-monsoon seasons. The samples were collected and sealed close to the discharge points to avoid further evaporation. All the physical parameters, such as electrical conductivity (EC), total dissolved salts (TDS), and temperature of springs and the environment, were collected in the field using portable instruments. In addition, 63 rain samples were also collected during this period from three stations using self-assembled rain gauges. To prevent evaporation of the rain samples, all the precipitation samples were collected early in the morning after the rainfall events. The stable isotopes (Deuterium and Oxygen) of spring and precipitation samples were measured in the GV-Isoprime Dual Inlet Isotope Ratio Mass Spectrometer (IRMS) lab of the National Institute of Hydrology (NIH), Roorkee. For hydrogen isotopic analysis, 1 ml of the water sample was equilibrated with H2 using a platinum catalyst at 50° C for 1 hour, and the resultant gas was introduced into the IRMS machine. The oxygen isotope of the sample was determined by equilibrating 1 ml of water with CO_2 gas at 50°C for 8 hours, after which the equilibrated gas was introduced into the mass spectrometer. All the measured values were represented in delta (δ) values. The measurement precision for the hydrogen isotope was ±1 ‰, and for the oxygen isotope was ± 0.1‰.

The isotopic values of springs for $\delta^{18}O$ isotopes during pre-monsoon season lie between -10.3 and -5.2 ‰ with an average of -8.9 ‰. The isotopic values of $\delta^{2}H$ show a wide variation with values ranging between -68.0 to -35.9 ‰ with a mean value of -58.1 ‰. The isotopic values of springs for $\delta^{18}O$ isotopes during post-monsoon season lie between -10.6 to -7.1 ‰ with an average of -8.9 ‰, whereas the isotopic values of $\delta^{2}H$ isotopes range between -63.9 and -46.2 ‰ with a mean value of -57.1 ‰. The isotopic values of precipitation for $\delta^{18}O$ isotopes range between -16.23 and 2.82 ‰, whereas the isotopic values of $\delta^{2}H$ isotopes vary between -125.08 and 20.51 ‰. The isotopic values of precipitation for oxygen and hydrogen isotopes show a wide spectrum of values due to source variation. Notably, the Local Meteoric Water Line (LMWL) line derived from the precipitation samples is positioned almost parallel to the Global Meteoric Water Line (GMWL) ($\delta^{2}H=8*\delta^{18}O+10‰$). The LMWL line has a slope (8.0) and intercept (11.7) derived from 66 samples collected from three rain gauges positioned at three different altitudes. The oxygen and hydrogen isotopic values of precipitation samples exhibited a good correlation (r^2= 0.97), while the individual rainfall events showed a more diverse range of isotopic values ($\delta^{18}O$ = -16.23 to 2.82 ‰, $\delta^{2}H$ = -125.0 to 20.5 ‰) for different rain events. The isotopic signature of springs from pre-monsoon (slope and intercept for pre-monsoon are 3.8 and -23.3) and post-monsoon (slope and intercept for post-monsoon are 5.6 and -7.2) seasons crossing the LMWL line showing the impact of evaporation in the spring's samples. The lapse rate of oxygen and hydrogen isotopes for precipitation are -0.4 ‰ and -4.1 ‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively, for a 100 m increase in elevation. The recharge elevation of all springs calculated from the isotopic lapse rate lies between the altitude range of 1386 to 2194 m in the study area.

This study used isotopic signatures of springs to understand the recharge source, recharge period, and recharge altitude in the lesser Himalayan region. The recharge altitude was calculated using the altitude lapse rate of the precipitation sample. The recharge altitude for each spring can be used to construct recharging structures like subsurface dykes, check dams, contouring, trenches, ponds, etc. These structures can help policymakers to mitigate the impact of climate change and anthropogenic stress. These isotopic results, along with on-field hydrogeological, hydrogeochemical, geospatial, and geophysical investigations, can enrich the comprehensive understanding of spring hydrology.

Keywords: *Spring, stable isotope, lesser Himalaya, LMWL, artificial recharge*

GROUNDWATER DATING IN TWO NORTHWEST INDIAN STATES

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This study investigates the groundwater age in the northwest Indian states of Punjab and Haryana using tritium (^3H) dating techniques. Tritium, a radioactive isotope of hydrogen with a half-life of 12.3 years, serves as a valuable tool for estimating the residence time, or age, of groundwater. This technique relies on the decay of tritium over time to determine how long water has been isolated from recharge sources, particularly effective for dating water with residence times of less than 60 years. The study aims to provide insights into the recharge potential and groundwater dynamics of the two states. The research focused on 16 locations across Punjab (including Ghanpur, Chamkaur Sahib, Guruhar Sahai, Sangrur, Dasuya, Garshankar, Sultanpur Lodhi, Kapurthala, Bhogpur, Saroya, Tanda, and Nakodar) and Haryana (including Firozpur Jhirka, Nagina, Kotla, and Karhera). These sites were chosen based on stable isotope values to assess recharge potential. To ensure data accuracy, a groundwater sampling protocol was implemented. The wellhead was secured, the surrounding area cleared, and well characteristics recorded. The static water level was measured to guide purging, which removed stagnant water until water quality stabilized. The sample volume required for tritium analysis was about 650 mL (millilitres). Groundwater was then collected from the pump discharge into designated containers, labelled, and transported to the Nuclear Hydrology laboratory of National Institute of Hydrology, Roorkee.

The tritium analysis involved a multi-step process. Pre-distillation removed impurities and enhanced conductivity, followed by electrolytic enrichment within a Tritium Enrichment Unit (TEU) over 25 days at low temperatures, typically between 0 and 5ºC. Post-distillation cleaning with lead chloride further purified the enriched water. Finally, the purified water was mixed with a scintillation cocktail (Ultima Gold) and analysed using a Liquid Scintillation Counter to detect beta emissions from tritium decay, enabling the determination of tritium activity (TU) in the original groundwater samples. Typical Minimum Detection Limits (MDLs) for modern Liquid Scintillation Counters with electrolytic enrichment range from 0.1 to 0.5 Tritium Units (TU). EasyView software was employed for data analysis and interpretation.

Determining groundwater age by analysing tritium concentrations using the radioactive decay equation: $t = (t_{1/2}) * \ln (A_0 / A) / \ln (2)$. Here, t represents the age of the groundwater, $t_{1/2}$ is tritium half-life (12.3 years), A_0 is initial tritium concentration in precipitation during infiltration, A is measured tritium concentration in the sample. The initial tritium concentration (A_0). To estimate initial TU values, rain samples were used. For Punjab, A_0 was determined to be 8 TU, while for Haryana, it was 15 TU. These values were used to calculate the age of groundwater at each sampling location. Standards with known high tritium activity were used to calibrate the analytical system and ensure reliable estimation of tritium concentrations in all samples, including those with very low or undetectable tritium levels. Groundwater is classified based on tritium concentration (TU) as: Modern Groundwater with >7 TU, indicating recent recharge; Mixture of Modern and Sub-modern Groundwater with 4-7 TU, showing a mix of recent and older water; Sub-modern

Groundwater with 2-4 TU, suggesting recharge from the pre-bomb era; and Old Groundwater with <1 TU, indicating recharge occurred well before the 1950s. The tritium analysis revealed a distinct contrast in groundwater age between the two states. Punjab is dominated by older groundwater, frequently with tritium concentrations below 1 TU, suggesting a slow rate of natural recharge. For example, Garshankar has a tritium level of 0.1463 TU. In contrast, Haryana shows a greater proportion of modern groundwater with higher tritium concentrations. Several locations displayed tritium levels exceeding 7 TU, indicating recent recharge. In some cases, the measured tritium concentration was higher than the initial concentration, suggesting very recent recharge. The contrasting groundwater age profiles observed in Punjab and Haryana reflect the influence of geological factors and proximity to the Himalayan rivers on recharge dynamics.

The prevalence of old groundwater in Punjab indicates a slow recharge rate attributable to fine-grained alluvial deposits of clay and silt that impede rainwater infiltration. The substantial thickness of alluvial deposits leads to deeper water tables, increasing travel time for infiltrating water. Conversely, the presence of modern groundwater in Haryana suggests more active recharge processes, influenced by the occurrence of sand and gravel lenses within the alluvial deposits, which facilitate greater infiltration. The thinner alluvial cover in Haryana potentially exhibits shallower water tables, promoting faster infiltration. Additionally, higher average rainfall in Haryana contributes to greater water availability for recharge. The report notes that while Haryana has more modern groundwater, Firozpur Jhirka (Mewat) shows older groundwater requiring further study of local hydrogeological conditions. The study provides a comprehensive analysis of groundwater age and recharge potential in Punjab and Haryana, emphasizing the influence of geological and climatic factors. This research also highlights the importance of employing advanced techniques like tritium dating to accurately assess groundwater age. Furthermore, the study emphasizes the need for careful monitoring of groundwater extraction and recharge rates to ensure the long-term sustainability of this vital resource in both Haryana and Punjab.

Keywords: *Groundwater recharge, tritium, Haryana, Punjab*

GROUNDWATER AGE DISTRIBUTION IN THE CAMBAY BASIN, INDIA: INSIGHTS FROM CARBON AND OXYGEN ISOTOPES

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The Cambay Basin is a graben structure defined by a prominent NNW–SSE-oriented fault system, with progressive down-faulting along parallel secondary faults that align with the main trend, along with intersecting orthogonal faults. The Deccan Basalt, dating back to the Late Cretaceous period, serves as the basement across most of the basin, except in the East Flank, where Proterozoic granitic rocks are also exposed at the surface. The basin's sedimentary cover, comprising Quaternary alluvial deposits overlying a sequence of Tertiary sedimentary formations, varies in thickness from a few meters near the eastern and western edges to approximately 3 km at the basin's center. The regional aquifer system within the Quaternary alluvium consists of alternating layers of sand and silty clay, with recharge occurring in the foothills of the Aravalli Mountains and discharge zones extending to areas such as the Little Rann of Kachchh, Nalsarovar, and the Gulf of Khambhat (LRK–NS–GK). Deccan Traps and Mesozoic sediments are exposed in parts of the West Flank, while the East Flank near the Aravalli foothills predominantly features granitic rocks.

This part of the Gujarat receives nearly 700 mm of rainfall and falls under the semi-arid region. In this area, groundwater plays a major role in providing water for irrigation and agriculture purposes. The high dependency on groundwater, lower rainfall, and unavailability of perennial rivers put this region into an overexploited zone in relation to groundwater abstraction due to the deeper groundwater mining going on. According to the Central Ground Water Board (CGWB) report on the quality of shallow aquifers, this area exhibits high levels of fluoride and nitrate in its shallow groundwater. The significant demand for water has led to using multi-aquifer bore wells, which sometimes function as artificial recharge structures for deeper groundwater. This allows pollutants from shallow aquifers to migrate to deeper ones. To investigate groundwater age distribution in the Cambay Basin, samples were collected from 58 locations, including hand pumps and tube wells, with depths ranging from 60 to 1100 feet. The samples were analyzed for stable isotopes of oxygen, hydrogen, carbon, and radiocarbon (^{14}C), following the standard protocols. Samples for stable isotope ($\delta^{18}O$, δD) analysis were collected in a 30 ml airtight bottle after rinsing the bottle thoroughly with the groundwater to be sampled. Samples from the immediate vicinity of any surface water body (lake, stream, canal, etc.) were avoided. For ^{14}C measurement samples were collected in 500ml HDPE air tight bottles and poisoned by mercury chloride ($HgCl_2$). Samples for $\delta^{13}C$ measurement of dissolved inorganic carbon in groundwater were collected in a 60ml amber glass bottle after poisoning it with mercury chloride. The oxygen and hydrogen isotopic analyses ($\delta^{18}O$ and δD) of these samples were done using the standard equilibration method in isotope ratio mass spectrometer Delta V Plus in continuous flow mode using Gas bench II at Physical Research Laboratory (PRL), Ahmedabad. The reproducibility of measurement was found to be better than 0.1‰ for $\delta^{18}O$ and 1‰ for δD. 14C were measured in dissolve inorganic carbon (DIC) present in groundwater. For this, approximately 10 mL of 85%

orthophosphoric acid is placed in a ~1 L evacuated flask (~1×10^{-2} mbar) and then groundwater sample is injected in the flask using a syringe with the amount adjusted according to the DIC concentration. The released CO_2 gas flows through three U-tubes. The first U-tube, placed in an alcohol-liquid nitrogen slush (-80°C), captures moisture. The following two U-tubes, immersed in liquid nitrogen (-196°C), freeze CO_2. The CO_2 undergoes multiple freeze-thaw cycles between traps to eliminate any remaining water or impurities. The CO_2 is expanded into a calibrated chamber connected to a pressure gauge to measure its volume accurately. Purified CO_2 is then transferred to a pre-evacuated glass ampule, ready for use in the graphite preparation system. Purified CO_2 (50-100 µmol) is introduced into a graphite preparation line, with the vacuum system containing pre-treated iron (5 mg) and zinc (25 mg) powders. The CO_2 undergoes reduction to elemental carbon (graphite) as the iron and zinc powders are heated to suitable temperatures. The resulting graphite deposits onto the iron powder's surface. The graphite-coated iron is pressed into a pellet and loaded into a 1 MV accelerator mass spectrometer at the Physical Research Laboratory (PRL), Ahmedabad, for radiocarbon analysis. Alongside the samples, international standards (Oxalic Acid I, Oxalic Acid II) and background materials (such as anthracite) are analyzed. Age estimates are corrected for isotopic fractionation effects in both sample preparation and the AMS process. Conventionally, radiocarbon age (using Libby half-life of 5568 yrs.) of any sample is calculated using the basic decay equation.

In this study, groundwater samples from shallow as well as deep aquifers were collected in 2023 during pre-monsoon season (May June) and analysed for stable isotopes of oxygen and hydrogen as Stable isotopes of oxygen and hydrogen play an important role in understanding the movement and mixing of two different water masses. The shallow groundwater isotopic values range between -0.8‰ to -5.8‰ with an average value of -3.0‰ while deeper groundwater isotopic values range between -2.7% to -4.5‰ with an average of -3.7‰. The regression line for shallow groundwater has a slope (6.1 ± 0.3), while deeper groundwater has a slope (7.3 ± 0.5). The higher slope and more depleted $\delta^{18}O$ of deeper groundwater suggest they are recharged from different water sources. In some locations, the isotopic values of dipper and shallow groundwater have a similar isotopic composition, indicating the areas where shallow and deep groundwater might interact due to multi-aquifer penetrated borewells. Radiocarbon dating revealed groundwater ages ranging from 500 to 40,000 years BP (these age are corrected for carbonate dissolution and callibarated using oxcal), varying spatially across the basin. In the eastern boundary near the Aravalli foothills, groundwater exhibited modern ages (500 to 2000 years BP), while in the western parts, ages extended up to 40,000 years BP. The extraction of paleowater in the region is significantly impacting the groundwater balance, posing long-term sustainability concerns.

Keywords: *Cambay basin, groundwater, stable isotopes, radiocarbon, paleowater*

ISOTOPIC AND HYDROCHEMICAL INSIGHTS INTO GROUNDWATER SUSTAINABILITY IN THE MIDDLE GANGA BASIN, INDIA

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This study examines groundwater isotopic composition to understand its dynamics, recharge mechanisms, and sustainability. The main objectives are to identify recharge areas, evaluate recharge processes, and determine groundwater sources. Surveys under the Global Network of Isotopes in Precipitation (GNIP) and Rivers (GNIR) measured oxygen and hydrogen isotope contents, including $\delta^{18}O$, $\delta^{2}H$, and ^{3}H, in precipitation and rivers. Managed by the International Atomic Energy Agency (IAEA) with the World Meteorological Organization (WMO), GNIP includes around 900 monitoring stations across 100+ countries. For this study, data from 1998–2016 for rivers and rainfall in the Middle Ganga Basin were analyzed. Unlike traditional methods where isotopic data supplement hydro-chemical findings, this research prioritizes isotopic analysis to delineate recharge zones and assess sustainability.

The study integrates isotopic data (^{3}H, $\delta^{18}O$, $\delta^{2}H$), hydro-chemical parameters (bicarbonate and electrical conductivity), groundwater fluctuation trends (1998–2016), and rainfall records (1991–2020) to understand groundwater systems comprehensively. The first objective is to determine the isotopic composition of rainfall, river, and groundwater samples using $\delta^{18}O$ and $\delta^{2}H$ values and establish Isotopic Water Lines (IWLs) for each source. These include the Local Meteoric Water Line (LMWL), River Isotope Water Line (RIWL), and Groundwater Isotope Line (GWIL), providing insights into sources and pathways. The second objective explores correlations between isotopic values and chemical variables like chloride and nitrate concentrations. The study area covers 95,000 km² in the Upper-Middle Ganga Basin, bordered by the Sharda, Ghaghra, and Ganga rivers, with the Lower Shiwalik range forming the northern limit. Rivers such as the Ramganga, Sai, and Gomti, along with canals, support agriculture. Groundwater samples were collected once for isotopic and chemical analysis, covering 20 districts for isotopes and 27 districts for chemical data. Laboratory analyses using Isotope Ratio Mass Spectrometry (IRMS) focused on $\delta^{18}O$, $\delta^{2}H$, ^{3}H, nitrate (NO_3^-), and chloride (Cl^-). Data from groundwater trends (1998–2020) and rainfall records (1991–2020) were analyzed, and maps were created to visualize isotopic distributions, canal networks, and groundwater fluctuations using Inverse Distance Weighted (IDW) interpolation.

The results reveal that regions with high tritium content (4.0–8.0 TU) and elevated bicarbonate levels are active recharge zones, where rainfall ranges from 400 mm to 1300 mm. Correlations between stable isotopes and electrical conductivity further illuminate aquifer interactions, aiding groundwater sustainability assessments. The values of $\delta^{18}O$ vary from -7.93‰ to -5.32 ‰ for deep aquifers. The values of $\delta^{18}O$ vary from -8.4‰ to -4.2 ‰ for shallow aquifers. The $\delta^{18}O$ of Budaun and Bareilly varies from -8.2‰ to -7.56‰ while that of Bijnor, Moradabad, Sitapur, and Ambedkar Nagar varies from -7.55‰ to -6.81‰. The $\delta^{2}H$ of Prayagraj and Pratapgarh varies from -52.45‰ to -50.04‰ while that of Varanasi, Moradabad, and Rae Bareilly varies from -50.04‰ to -45.02‰. The class -62.3‰ to -55‰, -55‰ to -50‰, -50‰ to -47.5‰, -47.5‰ to -45‰ and -45‰ to -38.5‰ the area covered are 374.58 km^2, 7850.98 km^2, 17534.36 km^2, 23613.68 km^2 and 11811.9 km^2 respectively. for class -9.8‰ to -7.8‰, -7.8‰ to -6.8‰ and -6.8‰ to -5.33‰ the area covered are 1323.682 km^2, 37425.02 km^2 and 22436.79 km^2 respectively. The value of d-excess follows the equation (d-excess = -87.6 + 1.7* Latitude + 0.57*Longitude -0.005* depth, and d-excess = 50.48 – 0.32*Latitude -0.42* Longitude -0.0005*depth) for d-excess ranges of 4‰ to 7‰, and 7‰ to 8‰, respectively.

The number of points or stations for Electrical Conductivity (EC), Chloride (Cl^-), and Nitrate (NO_3^-) are 190, 4, and 10 respectively. The groundwater quality in Uttar Pradesh (middle Ganga Basin) was investigated by collecting samples and analyzing key geochemical parameters, including EC and NO_3^- with values varying from 130 µS/m to 1620 µS/m, 0.32 ppm to 549 ppm, and 0 ppm to 174 ppm. There is a negligible linear relationship of the stable isotopes δ^2H or $\delta^{18}O$ or d-excess with latitude or longitude or depth (msl). In some aquifers, the contribution of water from rainfall is higher while in others the contribution of surface water is higher. The study concludes that the groundwater is recharged by water from different sources. The groundwater age of deeper aquifers (25 years and 45 years, TU = 1 TU to 8 TU) is more than shallow aquifers (0 years and 39 years, TU = 1 TU to 7 TU) in most of the areas. However, in some areas, the groundwater age in shallow aquifers is found to be higher (more than 60 years to 100 years). This may be due to longer travel time in shallow aquifers due to lower permeability and poor terrain features. There are many below 1 TU sites in the study area where dating with the help of Carbon. Uranium, Krypton, etc. must be carried out. These areas, characterized by stable groundwater levels, are largely supported by significant rainfall and dense canal networks. In contrast, regions with low ^3H content are marked by declining groundwater levels, indicating vulnerability to depletion.

This study has used an integrated approach and found a relationship between $\delta^{18}O$ and EC is EC = 104.56 $\delta^{18}O$ + 1405.8 with coefficient of determination equal to 0.0873. This relationship shows that the inter-aquifer interaction is limited to just 8.73% of all the samples taken. This study underscores the importance of isotopic analysis in assessing groundwater sustainability. The insights gained are invaluable for policymakers and water resource managers, providing actionable strategies to ensure the long-term viability of groundwater resources in the Middle Ganga Basin. This analysis will help assess the influence of human activities, such as agricultural runoff or urbanization, on the isotopic and chemical composition of the water. The results inform future monitoring and mitigation strategies aimed at improving water quality and ensuring sustainable water use in the region.

Keywords: *Isotope hydrology, hydrogeology, environmental tracers, aquifers*

CONTROL OF AQUIFER MATERIAL ON GROUNDWATER MINERALIZATION REVEALED THROUGH ISOTOPIC AND HYDROCHEMICAL PROXIES IN CENTRAL GANGA PLAIN

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The Ganga alluvial plain (GAP) includes the Central Ganga plain, which is densely populated and comprises thick, highly permeable sand layers interbedded with less permeable silt, clay, and kankar carbonate deposits. The occurrence of an alternate sequence of sand, silt, and clay has resulted in a multitier aquifer system in the central Ganga plain. The shallow, unconfined aquifer, typically less than 100 m deep, is heavily exploited through hand pumps and private motorized wells for domestic and agricultural purposes. Unregulated groundwater extraction has led to rapid groundwater depletion and increased vulnerability to contamination. To address these pressing issues, a comprehensive study was undertaken in the Varanasi Urban area to investigate factors controlling groundwater chemistry's vertical and spatial fluctuation in this intensively populated region under prevailing aquifer heterogeneity.

In May 2021, 70 groundwater samples were collected for significant ion, trace metal, and isotope analysis during the pre-monsoon period. Samples were gathered from wells belonging to residents accessible for public use. A grid file covering the study area, measuring 1.5 × 1.5 km^2, was created using ArcGIS 10.5 to facilitate the collection of groundwater samples from various depths. Each central point within the grid was designated as a survey point. Groundwater samples were collected in 250 mL polyethylene bottles after flushing out stagnant water from the dug wells by pumping for several minutes. Samples were filtered using 0.45μm millipore membrane filters. The major ions and trace metals samples will be taken separately, in compliance with American Public Health Association (APHA, 2012) guidelines. To preserve the water sample's pH (<2) for trace metal analysis, they will be filtered and stored in a 15 ml conical tube. The temperature, pH, and EC were measured in situ using portable instruments. Major ions and trace metals were measured using IC and ICPMS, respectively, at the National Institute of Hydrology (NIH), Roorkee, India. The acid titration method determined the bicarbonate (HCO_3) concentration in the water. The ion balance indicates that errors in most samples are within ±10%.

The physical and chemical characteristics of 70 groundwater samples from the study area have been analysed. The chemometric, statistical, and isotopic analyses revealed a strong association between Na^+, Ca^{2+}, Mg^{2+}, K^+, F^-, and HCO_{3-}, indicating the dominant role of silicate weathering in controlling groundwater chemistry. The major facies observed are freshwater types of Ca-HCO_3 and Mg-HCO_3 and a few mixed facies of Ca-Na-HCO_3 water type. The widespread occurrence of calcite and dolomite nodules abundant in the older alluvium of the study area and their dissolution leads to the formation of Ca-HCO_3 and Mg-HCO3 water types. The formation of more evolved water type Ca-Na-HCO_3 results from increased groundwater residence time in the flow direction. The excess of Na^+ over Cl^- suggests additional sources of Na^+ from silicate minerals rich in Na^+ (orthoclase) brought and deposited by the rivers draining peninsular India. The study further revealed that F^-

enrichment is primarily confined to shallow groundwater and is linked to soil minerals like mica and amphibole. The higher NO^{3-} values were observed in areas adjacent to agricultural lands. These findings indicate that groundwater chemistry is primarily influenced by mineral dissolution processes within aquifer material. It is the main reason for aquifer hydrochemistry's spatial and vertical variability.

All trace metal groundwater samples in this study fall within the specified standard. As per BIS (2012) drinking water standards, concentrations of nearly all metals are below the permissible limits, except for Mn, Hg and U. In the analysed samples, Mn concentrations range from BDL to 615.28 μg/L, with a mean value of 13.39 μg/L. The threshold level for Mn was exceeded in 1.5% of groundwater samples. Numerous studies have indicated that Mn exposure can be attributed to anthropogenic activities like industrial waste, agricultural runoff, household sewage, and geogenic sources. The measured concentrations of Hg ranged from BDL to 1.5 μg/L, with a mean value of 0.086 μg/L. The threshold level for Hg was exceeded in 1.5% of groundwater samples. Elevated levels of Hg in samples may be attributed to both geogenic sources (Hg-bearing minerals) and anthropogenic activities like industrial waste, agricultural runoff, and household sewage. In the analyzed groundwater samples, U concentrations ranged from 0.72 μg/L to 44.74 μg/L, with a mean value of 8.40 μg/L. The threshold level for U was exceeded in 5.55% of groundwater samples.

The stable isotopic results ($\delta^{18}O$ and $\delta^{2}H$) reveal that most groundwater samples exhibit a comparatively enriched isotopic composition. Urban Varanasi is characterized by a dense population and extensive built-up areas with a population density of 2400 persons per square kilometer. Further, hydro-geologically, the aquifer in this region is capped by a significantly thick clay layer, which limits infiltration and results in higher surface runoff into nearby depressions. Surface recharge occurs primarily through local water bodies such as ponds and lakes or in areas where the impervious clay capping is discontinuous, allowing for localized infiltration.

In this study chemometric, statistical and isotopic methods are applied to understand the hydrochemical characteristics and evolution of groundwater in the study area. The findings indicate that groundwater chemistry is predominantly influenced by mineral dissolution processes, with silicate weathering playing a dominant role in shaping the ionic composition. The major hydrochemical facies identified include $Ca\text{-}HCO_3$, $Mg\text{-}HCO_3$, and $Ca\text{-}Na\text{-}HCO_3$, influenced by the dissolution of calcite, dolomite, and silicate minerals transported by rivers. Elevated concentrations of F^- in shallow aquifers are linked to soil minerals, while localized NO_3^- enrichment is associated with agricultural practices. Trace metal analysis revealed that Mn, Hg, and U occasionally exceed permissible limits, attributed to geogenic and anthropogenic sources. Stable isotopic data ($\delta^{18}O$ and $\delta^{2}H$) indicate limited recharge due to the impervious clay layer and urbanization impacts, with localized infiltration through water bodies and clay discontinuities. The insights gained from this study can contribute to developing sustainable groundwater management strategies in similar hydrogeological settings, mitigating the adverse impacts of excessive groundwater extraction for agricultural practices and promoting long-term aquifer health.

Keywords: *Hydrochemistry, shallow aquifer, mineral dissolution, Central Ganga Plain*

HYDROLOGICAL AND ISOTOPIC CHARACTERIZATION OF HIMALAYAN SPRINGS: INSIGHTS FROM STABLE ISOTOPES, TRITIUM ANALYSIS, AND SEASONAL PRECIPITATION IN THE TAKOLI GAD WATERSHED, INDIA

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Across the Himalayas, springs serve as a critical and reliable source of fresh water for rural and urban populations. However, these indispensable resources face increasing threats, as many springs exhibit drying trends. This decline leads to reduced water discharge and deteriorated water quality, significantly impacting local communities that depend on them for their livelihoods. Despite their importance, the role of springs in river water discharge studies remains underexplored, particularly in the glaciated and non-glaciated terrains of the Indian Himalayas. Considering the vital role of springs in the hydrological cycle, this study investigates the water isotopic composition and hydrochemistry of spring water and precipitation in the Takoli Gad watershed in the Lesser Himalayas.

Systematic water sampling was conducted across three key seasons: pre-monsoon, monsoon, and winter. A total of 434 spring water samples were collected, including 125 samples during the pre-monsoon season, 155 during the monsoon season, and 154 during the winter season. All the samples were analyzed for $\delta^{18}O$ and δD. Additionally, 29 representative spring water samples were collected and analyzed for Tritium dating. The lower number of spring water samples collected during the pre-monsoon season is attributed to the lean discharge period, during which some springs dry up. During each sampling session, in situ measurements of pH, electrical conductivity (EC), water temperature, and ambient temperature were recorded. The water samples were stored in high-density polyethylene bottles to prevent contamination. For stable isotope analysis, 125 mL bottles were used, while 1-liter bottles (29 samples) were utilized for tritium analysis. The bottles were tightly sealed and stored at 4°C until analysis. Stable isotope measurements ($\delta^{18}O$ and δD) were performed using an Isotope Ratio Mass Spectrometer MAT 253 PLUS coupled with Gas Bench II, adhering to stringent quality control protocols. The isotopic compositions were reported relative to Vienna Standard Mean Ocean Water, achieving a precision of ±0.1‰ for $\delta^{18}O$ and ±1.0‰ for δD. Tritium analysis involved electrolytic enrichment in a 20-cell unit, maintaining sample temperatures between 0°C and 5°C. Tritium activity was measured using an ultra-low-level liquid scintillation counter (Quantulus Wallac model 1220), with results reported in tritium units (TU) and a 2-sigma error margin.

The results revealed clear seasonal variations in isotopic composition and EC. $\delta^{18}O$ values ranged from -6.55‰ to -9.50‰ (pre-monsoon), -7.71‰ to -10.49‰ (monsoon), and -7.21‰ to -9.44‰ (winter), while δD values ranged from -43.78‰ to -65.94‰, -51.16‰ to -73.09‰, and -50.57‰ to -65.37‰, respectively. These seasonal shifts reflect monsoon precipitation's influence on spring recharge during the monsoon season, while evaporation processes drive isotopic enrichment during the pre-monsoon. This pattern is corroborated by d-excess values, which peaked during the monsoon and were lowest in the pre-monsoon.

Notably, winter rainwater exhibited the highest d-excess values due to the influence of westerly winds. Seasonal EC variations ranged from 70–1120 µS/cm (pre-monsoon), 50–730 µS/cm (monsoon), and 70–930 µS/cm (winter). High EC values during the pre-monsoon are attributed to limited rainfall, prolonged groundwater residence times, and reduced dilution, whereas the monsoon season’s lower values result from substantial precipitation-induced dilution. EC inversely correlated with elevation, as higher-altitude springs experienced shorter rock-water interaction times compared to their lower-altitude counterparts. Depression springs consistently displayed higher EC values, indicative of extended residence times and slower flow rates. Seasonal discharge fluctuations were also observed, with peak discharge during the monsoon and the lowest discharge during the pre-monsoon, directly influencing EC patterns.

Spring water pH ranged from slightly acidic to alkaline, with bicarbonate ions contributing to alkalinity via carbonic acid reactions. Tritium concentrations varied between 1.5 TU and 14.2 TU, indicating groundwater ages from recent to approximately 36 years. These findings underscore active recharge processes while highlighting the vulnerability of groundwater to environmental and anthropogenic changes. This comprehensive study enhances understanding of Himalayan springs' hydrological, isotopic, and ionic dynamics. The observed seasonal variations underscore the significant role of monsoon precipitation in recharging springs, complemented by winter precipitation influenced by westerlies. Fluctuations in EC and pH reflect the interplay of geological interactions, groundwater residence times, and seasonal dilution. These findings provide a scientific basis for sustainable spring rejuvenation practices and guide policymakers in conserving recharge zones, mitigating land-use changes, and adopting sustainable management strategies to ensure the longevity of Himalayan springs.

Keywords: *Himalayas, springwater, precipitation, stable isotopes, tritium, seasonality*

UNDERSTANDING SURFACE WATER GROUNDWATER INTERACTIONS IN THE UPPER NARMADA RIVER BASIN AND ITS HYDROLOGICAL IMPLICATIONS

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Groundwater and surface water are interconnected components of the hydrological system. In gaining streams, groundwater discharges into rivers and lakes, contributing to their base flow. Conversely, losing streams recharge underlying aquifers. This interaction is dynamic and depends on factors such as geology, land use, and climatic conditions. Understanding these interactions is critical for managing water resources holistically. The Narmada river is one such river which is perennial but non snow fed. This river originates from the Narmada Kund (a small reservoir) located at Amarkantak and travels nearly 1300 km before debouching into the Arabian Sea. This river is life line of Madhya Pradesh and Gujarat. Over half of the Narmada River basin is dedicated to agriculture, with groundwater serving as the primary source of irrigation and drinking water. Additionally, water from the Narmada River is transported via the Narmada Canal to water-scarce areas of Gujarat and parts of Rajasthan for agricultural and domestic purposes. Given the critical role of the river in sustaining water resources, understanding the interactions between groundwater and the river along its length, and how these interactions change spatially and temporally, is essential. Tools such as stable isotopes of oxygen, hydrogen, along with hydrogeological parameters, have been widely employed in hydrological studies to investigate various processes, including hydrograph separation, quantification of baseflow, and seasonal groundwater recharge dynamics. Our objectives for this study is to understand spatiotemporal variations in surface water groundwater interactions along the Narmada river for upper Narmada Basin (Amarkantak to Hosangabad, covers nearly 720 km length). To achieve this objective groundwater from shallow aquifers from 92 locations and river water (Narmada and its tributaries) from 23 locations were collected for pre-monsoon (June 2024) and post-monsoon (Nov 2024) seasons. These samples were collected from 30km interval along the river and across the river near the bank and 5km away up to 15km on both the sides.

Basic parameters such as pH, EC, and temperature were measured in field using Thermoscientific PC 450 Multi-parameter Meter Kit. The isotope samples were collected in 30ml HDPE airtight bottles after rinsing it thoroughly with the sampled water. The groundwater samples were collected from dug wells and hand pumps after purging it for 10 minutes to avoid the effect of evaporation from stagnant water while river water samples were collected from mid channels through rope and bucket to avoid any spurious signature from river water near bank due to some small channel contamination. These samples were analyzed for their stable isotope compositions of oxygen ($\delta^{18}O$) and hydrogen (δD) using Dual Inlet Isotope Ratio Mass Spectrometry (DI-IRMS) and Continuous Flow Isotope Ratio Mass Spectrometry (CF-IRMS). Both instruments are housed in the Nuclear Hydrology Laboratory at the National Institute of Hydrology, Roorkee.

For the isotopic analyses, a gas equilibration method was employed, which is a widely recognized procedure for assessing water samples. A small volume of water (approximately 300 μL) was used for each analysis. For oxygen isotope analysis ($\delta^{18}O$), the water samples were equilibrated with carbon dioxide (CO_2) gas, while for hydrogen isotope analysis (δD), hydrogen (H_2) gas was used. During this equilibration process, the respective gases absorbed the isotopic characteristics of the water sample, allowing for a precise measurement of the isotopic ratios. The equilibrated gases, containing the isotopic signatures of the water, were then introduced into the mass spectrometer. The IRMS measured the ratios of the isotopes, specifically $^{18}O/^{16}O$ for oxygen and $^{2}H/^{1}H$ (D/H) for hydrogen. These ratios were further used to compute the delta values ($\delta^{18}O$ and δD) of the samples, which provide information about the relative abundance of the isotopes compared to a standard reference. The reproducibility of the measurements was ensured through repeated analyses of multiple aliquots of a secondary laboratory standard. The results demonstrated high precision, with reproducibility better than 0.1‰ for $\delta^{18}O$ and 1‰ for δD.

The isotopic compositions of oxygen and hydrogen are expressed using the delta (δ) notation, which represents the ratio of the less abundant isotope to the more abundant isotope (R = $^{2}H/^{1}H$ or $^{18}O/^{16}O$). This ratio is compared to a standard reference material (Vienna Standard Mean Ocean Water, or VSMOW) and is expressed in per mil (‰) units. The groundwater $\delta^{18}O$, δD, and d-excess for pre-monsoon season varies between -7.2‰ to -0.3‰, -46.4‰ to -11.6‰, and -12.1‰ to 16.0‰ with an average of -4.3‰, -29.4‰, and 4.8‰ while for the post-monsoon season the ranges are -7.4‰ to -0.4‰, -51.0‰ to -15.2‰, and -11.6‰ to 13.7‰ with an average of -4.5‰, -31.0‰, and 4.7‰. The river water $\delta^{18}O$, δD, and d-excess for pre-monsoon ranges between -4.4‰ to 4.0‰, -38.9‰ to 7.9‰, and -24.0‰ to 3.5‰ with an average of -1.7‰, -18.5‰ and -5.0‰ while the post-monsoon values varies between -6.7‰ to -4.0‰, -49.8‰ to -29.2‰, and 0.0‰ to 8.3‰ with an average of -5.3‰, -37.5‰, and 4.4‰. The average isotopic composition of groundwater indicates that there is no seasonal variation but when it plotted spatially some of the region shows depletion in post-monsoon season which indicates freshwater influx in groundwater during monsoon season. River water isotopic composition varies spatially as well as temporally during pre-monsoon season Narmada kund water isotopic composition was -2.7‰ as river flow towards Bargi dam (near Jabalpur) river water isotopic composition initially increases and went up to 4.0‰ and then started decreasing up to -1.7‰ after the dam river water isotopic composition was -4.9‰ and it went up to -4.1‰ similar kind of pattern was also observed during post-monsoon season but the values were much lower i.e. Narmada kund water isotopic composition was 5.9‰ it went up to -4.4‰ and it started decreasing up to -5.5‰ and after the dam river water isotopic composition was -6.7‰ and it went up to -5.6‰. Similar pattern was also observed in pH values of river water during both the season from Narmada kund to Hosangabad. Based on the isotopic data and pH some of the preliminary inferences drawn from this study are: (1) The initial increase in $\delta^{18}O$ value indicate higher extent of evaporation (2) The decrease $\delta^{18}O$ and pH before the dam indicated that this area receives base flow as groundwater in this part of lower isotopic composition and low pH values compared to river. (3) a decrease in isotopic composition after the dam is because of the stratification in isotopic composition of reservoir water (upper part of the reservoir water become enriched due to evaporation while bottom water preserves its initial and this water is further released in river).

Keywords: *Upper Narmada Basin, groundwater, stable isotopes, base flow, seasonal variation*

ISOTOPIC COMPOSITION AND VARIABILITY OF SNOWPACK IN THE HIMALAYA (2011–2022)

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The Himalayan region is known to be sensitive to changes in global climate and is considered a crucial component of the earth's climate system. The snow and ice cover in the Himalaya act as a natural archive of environmental and climatic changes, and the isotopic composition of the snow provides a valuable record of these changes. The stable isotopes of oxygen and hydrogen in snow and ice reflect the temperature and moisture conditions during snow formation and can provide information on the precipitation source, transport, and recycling processes. The stable isotopic composition of snow and ice in the Himalaya have significant spatial and temporal variations. Mountain hydrology research has increasingly focused on the role of isotopic analysis in understanding snowpack dynamics. Snowpack's are critical water reservoirs in mountainous regions contributing to downstream water security significantly. This study examines the snowpack's isotopic composition ($\delta^{18}O$, D, and d-excess) over a decade (2011–2022), highlighting spatial and temporal variability, relationships among isotopic parameters, and implications for hydrological modelling and climate studies. The work builds on foundational studies, including Dansgaard's framework on isotopic fractionation in precipitation and applications in snow hydrology. Snowpack samples were collected annually from a Himalayan site over the 11 years. The isotopic composition of the snowpack was analyzed using cavity ring-down spectroscopy (Piccarro), yielding high-resolution data on $\delta^{18}O$, D, and d-excess. Depth profiles were constructed to study vertical isotopic gradients, while temporal trends were assessed to identify inter-annual variability. Relationships between $\delta^{18}O$ and d-excess were explored, and the snowpack meteoric water line (SMWL) was derived.

The $\delta^{18}O$ profile exhibited significant variability with depth, reflecting processes such as fractionation during precipitation and post-depositional modifications. Enriched $\delta^{18}O$ values near the surface were associated with recent snowfall, while deeper layers showed depletion, indicating older snow and potential sublimation effects. These findings align with previous studies on Himalayan snowpack isotopes. The d-excess profile highlighted evaporative enrichment and moisture source variations. Elevated d-excess values in certain layers suggested contributions from non-local moisture sources, including westerlies, while lower values indicated local recycling. Such patterns are consistent with insights from studies on d-excess as a tracer for hydrological processes. Inter-annual variability revealed significant fluctuations linked to changes in atmospheric circulation patterns, such as the Indian Summer Monsoon and Western Disturbances. These findings underscore the sensitivity of snow isotopes to climatic drivers. The derived Snowpack Meteoric Water Line (SMWL) ($\delta^2H = 8*\delta^{18}O + 10\pm0.5$) closely aligned with the global meteoric water line (GMWL), suggesting minimal kinetic fractionation. Deviations in specific years indicated shifts in precipitation regimes. A negative correlation between $\delta^{18}O$ and d-excess was observed, reflecting the interplay between condensation temperature and moisture source dynamics. This relationship provides a robust indicator for tracing snowpack origin and evolution.

The isotopic signatures of snowpack provide critical insights into precipitation processes, snow dynamics, and climatic variability. Enriched $\delta^{18}O$ and variable d-excess values underscore the influence of both regional and local factors on snow isotopes. The SMWL's stability over the study period emphasizes the dominant role of synoptic-scale precipitation events in shaping isotopic patterns. The findings have significant implications for mountain hydrology. The isotopic characterization of snowpack enables improved parameterization of snowmelt models through isotope-derived insights into accumulation and ablation processes, enhanced understanding of snowpack contributions to streamflow, critical for water resource management and climate change impact assessments by linking isotopic trends to shifts in atmospheric moisture sources. This study highlights the value of isotopic analysis in advancing our understanding of snowpack dynamics in the Indian Himalaya. The observed variability in $\delta^{18}O$, D, and d-excess, alongside their relationships, provides a comprehensive picture of the interplay between climatic drivers and snow hydrology. Future work should focus on integrating isotopic data with high-resolution climate models to predict snowpack responses under changing climatic conditions.

Keywords: *Snowpack, stable isotopes, mountain hydrology, Himalaya, climate variability*

ASSESSING GROUNDWATER QUALITY IN JHAJJAR, HARYANA: HYDROCHEMICAL AND ISOTOPIC INSIGHTS FOR SUSTAINABLE MANAGEMENT

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The rapid urbanization and industrialization in alluvial plains, known for their high permeability, have led to an imbalance between water supply and demand, significantly impacting groundwater resources. Key factors influencing aquifer hydrochemistry include recharge water, rock-water interactions, land use, and human activities. Increased groundwater depletion and contamination are exacerbated by changing precipitation patterns, high-water-consuming crops, industrial operations, and population growth. The Indo-Gangetic Plain (IGP), particularly the Jhajjar district, illustrates these challenges, with excessive extraction since the Green Revolution resulting in depletion, salinization, and elevated levels of TDS and fluoride, posing serious health risks. The paper addresses the objectives (i) groundwater quality, contamination, and the pollution sources, (ii) hydrological processes involving groundwater recharge and evaporation dynamics, and (iii) management strategies to address salinization and contamination for sustainable resource use. This study focuses on the Jhajjar district in southwestern Haryana, part of the National Capital Region (NCR) of Delhi. Despite its potential as a freshwater recharge zone, the district faces groundwater deterioration due to fluoride, sulfate, chloride contamination, and salinity, raising health concerns like dental fluorosis. Groundwater serves as the primary source for drinking, industrial, and agricultural needs. The region, with alluvial topography consisting of clay, sand, and kankar sediments, faces challenges from over-irrigation, waterlogging, and salinity.

Groundwater samples were collected from 21 locations across a 10x10 km grid. Each well was purged for 5 minutes before sampling to prevent contamination. Sampling bottles were treated with hydrochloric acid (HCl), rinsed with water, and acidified with nitric acid (HNO_3) to preserve trace metals. On-site measurements included pH, EC, TDS, and water table depth. Anions and cations were analyzed using ion chromatography and atomic absorption spectrophotometry. Samples were stored at 4°C, and spatial analyses were conducted using ArcGIS 10.3. The saturation index (SI) was calculated using PHREEQC software. Stable isotopes $\delta^{18}O$ and $\delta^{2}H$ were analyzed by IRMS to study groundwater-surface water interactions, recharge, and geochemical processes. Cluster analysis categorized groundwater into distinct groups based on land use and climate influences. Hydrochemical analysis revealed that groundwater in Jhajjar district is predominantly alkaline, with pH values ranging from 7.52 to 10.31. Total Dissolved Solids (TDS) levels exceeded permissible limits in most samples, indicating significant salinization. Electrical conductivity (EC) values ranged from 700 to 18,430 μS/cm, and TDS from 351 to 9,215 mg/L. Elevated TDS and EC are mainly due to salt encrustation and irrigation return flows. Sulfate concentrations varied from 23.3 to 1,851.4 mg/L, influenced by agricultural chemicals, while bicarbonate levels ranged from 122 to 394 mg/L, caused by carbonate dissolution.

Nitrate contamination ranged from 10.2 to 54.3 mg/L, especially high in south-eastern and south-western regions, linked to excessive fertilizer use and agricultural runoff. Fluoride levels ranged from 0.6 to 6.8 mg/L, with 66% of samples exceeding the WHO limit of 1.5 mg/L, particularly in the north-eastern and central areas. Elevated fluoride concentrations are associated with alkaline pH, ion exchange, and local clay-silt formations. A correlation matrix indicated strong associations between pH, EC, TDS, Na^+, and Cl^-, showing that agricultural activities significantly contribute to pollution and salinity. The Mineral Saturation Index showed under-saturation concerning to anhydrite, gypsum, and fluorite, facilitating the dissolution of sulfate and fluoride ions. Hierarchical Cluster Analysis classified the groundwater into three groups, ranging from freshwater to highly saline, highlighting the variability in groundwater quality and the need for targeted management strategies.

The study found significant impacts of urbanization and irrigation on groundwater salinity and isotopic composition. Canal irrigation in peri-urban areas resulted in lower chloride concentrations and depleted $\delta^{18}O$ values, aiding aquifer recharge. In urban areas like Jhajjar, elevated chloride concentrations and enriched $\delta^{18}O$ values indicated evaporation and groundwater depletion, raising concerns about saline plumes. Fluoride concentrations were lower in canal-irrigated areas but higher in urban zones. Reverse ion exchange and carbonate weathering dominate the region's hydrological processes, with calcium being replaced by sodium in wastewater-infiltrated areas. Increasing EC and chloride concentrations from Water Group (WG) I to III indicates a transition to more saline conditions, with WG II and III resembling ocean-water ratios. The dissolution of gypsum and the region's flat, waterlogged terrain contribute to high sulfate concentrations, particularly in urban areas. Local precipitation is identified as the main groundwater source, with significant spatial variation in isotopic compositions ($\delta^{18}O$ and $\delta^{2}H$). Canal irrigation and evapotranspiration play key roles in enhancing groundwater recharge, as indicated by elevated D-excess values.

The key findings of the study reveal significant concerns regarding groundwater quality, pollution sources, and hydrological processes in the district. Groundwater is primarily alkaline and highly saline, with TDS and EC levels exceeding WHO standards in 95% of the samples. Agricultural practices, particularly excessive fertilizer use, contribute to nitrate and fluoride contamination, with high fluoride levels in urban areas posing considerable health risks. Urbanization and irrigation practices also influence groundwater salinity and isotopic composition. Canal irrigation in peri-urban areas helps mitigate chloride and fluoride concentrations, while urban regions experience higher salinity due to evaporation and groundwater depletion. Hydrological processes such as reverse ion exchange and carbonate weathering play a crucial role in groundwater mineralization. Isotopic analyses indicate that local precipitation is the primary source of groundwater, with variations in $\delta^{18}O$ and $\delta^{2}H$ reflecting the impact of evaporation and recharge mechanisms. The study underscores the importance of targeted management strategies to address salinization and fluoride contamination. It emphasizes the need to protect recharge zones, promote sustainable agricultural practices, and raise awareness among stakeholders to safeguard water resources and public health.

Keywords: *Groundwater quality, salinization, isotopic composition, correlation matrix*

HYDROCHEMICAL AND ISOTOPIC DYNAMICS OF (SUB)-SURFACE WATER RESOURCES IN CHITTORGARH, RAJASTHAN

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The (sub)-surface water resources are highly susceptible to geological and anthropogenic processes. These resources are essential in meeting agricultural demands and providing potable water to the local communities. However, as water quality deteriorates and contamination levels increase, bridging the significant research gap in understanding the hydrochemical and isotopic processes that govern these resources becomes essential. This is particularly important for semi-arid regions like Chittorgarh in Rajasthan, where geological and anthropogenic factors interact significantly. Chittorgarh is located in the southern part of Rajasthan between 74° 26′ 54″ to 74° 51′ 43″ East and 24° 42′ 35″ to 25° 05′ 41″ North with a geographical area of 950 square kilometers and mean annual rainfall of approximately 850 mm. The groundwater in the region occurs mainly within the weathered, fractured, and jointed hard rocks like limestone, shale, granite, and gneiss, which exhibit very low permeability and poor storativity. In this context, surface water resources become the primary water sources; they are often insufficient or unreliable due to the region's erratic rainfall patterns.

This study focuses on analyzing the water chemistry, identifying the potential contaminants, and evaluating isotopic characteristics to better manage these (sub)-surface water resources in Chittorgarh, Rajasthan. It employs in-situ and laboratory-based methods to assess the hydrochemical characteristics of groundwater (n=44) and surface water (n=26) collected in the post-monsoon season of 2023 and the pre-monsoon season of 2024 using the grab sampling techniques. Additionally, for stable isotope (^{2}H and ^{18}O) analysis, six representative groundwater samples and four surface water samples collected in the post-monsoon season were analyzed. In-situ analysis of the samples was performed to measure pH, TDS, EC and DO using the multi-meter electrode. Ion chromatography (IC) was used to determine the concentration of major ions, including Calcium (Ca^{2+}), Potassium (K^{+}), Magnesium (Mg^{2+}), sodium (Na^{+}), Floride (F^{-}), sulphate (SO_4^{2-}), nitrate (NO_3^{-}) and Chloride (Cl^{-}). The titration technique was used to determine the alkalinity levels. The overall ion measurement accuracy was checked by charge balance error, and the values were within the acceptable limit (±10%).

The suitability of (sub)-surface water resources for irrigation was evaluated using parameters like percent sodium (%Na), sodium absorption ratio (SAR), residual sodium carbonate (RSC), permeability index (PI), and magnesium hazard (MH). Meanwhile, the hydrochemical facies were identified based on the chemical composition of the water samples using the Piper plot and Gibbs diagram. The groundwater samples largely complied with IS 10500:2012 water quality standards. However, 46% of the groundwater samples exceeded the BIS acceptable limit (45 mg/l) for nitrate concentrations in the post-monsoon season, with this percentage increasing to approximately 87% during the pre-monsoon period. The elevated nitrate concentration, especially in the pre-monsoon period, could be attributed to several factors like excessive use of fertilizers, sewerage, animal waste, organic manure, the geology of sub-surface soil layers, etc. Additionally, the absence of significant water flow and limited recharge can cause accumulated nitrate concentrations to become more concentrated in the groundwater. In contrast, most surface water samples were within BIS-acceptable limits during pre- and post-monsoon season. This is likely due to the continuous flow and mixing in surface water, leading to the dilution of contaminants in the surface water samples.

The ratios of heavy stable isotopes were measured using Dual Inlet Isotope Ratio Mass Spectrometer-DI IRMS. The measured values were reported as delta (δ) values. The precision of measurement for δ^2H was ± 1‰, and that for $\delta^{18}O$ was ± 0.1‰ respectively. The mean value of $\delta^{18}O$ and δ^2H in groundwater was found to be -4.14 ‰ and -32.29 ‰, whereas the average value of $\delta^{18}O$ in surface water samples was found to be -1.56 ‰ and -22.81 ‰ respectively. The overall slope of the groundwater sample (3.64) was less steep than the LMWL (7.8), indicating the occurrence of very high evaporation in meteoric water before infiltration through the vadose zone. The variation in $\delta^{18}O$ and δ^2H reflected no significant interaction between groundwater and surface water resources, indicating these water bodies are primarily influenced by separate sources. The distinct variation in isotopic signatures of groundwater and surface water can be attributed to natural intermittent processes such as evaporation, infiltration, percolation, or anthropogenic-driven processes.

Contamination of (sub)-surface resources is a persistent challenge, particularly in semi-arid regions where (sub)-surface water resources are often limited and highly variable. This study emphasizes the importance of monitoring hydrochemical and isotopic parameters in understanding the behavior and quality of (sub)-surface water resources in semi-arid regions. Hence, properly managing these resources is imperative to avoid contaminating these water resources and make informed decisions for sustainable development. This research provides critical insights into developing effective management strategies for the region, contributing to the long-term sustainability of water resources in the Chittorgarh region.

Keywords: *Water quality, (sub)-surface water resources, semi-arid regions, ion chromatography nitrate concentrations, stable isotopes*

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10th International Groundwater Conference (IGWC 2025)

GROUNDWATER VISION 2047

Towards Water Security under Changing Climate

March 05-07, 2025, NIH Roorkee, India

Santosh Murlidhar Pingale • Nitesh Patidar • Sumant Kumar • Gopal Krishan

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The International Conferences in IGWC series are the meeting point for groundwater professionals and researchers, bringing together experts from various inter-related disciplines in the field of Groundwater Hydrology. Groundwater has emerged as a major resource in safeguarding agriculture and drinking water security in many parts of the globe. Integral to life and indispensable for comprehensive growth and development, Groundwater is a key resource for India in achieving its holistic vision of a developed nation by 2047, the 100th year of its independence. The conference themes are aligned with India's vision and mission for sustainable and inclusive growth, emphasizing a multi-pronged strategy to create livelihood opportunities, develop essential infrastructure, and address environmental concerns, with sustainable groundwater management being a key component. The conference themes include groundwater management and modelling, agriculture water management, climate change, environmental flows and river rejuvenation, mountain hydrology and springshed management, coastal water resources management, and advanced techniques in groundwater management and exploration, etc.

The abstracts of keynote and research papers presented during the International Groundwater Conference held during March 05 to 07, 2025, in Roorkee, India, are provided in this conference volume.

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