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 ^4He, $^3He/^4He$, ^{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 ΔHe%, 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), (δ^2H= 7.66 δ^{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 δ^{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*