Theme 4

WATER RESOURCES IN ARID AND SEMI-ARID REGIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

zones depict the suitability level for conservation of water resources in the region to develop different action plan like rainwater harvesting, check dams, recharge pits, lake/reservoir etc. The ArcGIS platform facilitated the spatial analysis of data, allowing us to delineate the areas with different suitability zones. Based on the possibility for water conservation, the Kalahandi district has been identified as various zones using suitability map for conservation of water resources.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The present study is carried out in the LRB basin, within the BA, which covers an area of approximately 17,726 km² and is characterized by its high altitude, with a physiographic barrier that features peaks exceeding 6 km above sea level, such as Mount Sajama. The basin is a longitudinal tectonic depression filled mainly with Tertiary and Quaternary sediments. Field and laboratory parameters of 96 groundwater samples collected from sources used for drinking and domestic purposes in the LRB were analyzed. Groundwater sampling followed standard procedures (EPA, 2017; ISO 5667-1) to ensure representative data. In-situ field parameters, including pH, water temperature, electrical conductivity (EC), and redox potential (Eh), were measured using HANNA-HI 98194 and HACH-HQ 40D multiparameter instruments. Alkalinity (as HCO_3^-) was determined in-situ by acid-base titration using a Hach digital titrator (model 16900). Laboratory analysis included major ions and trace elements by IC and ICP-MS.

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

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

STUDY OF GROUNDWATER DISCHARGE IN SELECTED AREA OF TAPI BASIN

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

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

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

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

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

Terrain analysis is fundamental to research and development, as land-surface topography strongly influences groundwater flow and water-table dynamics. Elevation data was accessed through the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). This data has a spatial resolution of 15 m and is organized in 1°×1° tiles. For the study area, two specific tiles, ASTGTM2_N18E074 and ASTGTM2_N18E073, were used to process the DEM. Groundwater fluctuations are also influenced by drainage patterns and density. Drainage density, especially in hard rock terrains, is crucial for groundwater availability and helps identify groundwater potential zones. Drainage analysis was conducted by integrating the vector drainage layer of the study area in GIS. A drainage density map was produced using ArcMap's 'Create Fishnet' tool. The catchment area was divided into 1 km^2 square cells, and the total length of streams within each cell was calculated and recorded in a database. This data was then joined to the 1 km^2 grid of the catchment area.

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

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

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

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