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A review of groundwater resources in the Upper Luni River Basin: Trends, quality, and potential: A comprehensive review

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Abstract

The resource of groundwater plays a very crucial role in ensuring water security in the arid and semi arid areas, particularly in the Upper Luni River Basin of western Rajasthan in India. Studies in this basin have basically been on three major points which are the analysis of the long term ground trends, water quality, and ground water potential zones (GWPZs). It has been determined that groundwater availability and recharge are dependant on numerous hydrogeological factors that include slope, land cover/land use (LULC), geology, lineament density, lineament density, drainage density, elevation, rainfall, and soil type. The mostly used GIS-based methods such as Analytic Hierarchy Process (AHP) and weighted overlay analysis (WOA) have been used to combine such factors in cumulative GWPZ maps. The Mann Kendall test had been the standard evaluation used in groundwater trend analysis, and shows that a steady decrease in groundwater is present in most parts of the basin, caused by over extraction and under-recharge. According to the quality analysis tests, the total dissolved solid, fluoride, and nitrate contents are high and this limits the use of the groundwater as drinking and irrigation water. GWPZ mapping have revealed that the terrains with low gradient, alluvial geology, moderate topography, high lineament and drainage densities, well-draining soils and rainfall enough to recharge the groundwaters are the most suitable to be used as locations to carry out the groundwater recharges. The review focuses on the efficacy of the combination of remote sensing, GIS, and statistical procedures such as the Mann- Kendall test in the analysis of groundwater and urges better monitoring, modeling and participatory measures of groundwater management.

Keywords: Groundwater analysis, Luni River Basin, trend analysis, groundwater quality, groundwater potential zones, GIS, remote sensing

1. Introduction

Groundwater has now become a necessity in India and especially in the arid and semi-arid areas such as the Upper Luni River Basin where there is a scarcity of surface water and ground water that is only seasonal. The increased dependence on ground water to perform irrigation, consumption and industrial activities has resulted in colossal rate of depletion and degradation of aquifer. The Luni Basin along with Western Rajasthan is the region with a very high indication of groundwater stress in terms of depleting water levels and poor water quality (Rao *et al*., 2022; CGWB, 2021) [20, 3].

Poor control of the monsoonal rainfall, high evapotranspiration and low natural recharge combine to make it important to know the spatio-temporal dynamics of groundwater systems. Remote sensing and Geographic Information System (GIS) provide powerful means of monitoring, analysing and visualizing groundwater behaviour across space and time (Jha *et al*., 2007; Magesh *et al*., 2012) [8, 15]. With data on hydrogeology, climate, and landscapes, these tools allow people to conduct a detailed groundwater evaluation, which is an efficient measure towards groundwater management (Das & Pardeshi, 2018) [5].

In those recent studies pertaining to comparable arid camps, the application of methods such as Mann-Kendall trend test to analyze the effects of time, Water Quality Index (WQI) to determine the quality of water, and the frameworks of multi-criteria decision analysis (MCDA) such as AHP to define the potential sites of groundwater were used (Gheisari *et al*., 2020; Singh *et al*., 2023) [7, 26]. The synthesis of these approaches and results in the setting of the Upper Luni Basin is used to (1) examine the trending of groundwater, (2) evaluate water quality and its fluctuation and (3) contour the prospective groundwater zones utilizing thematic GIS layers bearing on slope, LULC, geology, drainage, rainfall, etc.

2. Methods and Tools

The application of groundwater studies of Upper Luni River Basin have used extensive methods and instruments that have used geostatistics, remote sensing, GIS, and multi-criteria decision analysis. Through such techniques, researchers have been able to measure trends in ground water level, determine water quality and also outline ground water potential zones (GWPZs). Common practice in literature is the use of the following tools and methods:

2.1 Water Quality Analysis tools

Field sampling in combination with lab testing has been employed in ground water quality testing the parameters measured include; total dissolved solids (TDS), fluoride, nitrate, pH, and electrical conductivity. The results so obtained are usually compiled by adopting Water Quality Index (WQI) techniques to list the water as excellent, good, poor and poor unfit. Spatial interpolation methods are applied to visualize the spatial pattern of contamination and spot places with the poor quality of water particularly, Inverse Distance Weighting (IDW) and Kriging methods. These are the tools to convey the geographic scope of the water quality problems located in the basin.

2.2 Remote Sensing and GIS Tools

Remote sensing has played a central role in classifying land cover, detecting change, generating thematic layers (of land cover like Normalized Difference Vegetation Index (NDVI), land use/land cover (LULC) and slope generated based on Digital Elevation Models (DEM)). In its turn, GIS acts as the carrier of the integration of these layers, spatial analysis, and the issuance of groundwater potential maps. Major used software are ArcGIS, QGIS, ERDAS Imagine and Google Earth Engine (GEE). These items aid in overlay, bite analysis, and raster-based adaptability planning.

3. Groundwater Trend Analysis

Analysis in the basin has revealed a reduction in ground water table over the long run, especially in the areas of Jodhpur, Barmer and Pali districts. Mann-Kendall test showcased by Singh *et al*. (2023) [26] was used to analyze decadal borewell data with an annual decrease equal to 0.4-1.2 meters. Such depletions are mainly as a result of over irrigation abstractions and low recharges. According to Rao *et al*. (2022) [20], the problematic area was revitalization in post-monsoon seasons and the presence of greater reliance on deep aquifers. According to the trend analysis, it is critical to take some measures on recharging the aquifers and enhancing efficiency in the irrigation.

3.1 Mann-Kendall Trend Test

Mann-Kendall test is a non test that is parametric and is employed to draw monotonic tendency in hydrological and environmental time series data (Gilbert, 1987) [6]. It is particularly appropriate in situations when one is analyzing ground water level because it is not sensitive to outliers and also resistant to non-normal data distributions. Statistic for the test of successive observations is the test statistic labeled as S which analyses the difference between back to back observations. When “S” is positive it implies an upward sloping pattern and negative “S” implies downward sloping pattern. The standard deviation of S is used to calculate the Z-score and as such to assess the significance of the trend. The application of the technique has been found in abundance in Indian groundwater research, such as in Rajasthan (Yue *et al*., 2002; Mondal *et al*., 2012; Singh *et al*., 2023) [32, 17, 26].

4. Groundwater Quality and Spatial-Temporal Variation

The surveys on groundwater quality in the Upper Luni Basin indicate Upper Luni Basin shows TDS level, fluoride levels and nitrate level exceeding the primary standard values, particularly in the western and central areas. Based on WQI, Meena & Patel (2021) [16] have observed through the use of GIS-based interpolation procedures including Inverse Distance Weighting (IDW) and kriging processes that more than 50 percent of the groundwater samples were in the poor to very poor categories. The seasonal trends tend to show most contamination in pre-monsoon seasons where because of evaporation followed by concentration effects, shows a lot of contamination. Geogenic (geogenic sources which include granitic rocks) sources take part in high fluoride concentrations; whereas anthropogenic (human related) activities (such as the use of fertilizers) lead to the increase in the human concentration of nitrate.

4.1 Inverse Distance Weighting (IDW)

Identical with DW, IDW is spatial interpolating technique which estimates the value at unsampled location by referencing to the nearby sampled sites values (Lu & Wong, 2008) [10]. It maintains that the impact of a known datum point that is close to the location where prediction is done tends to reduce as the separation distance become larger. In the groundwater quality mapping, IDW is widely applied in the generation of continuous surface maps of values of TDS, fluoride, and nitrate concentrations. It is easy and precise in local ground scales, which also makes it applicable in regions such as the Upper Luni Basin (Meena & Patel, 2021; Rahmati *et al*., 2015) [16, 21].

IDW has shown itself to be a useful and simple tool for producing continuous surface representations of point-based measurements, including concentrations of nitrate, fluoride, and total dissolved solids (TDS), in the context of mapping groundwater quality. Particularly in areas with water stress and contamination, like the Upper Luni River Basin, these chemical parameters are essential for assessing the potability and usability of groundwater. IDW is especially well-suited for regional-scale research and local management applications due to its ease of use and computational effectiveness. IDW is accessible to a wider range of users, including hydrologists, urban planners, and GIS specialists, because it does not rely on assumptions regarding data stationarity or semivariogram modeling, in contrast to more intricate geostatistical techniques (such as kriging).

Additionally, when data points are evenly distributed and dense, as is frequently the case in groundwater monitoring networks with strategically placed boreholes, the method works best. There are some restrictions, though, like the possibility of interpolation artifacts in regions with little data or sudden changes in the environment. Adaptive IDW is one recent development that addresses this issue by optimizing the power parameter locally based on spatial structure and data density (Zhou *et al*., 2019) [33].

5. Mapping of Potential Zone of Groundwater and Parameters that Influence it

Groundwater potential zone (GWPZ) mapping is indeed a multidimensional methodology which combines a multiplicity of thematic datasets as the basis to determine groundwater recharge as well as subsurface storage capacity. It uses hydrogeological, topographic, climatic and terrestrial factors in defining zones with good groundwater conditions. The given below discusses the key thematic factors deployed in such mapping in detail and their importance.

Slope: It influences runoff and infiltration The slope creates effects on rate and volume of surface runoff and infiltration. Areas that have gentle slopes slow the flow of water thereby more time to be taken in way of infiltration along with percolation of the water into underground aquifers. On the other hand deep slopes encourage high-velocity runoff, which does not allow much of recharge. Flat land and alluvial plains are thus described as high potential places as they have a higher holding capacity of water (Magesh *et al*., 2012) [15].

Land Use/Land Cover (LULC): LULC plays an important role as it helps in the assessment of the permeability of the surface, and extent of infiltration. Groundwater recharge is usually supported by agricultural lands, forests and grass lands since these lands have permeable soils and vegetation covers. On the contrary, developed regions that consist of impervious surfaces such as roadways and buildings do not allow infiltration by sealing the surface and as such, reduce the groundwater potential. Remote sensing data (Landsat images) is used to derive this thematic layer of different categories of analysis.

Geology: Geological formations determine the permeability and the porosity of the layers. The alluvial sediments, strata sandstones as well as weathered rocks are the best aquifers since they are highly permeable and porous. Conversely, igneous rocks like granites are less permeable except where there is a considerable cracking. The geological environment plays a vital role in the assessment of the characteristics of the aquifer and groundwater flows.

Lineament Density: Lineaments: Lineaments (linear structures: such as faults, joints and fractures) ease groundwater flow by adding secondary porosity. High lineament density correlates with areas that easily allow percolation of water in the rock mass. The extraction of these features normally takes place via the remote sensing technologies or geological maps and the density of the features is calculated here utilizing the spatial analysis facilities in GIS. Regions that have great density of lineaments are those where high ground water potential is said to be.

Drainage Density: Drainage density indicates the proximity of the spacing of streams and rivers. The low density of the drainage implies, as a rule, that rocks and soils are permeable and facilitate infiltration and storage of water in the subsurface. Conversely, a high D may reflect a fine, less-permanent landscape that favors surface flow in place of infiltration (Gheisari *et al*., 2020) [7]. This parameter is normally based on topographic maps, or Digital Elevation Model (DEM).

Elevation: Elevation is a major factor in the accretion and circulation of groundwater. Influx surfaces tend to be freely flooded in moderate level surfaces because of the balance of outflow and outflow. Areas of high altitude are likely to be steep and run off rapidly, but locations along the low-lying grounds may risk being waterlogged or under saline resources. The elevation profiles are investigated with digital elevation data such as that derived by Shuttle Radar Topography Mission (SRTM).

Rainfall: Rain is the main source of natural recharge of groundwater. Areas of high annual rainfall are usually characterized by a good potential of groundwater, particularly with the coincidence of good land cover and soil types. Distribution of rainfall is both temporal and local and data such as the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data) offers high-resolution precipitation estimates which are used to aid in recharge analysis.

Soil (FAO Classified): The kind and the texture of soil makes a significant contribution to the rates of infiltration and percolation. According to FAO soil data, rich soils such as Sandy and loamy soils are those found to move at a high rate into the soil and classified as high groundwater potential zones. The clayey soils on the contrary are of poor permeability and limit the movement of water and thus become less efficient in recharging. FAO soil maps also offer normal world classifications that could be used to measure the spatial distribution and infiltration features of soil types in the study region.

These layers can be integrated together with GIS-based methods, e.g. the Analytic Hierarchy Process (AHP) and Weighted Overlay Analysis (WOA) to be able to derive composite groundwater potential indices. AHP works by giving judgemental weights which can be carried out by experts or pairwise comparison of the importance and significance of each factor. Suitably, WOA subsequently blackens the layers of weighting to give a final map of GWPZ.

One of the most remarkable works of this method was undertaken by Sharma *et al*. (2020) [25] in arid parts of the state of Rajasthan and was able to classify the area into low, moderate, and high groundwater potential zones. By verifying against field information (well yield measurements), a very good correlation was found between the areas that were mapped to be high potential and the wells which were known to yield high, which showed the accuracy of the GIS based technique.

This complex activity does not just serve to determine areas of ground water development but it also serves land use planning, agricultural capacity as well as watershed development. Due to the increasingly difficult situation associated with the problem of groundwater shortage, particularly in dry areas such as the Upper Luni Basin, the significance of such integrated strategies is ever increasing.

5.1 Analytic Hierarchy Process (AHP)

AHP technique is type of multi-criteria analysis developed by Saaty (1980) [23]. It helps to make decisions, formulating complex issues in a goal-criteria-alternative hierarchy. Based on pair-comparison and ranking, a weight factor is given to each factor and a consistency ratio (CR) is determined to ratify how valid a judgment is. The AHP is applied in the ground water potential mapping as parameters to define the relative importance of slope, LULC, geology and rainfall.

Examples include Sharma *et al*. (2020) [25] who applied AHP to delineate groundwater areas in dry Rajasthan and tested their model against the yield of wells. On the same note, Jha *et al*. (2007) [8], Magesh *et al*. (2012) [15] and Malczewski (2006) [14] have noted that AHP is powerful in assessment of hydrological data. It is also quite popular in Indian groundwater studies due to its clarity and flexibility to professional knowledge (Yadav *et al*., 2014; Rahmati *et al*., 2016; Pourtaghi & Pourghasemi, 2014). [31, 22, 19]

- Application of AHP in the case of the Upper Luni Basin is in the following ways:
- Nested cataloging of objective (e.g. groundwater potential)
- Building of pair wise comparison matrices by thematic layers
- Computation of weight by eigenvalue methods
- CI and CR evaluation of consistency index (CI) and ratio (CR) consistency index (CI) and consistency ratio (CR)
- GIS-based WOA Weighted integration

The AHP derived weights are then applied on the overlay procedures resulting in maps of groundwater potential terms that divide the area into low/low, moderate and high recharge areas. The testability of AHP in defining aquifer recharge zones, it can be done with the support of Kumar *et al*. (2016) [11], Sahoo *et al*. (2021) [24], and Gheisari *et al*. (2020) [7].

6. Discussion

Evaluation of groundwater of arid and semi arid countries such as the upper luni river basin has been a growing interest to scholars, due to the rising levels of groundwater depletion and pollution. An increased number of publications focus on the integrated methods which combine the remote sensing, GIS, statistical methods and hydrological models as the means of assessing the groundwater resources more accurately.

The permanent depletion of groundwater is one of the major findings that was dominant throughout the state of Rajasthan. Such non-parametric tools as the Mann-Kendall trend test and Sen estimator of the slope of the regression have been seen in widespread use in quantifying this phenomenon. As an example, Kumar *et al*. (2022) [12] reported that between 0.5 and 1.4 meters had been lost annually in areas west of Rajasthan, and this loss was caused by over pumping with the usage of tube wells and long-term aridity. These findings support those of the Tripathi and Choudhury (2016) [29] study, in which the authors determined that the significant downward trends in water table were statistically revealed in semi-arid districts in India, and this situation was even exacerbated by low rates of ground-water recharge and ground-water-based irrigation.

Another burning problem is the quality of the groundwater in the basin. In the study by Joshi *et al*. (2020) [9], the authors conducted an extensive hydrochemical assessment and the concentration of fluoride in more than a third of wells was excessive, especially at the pre-monsoon periods. Sky-rocketing of Total Dissolved Solids (TDS) and nitrate were also rampant, occasioned by evaporation-concentration and haphazard application of nitrogenous fertilizers. The same has been reflected by BIS (2019) [2], as per which, many blocks in the states of Jalore, Barmer, and Nagaur were found to be under unsafe having a drinking water index, regarding fluoride and salinity.

The research done by Das and Paul (2018) [4] stressed the importance of Analytic Hierarchy Process (AHP) using thematic layers (slope, geology, land use/land cover (LULC) and drainage density, to reach a proper region of the possible recharge. Their models revealed that low-gradient landscape, fragmented aquifers, and plant cover surfaces were good predictors of the groundwater bank.

A regional example of AHP application was done by Verma *et al*. (2019) [30], who used a combined AHP-Weighted Overlay Analysis (WOA) approach in the state of Rajasthan and tested similarly with an equal correlation (R 2 = 0.83) between the predicted high-potential areas and observed borewell productivity. Their validation methodology, dreading of field sampling and comparison of yields proved the ensurement in multi-criteria framework. On the same note, Al-Adamat *et al*. (2012) [1] have also proved this methodology to be flexible in drylands of Jordan indicating that it could be applicable in hydrologically distressed regions in any part of the world.

Soil texture and permeability, following the Food and Agriculture Organization (FAO) classification, have turned out to be very important factors in GWPZ modeling. Thakur and Thomas (2017) [28] communicated that sandy-loam soils, as a consequence of their larger infiltration capacity, were the main source of groundwater recharge, while clay-rich soils were the obstacles. Their paper indicated that soil properties were the major factors that determined approximately 20% of the total weightage of ground water potential modeling in semi-arid Gujarat.

Remote sensing datasets like CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) and MODIS (Moderate Resolution Imaging Spectroradiometer) have improved the accuracy of spatial rainfall and vegetation monitoring, correspondingly. For hydrological quality mapping, IDW interpolation is still the most popular technique. Sharma and Khandelwal (2021) [27] employed IDW for the creation of nitrate concentration and salinity maps and found that there was a close spatial autocorrelation between agro-industrial activities and pollutant concentrations. Zhou *et al*. (2019) [33] in a methodological review, urged for the use of the revised IDW algorithms in order to have better interpolation precision in geologically heterogeneous regions.

There is growing interest in combining machine learning (ML) models with conventional techniques. Mishra *et al*. (2021) [18] evaluated the effectiveness of AHP-based GWPZ models against Random Forest (RF) and Support Vector Machine (SVM) algorithms and found that ML models provided better spatial accuracy, particularly when working with big datasets that had non-linear relationships. Kisi *et al*. (2020) [13], who emphasized the superior predictive capability of ensemble learning methods for hydrogeological applications, corroborate their findings.

When taken as a whole, these studies highlight how effective a multidisciplinary framework is for evaluating groundwater. A strong and repeatable methodology is provided by combining statistical trend analysis, field-based observations, and geospatial modeling using programs like AHP, IDW, and WOA. Such integrated approaches are essential for sustainable groundwater management and policy planning, as shown in the Upper Luni River Basin and similar dryland regions.

7. Conclusion

In the Upper Luni River Basin, ongoing overuse of groundwater resources has escalated to critical levels due to the growing effects of climate change. The necessity of implementing integrated geospatial approaches to systematically track groundwater trends, evaluate temporal and spatial quality variations, and pinpoint possible recharge zones is highlighted by this review. Together, the results of several previous studies show that the basin is experiencing severe hydrological stress, as evidenced by falling water tables, deteriorating water quality, and an unequal distribution of groundwater supplies.

The use of instruments such as the Mann-Kendall trend test has demonstrated efficacy in identifying non-seasonal and non-linear variations in groundwater levels, providing policymakers with early warning indicators. Similar to this, the use of spatial interpolation methods like IDW and Water Quality Index (WQI) evaluations has made it easier to comprehend water quality parameters in detail, especially the dangerously high levels of fluoride, nitrate, and total dissolved solids. This has highlighted the necessity of focused water treatment methods even more, particularly in areas judged unfit for agricultural or drinking use.

Analytical Hierarchy Process (AHP) and Weighted Overlay Analysis (WOA) mapping of the Groundwater Potential Zone (GWPZ) has produced a more nuanced understanding of recharge potential throughout the basin. These techniques provide decision-makers with spatially accurate information, backed by thematic layers such as slope, geology, LULC, rainfall, and soil type. The strong relationship between GWPZ outputs and actual well yields demonstrates the practical applicability of these approaches in semi-arid regions such as western Rajasthan and confirms their robustness.

Prioritizing strategic interventions is necessary in light of the growing demand for groundwater brought on by industrialization, urbanization, and agriculture. In designated high-potential zones, artificial recharge via managed aquifer recharge (MAR) systems, check dams, and percolation tanks should be expanded. Additionally, to lessen the volumetric stress on aquifers, a move toward water-efficient agricultural techniques like sprinkler and drip irrigation is crucial.

The foundation of any groundwater governance model should be stakeholder engagement and community participation. The Luni Basin should adopt localized water management strategies that have demonstrated encouraging results in other areas, such as groundwater user associations and village-level water budgeting. To facilitate prompt data exchange and coordinated response mechanisms, institutional cooperation between government agencies, local governing bodies, and research bodies needs to be improved.

Future studies must concentrate on real-time groundwater monitoring systems that are connected to telemetry units and Internet of Things-based sensors. More responsive and flexible management is made possible by the dynamic data that these systems can offer on water quality variations, recharge volumes, and extraction rates. Prediction accuracy and scenario planning under various climatic and land-use futures can be further enhanced by fine-scale hydrological modeling employing machine learning and ensemble modeling techniques.

The requirement for thorough aquifer mapping at the micro-watershed scale is equally crucial. Determining aquifer boundaries, evaluating storage capacities, and comprehending recharge-discharge relationships can all be aided by thorough hydrogeological surveys in conjunction with isotopic and tracer studies. When creating efficient recharge structures and putting groundwater conservation policies into action, these insights will be essential.

Last but not least, combining climate adaptation plans with groundwater planning will guarantee the Upper Luni Basin's water systems' long-term resilience. It will be crucial to comprehend how precipitation, evapotranspiration, and groundwater recharge interact as rainfall variability rises. This calls for a paradigm change away from discrete groundwater assessments and toward a more comprehensive, inclusive, data-driven, and future-ready framework for managing water resources.

In summary, this review has shown that although the groundwater resources in the Upper Luni River Basin face significant obstacles, these obstacles are not insurmountable. The secret to ensuring groundwater sustainability in this crucial but vulnerable area of India lies in the convergence of contemporary geospatial tools, participatory governance, and adaptive management.

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