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ASSESSMENT AND VALIDATION OF GROUNDWATER POTENTIAL ZONES USING ANALYTICAL HIERARCHY PROCESS (AHP) AND OBSERVED YIELD DATA IN THE CENTRAL KHARUN RIVER BASIN, CHHATTISGARH, INDIA

SUBHADARSINI J.[1*], JHARIYA D.C.[2], VIDYARTHI V.K.[3], SAHU M.[4]

[1]Research Scholar, Department of Applied Geology, National Institute of Technology Raipur, G.E Road, Raipur-492010, Chhattisgarh, India
[2] Associate Professor, Department of Applied Geology, National Institute of Technology Raipur, G.E Road, Raipur-492010, Chhattisgarh, India
[3]Assistant Professor, Department of Civil Engineering, National Institute of Technology Raipur, G.E Road, Raipur-492010, Chhattisgarh, India
[4]Assistant Professor, Department of Information Technology, National Institute of Technology Raipur, G.E Road, Raipur-492010, Chhattisgarh, India

(*) jsubhadarsini.phd2022.geo@nitrr.ac.in

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ABSTRACT

Groundwater is an essential natural resource used in multiple grounds such as municipal, agricultural, and industrial water supply. To sustainably manage groundwater resources, it is important to assess groundwater potential zones (GWPZs). This study adopted a combination of the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) techniques to systematically assess and map groundwater availability zones within the Central Kharun River basin, which is located in parts of Durg and Raipur Districts of Chhattisgarh, India. Thematic layers are created for nine significant factors, including depth to groundwater level, lithology, rainfall, soil, slope, geomorphology, lineament, drainage density, and land use and land cover (LULC) of the study region. These thematic layers are prepared by using GIS techniques. Based on relative contributions of each factor in groundwater occurrence, weights have been assigned using the AHP method. The model results have been validated against 15 observed well yields from monitoring wells by plotting the receiver operating characteristic (ROC) curve and area under the curve (AUC). Overall, the study classifies the basin into three distinct GWPZs: low, moderate, and high. Sensitivity analysis (SA) highlights that groundwater level exhibits highest mean sensitivity index ($SI = 0.39$), followed by lithology ($SI = 0.24$) and rainfall ($SI = 0.15$), indicating them as the most significant factors that influence GWPZs. The findings of the analysis demonstrate the effectiveness of the integrated

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AHP-GIS approach and provide valuable guidance for the planning and sustainable resource management of groundwater resources.

Keywords: Analytical Hierarchy Process (AHP), GIS, Groundwater potential zones (GWPZs), Central Kharun river basin, Observed well yield.

INTRODUCTION

With rapid growing population and to meet the increased water demand, groundwater is highly exploited as it is one of the fresh forms of water on earth. It is not merely a source of drinking water for humans but also supports various other functions (Chaudhari et al., 2022; Rusli et al., 2024), including agricultural irrigation, industrial activities, and maintenance of wetland and aquatic ecosystems. The volume of water resources stored within aquifers can be estimated through a variety of methods, each offering its own distinctive merits and scientific value (Chibane and Ali-Rahmani, 2015; El Moukhayar et al., 2015; Bemmoussat et al., 2017; Hountondji et al., 2020; Jaiswal et al., 2023; Rajput et al., 2023; Deb, 2024; Qureshi et al., 2024). Groundwater constitutes nearly 97% of all available freshwater resources globally, excluding glaciers and ice caps, making it an essential component of the hydrological cycle and a critical buffer against surface water variability (Ouis, 2012; Famiglietti, 2014; Ngouala et al., 2016; Fatemi and Molavi, 2025).

In developing nations such as India, groundwater accounts for more than 60% of irrigated agriculture and approximately 85% of rural drinking water supply, underscoring its irreplaceable role in sustaining food security and public health (Giordano, 2006; Aroua, 2018; Baba Hamed, 2021; Aroua, 2022; 2023; Ihsan and Derosya, 2024). As a result of increased aridity and decreased water supplies in many areas due to global warming, water scarcity may grow increasingly worldwide (Remini, 2020). So, it is important to understand the region-specific problems in terms of groundwater availability, which can help in effective and sustainable management of this resource.

However, Inadequate effective implementation of sustainable water resource management practices can result in adverse effects on outcomes such as decline in groundwater levels, land degradation, deterioration of water quality, and other socio-economic and environmental issues (Kumar et al., 2014; Belhadj et al., 2017; Chaudhari et al., 2021; Sourogou et al., 2021; Singh et al., 2022; Pandey et al., 2022; Lachache et al., 2023; Sahu et al., 2024; Mohamad et al., 2024; Chabokpour et al., 2025).

Water table declination observed across several Indian states, including Chhattisgarh, Madhya Pradesh, and Rajasthan, is a direct consequence of unregulated groundwater extraction that significantly exceeds natural recharge rates (Gaaloul, 2015; Remini, 2019), and has been further aggravated by erratic monsoon patterns and increased agricultural water demand (CGWB, 2022). Addressing this growing crisis necessitates a scientifically rigorous, spatially explicit understanding of groundwater availability and recharge dynamics at the basin scale (Gleeson et al., 2012). Addressing this challenge requires advanced techniques and tools to enhance the planning and management in a sustainable way in the field of water resource development (Paulo-Monteiro and Costa-Manuel, 2004; Bahir et al., 2015; Jayasena et al., 2021; Ouattara et al., 2022; Kezzar and Souar, 2024).

Groundwater potential (GWP) assessment is a crucial process for acquiring knowledge on groundwater availability in an area. Traditional methods for groundwater exploration such as borehole drilling and geophysical survey are although effective, often costly and time-consuming, and very limited in spatial extent (Remini, 2025); therefore, the integration of GIS with Multi-criteria decision making (MCDM) approaches offers a more efficient and comprehensive alternative for GWP assessment. Though very precise and point specific, the traditional hydrogeological exploration approach suffers from a limitation due to failure in representing the spatial heterogeneity of hydrogeological parameters over large and topographically diverse basins (Todd and Mays, 2004). On the other hand, GIS-based techniques (Saadi et al., 2016; Faregh and Benkhaled, 2016; Adja et al., 2021) permit incorporation of multiple hydrogeological, geomorphological and climatological factors at one time on a large spatial scale and can be used to assess GWP across the basin as a whole with less time consumption and expenditure (Magesh et al., 2012). Such a practice is being adopted extensively in South Asia, Africa, and Middle East due to paucity of data and financial limitations for traditional subsurface investigation (Rahmati et al., 2015).

GIS provides an effective platform for managing, analyzing ad visualizing complex geospatial data. A diverse remotely sensed data covering extensive and inaccessible regions, which can be effectively managed and analyzed within a GIS platform. It also offers valuable details concerning the factors that govern the presence and dynamics of groundwater, encompassing aspects like topography, geology, stratigraphy, structural controls, geomorphological features, soil, Land use land cover (LULC), and other features (Thakur et al., 2017). The advent of freely accessible satellite datasets such as Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs), Landsat, and Sentinel imagery has further democratized the application of GIS in groundwater studies, enabling researchers in data-scarce regions to derive critical thematic layers including drainage density, lineament density, slope, and land use without reliance on expensive proprietary datasets (Mitra and Roy, 2023). In the Indian context, datasets provided by the National Remote Sensing Centre (NRSC) and Bhuvan geoportal have proven particularly valuable for basin-scale hydrogeological mapping, offering high-resolution topographic and land cover data tailored to Indian physiographic conditions (Krishnamurthy et al., 2014).

In addition, AHP approach further simplifies the problems into a hierarchical structure of to simplify the importance of above-mentioned aspects in acquiring zones as per availability of groundwater occurrence. The AHP is a MCDM model (Chowdhury et al., 2010; Mehta et al., 2024) within a GIS environment, and the term is first introduced by Thomas Saaty (1980). It is one of the most widely employed MCDM methods in hydrogeology studies, facilitating structured assignment of weights to key factors using pairwise comparisons that minimize subjectivity and enhance the accuracy of groundwater potential assessment.

Researchers from all over the world have investigated GWPZ identification by utilizing GIS and remote sensing (RS) techniques for a better understanding of subsurface occurrence of water (Mukherjee et al., 2012; Das, 2017; Lakshmi and Reddy 2018; Nithya et al., 2019; Patel et al., 2022, Ying et al., 2023). According to Murmu et al., (2019), this technique serves as most productive and efficacious approach to managing spatial data. It also offers a method of evaluating and measuring input to establish ratio scale priorities for each factor. These priorities facilitate the allocation of influences among different factors. Nithya et al., (2019) have applied AHP and GIS techniques to assess GWPZs in the Chittar basin, Tirunelveli district of Tamil Nadu. More similar study has been carried out by Saranya and Saravanan (2020). They have mapped GWPZs in Kancheepuram District, Tamil Nadu, India and found out that the most influencing factors such as geomorphology, drainage density and precipitation are majorly influencing the groundwater occurrence spatially and successively categorized the area into five zones as per potential nature for storing water. Comparable multi-criteria GIS-based studies conducted in other parts of peninsular India have consistently highlighted the dominant role of geological structure, lineament density, and drainage morphometry in controlling groundwater occurrence in hard rock terrains (Prasad et al., 2008; Jha et al., 2010). In the central Indian context, studies conducted in the Mahanadi basin and its tributaries have demonstrated that the integration of geomorphological and geological thematic layers within a GIS-AHP framework produces GWPZ maps with validation accuracies exceeding 75% when compared against field-measured bore well yield data, affirming the suitability of this approach for the Kharun River Basin which shares similar lithological and structural characteristics (Thakur et al., 2017; Nag and Chakraborty, 2003).

Achu et al., (2020) have conducted mapping of GWPZs in a tropical river basin using RS, GIS, and AHP techniques and identified different zones as per groundwater availability. Study highlighted that, integration of these techniques and tools can be used in regional groundwater management where data are limited. The study further demonstrated that even in data-limited tropical environments, a carefully selected suite of thematic layers including geomorphology, geology, lineament density, soil, drainage density, slope, and rainfall can collectively explain a substantial proportion of the spatial variability in groundwater occurrence, provided that appropriate relative weights are assigned through a systematic AHP-based evaluation process (Achu et al., 2020). This finding supports scalability and transferability of the GIS-AHP methodology to other tropical and semi-arid river basins, including the Central Kharun River basin in Chhattisgarh, where similar data constraints prevail and where hydrogeological complexity demands a robust multi-criteria spatial evaluation framework (Fashae et al., 2014).

In the present study, steps to GWPZs assessment consist of (a) thematic layer preparation of various factors using GIS techniques for the study area, (b) weight derivation for each factor by applying AHP approach, and (c) assessing the GWPZs by applying weighted overlay analysis for the Central Kharun River basin. The required data are gathered from different sources.

The structure of this paper is divided into 5 sections. After introduction in section 1, section 2 describes about the geographical location of the study region and other information such as total area covered and prevailing climatic conditions. Materials and methodology are described in section 3 of this paper, where thematic layers are described, representing spatial variability in terms of geological, hydrogeological and structural setup of the study region, followed by a description of AHP-based weightage derivation and overlay analysis. Results and conclusion are constricted in section 4 and 5, respectively. This research aims to conduct systematic evaluations of GWPZs by integrating field investigations, GIS, and AHP approach.

STUDY AREA

The central Kharun river basin (Fig.1), a tributary of the Shivnath River, has been chosen as the study region. This region is spread across parts of Durg and Raipur districts in Chhattisgarh, India and is located within the latitude range of 21°0'0" to 21°25'0" and the longitude range of 81°20'0" E to 81°46'0". The entire area of this region is approximately 1,131.74 km^2. Groundwater recharge in the area mainly occurs through rainfall received during southwest monsoon. The average annual rainfall in Durg and Raipur district is approximately 1052mm and 1370 mm, respectively. Kharun River in the region exhibits dendritic drainage pattern influenced by the underlying geological control. The study area is characterized by limestone dominated hard rock terrain exhibiting an elevation variation range from 188 to 285 meters above mean sea level (m amsl) (Fig. 1). The slope value across the Central Kharun River basin varies from 0 to 81.4 degrees, with most areas featuring gentle to moderate inclines (0 to 14 degrees). Pediplain, alluvial plain, point bar, river channel, and other water bodies are the major geomorphological landforms of the study area. Most of the area is dominated by pediplain with a characteristic gentle sloping surface, shaped by extensive erosional activity. The main river flows from south towards the north direction of the study area.

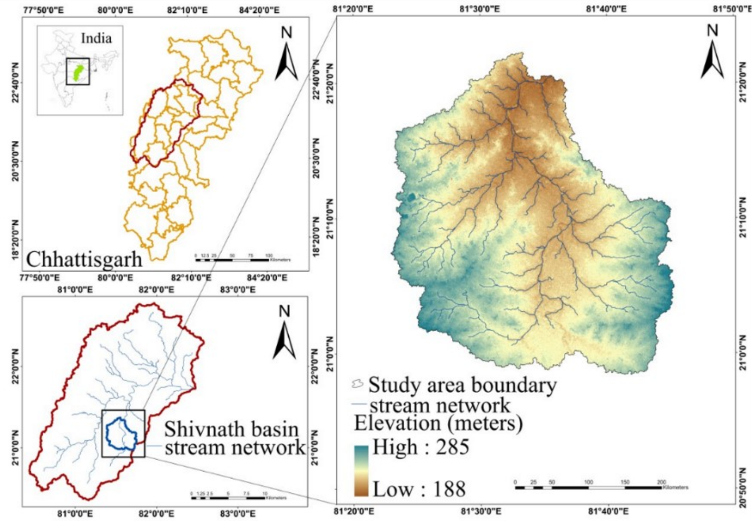

Figure 1: Location map of the Central kharun river basin

MATERIAL AND METHODOLOGY

All relevant hydrogeological and climatic datasets required for the assessment of GWPZs are collected and processed to generate thematic layers. This section represents the step-by-step preparation of these thematic layers and describes the application of AHP approach used for determining their weightage and execution overlay analysis.

Thematic layer preparation

To identify GWPZs in the Central Kharun river basin, nine factors including groundwater level (GL), lithology (LL), rainfall (RF), soil (SL), slope (SP), geomorphology (GM), lineament (LT), drainage density (DD), and LULC are taken into consideration. A systematic procedure is followed in order to accurately demarcate possible GWPZs within the river basin. The process has involved the preparation of nine thematic layers, for which digital elevation models, and other required data have been gathered from multiple sources as mentioned in the Table 1, and thematic layers are generated in ArcGIS software. Field investigation is carried out in the pre-monsoon period of 2024 to gather information about depth to the groundwater level from spatially distributed wells in the study region. Groundwater levels are measured from 63 dug wells to observe the groundwater dynamics throughout the study region. Using ArcGIS tools, LULC, soil, and Lithology are extracted and prepared for overlay analysis. GIS methodologies have been used in the process of GWPZs demarcation to ensure that the data is accurately analyzed and interpreted. The resulting thematic layers provide valuable insights into the study region, making it simpler to locate possible groundwater occurrence. The accuracy and reliability of the outcomes have been ensured by the careful and precise handling of the procedure. Fig. 2 illustrates the adopted systematic methodology for GWP assessment.

Table 1: Description of data sources

SN	Data	Spatial resolution	Source
1	*GL*	5×5 km grid	Field investigation (level measurement in mbgl)
2	*LL*	-	https://bhukosh.gsi.gov.in/
3	*RF*	$(0.25^\circ \times 0.25^\circ)$	Indian Meteorological Department
4	*SL*	-	https://www.fao.org/
5	*DEM*	12.5	Alaska Satellite Facility DAAC
6	*GM*	-	https://bhukosh.gsi.gov.in/
7	*LT*	30m	Bhuvan
8	*LULC*	10m	https://livingatlas.arcgis.com/landcoverexplorer/

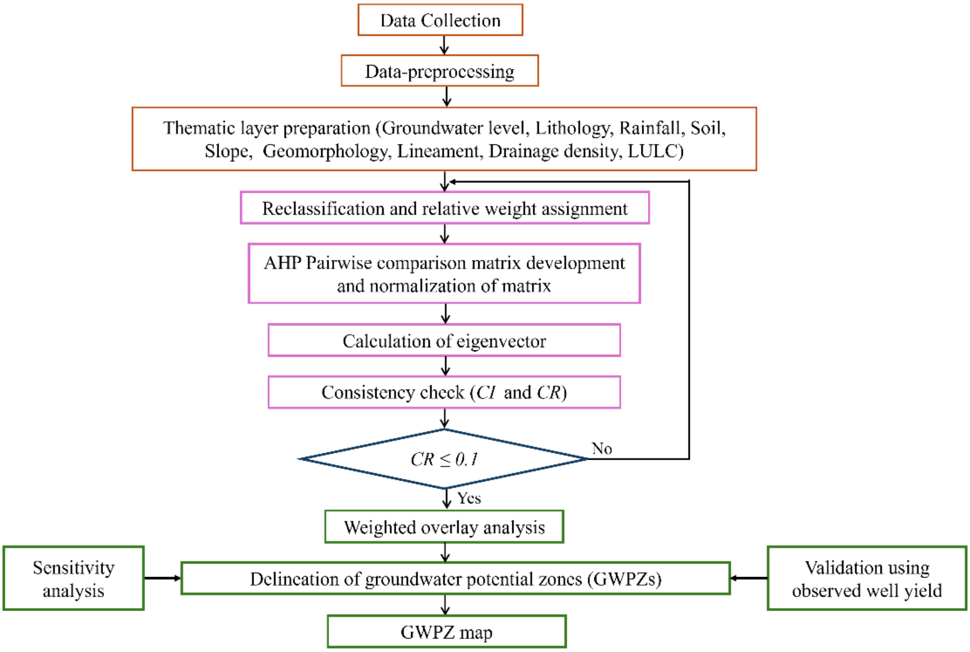

Figure 2: Methodology flow chart

DEM data with a 12.5-meter resolution is processed to create drainage density and slope thematic layers by using line density and surface tools, respectively. Inverse distance weighted (IDW) and kriging methods are used to prepare spatial distribution thematic map of rainfall and groundwater level map respectively.

Groundwater level

Groundwater level is an essential parameter in hydrogeology. It holds significant importance in groundwater availability and accessibility. Groundwater levels fluctuate based on factors such as geological variation, drainage density, distribution of lineaments, precipitation, LULC, and more (Chowdhury et al., 2010). Contour maps have been generated by utilizing pre-monsoon water level data. For which groundwater level data are collected from different locations which spatially distributed throughout the study area. Levels are measured from a total of 63 dug wells with the help of water level sensor detector instrument. The water levels vary from 4m to greater than 10m, which are considered very shallow, shallow, medium, deep, and very deep, respectively (Fig. 3a). Groundwater level directly indicates the groundwater availability. In case of shallow level, groundwater availability is high as compared to the deeper level of groundwater occurrence.

Lithology

Understanding the characteristics of rocks is crucial in assessing the scenario of groundwater occurrence in a region, as lithology significantly impacts porosity and permeability properties of aquifers. Type of rock directly influence the occurrence, movement, and storage of water. Dolomitic stromatolitic limestone dominates and covers maximum area with some localized occurrence of dolomitic limestone with sandstone, shale, laterite, and ferruginous sandstone in the study region (Fig. 3b). Groundwater occurrence within this rock formation is highly controlled by secondary porosity such as solution cavities, joints and fractures. In this case permeability is highly dependent on development of solution cavities and fractures within the limestone formation. Due to porous and permeable nature of this rocks favour for water storage and movement within the interconnected passages and contribute as a highly rated factor after water level for groundwater occurrence within the Central Kharun River basin.

Rainfall

Rainfall is essential for sustaining groundwater levels by replenishing aquifers and recharging underground water sources that are essential for sustaining water supplies. Spatial variation of rainfall governs the rate of groundwater recharge from area to area. Abundant rainfall results in water sources for subsurface recharge, while insufficient precipitation leads to lower levels of recharge. Total five distinct classifications have been done as per rainfall receives by the area (Fig. 4a). The area receives rainfall between 798-915 mm/year is classified as very low, in between 915-990 mm/year as low, 990-1059 mm/year as moderate, 1059 -1147 mm/year as high and very high for area receives rainfall in between the range of 1147-1242 mm/year. Each distinct class has been assigned a corresponding rank to facilitate a comprehensive mapping of groundwater availability, ensuring a structured and quantitative approach to the analysis.

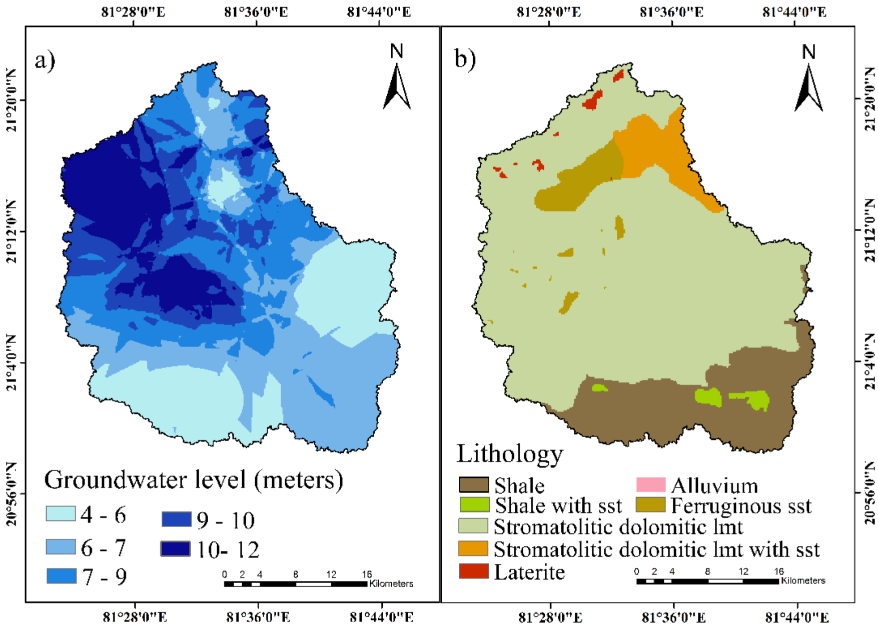

Figure 3: (a) Groundwater level map and (b) Lithology map of the study region

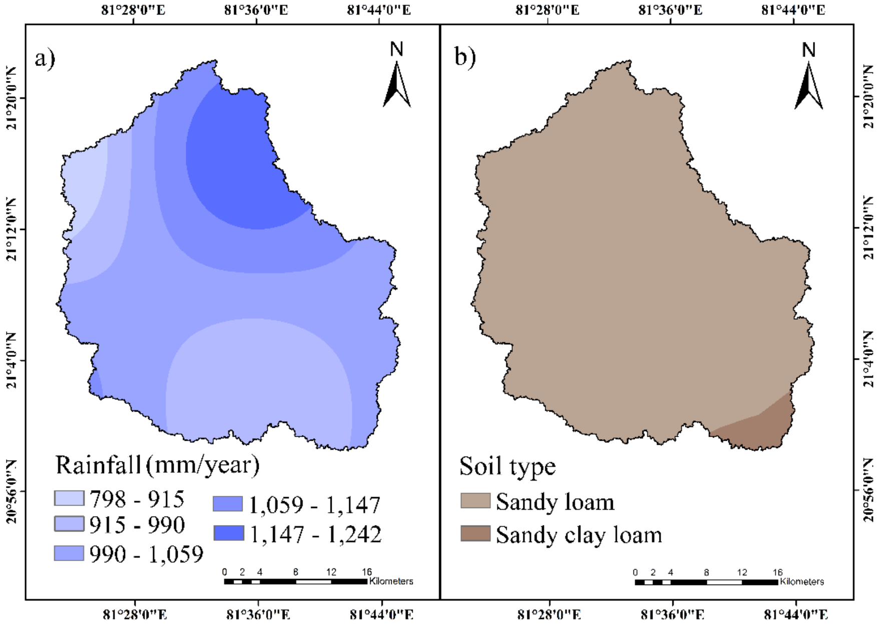

Figure 4: (a) Rainfall map and (b) Soil map of the study region

Soil

The recharge of groundwater and surface runoff is significantly controlled by the composition of soil. According to studies, recharge process depends on a number of variables, including soil types, infiltration rate, percolation, and permeability (Kaliraj et al., 2014; Murmu et al., 2019). Sandy loam and sandy clay loam is predominantly present within the study region (Fig. 4b). Soil porosity and permeability property dependent on the size of the grains. Small grain size produces very tiny pores and reduces permeability.

Slope

Slope of the terrain is also an important factor and it has a remarkable impact on how effectively water is able to move downward and percolate through soil layer. According to research (Patra et al., 2018; Shao et al., 2020), a lower slope is favourable for maximum infiltration of water, while a higher slope can limit this process. It's worth noting that a majority of the study region features a slope of 1 to 6 degrees, which is particularly conducive to greater infiltration (Fig. 5a).

Geomorphology

Geomorphology is an important factor that gives general information about occurrence of different landforms in an area (Shao et al., 2020). In the Central Kharun river basin predominant landforms are river, pediplain, alluvial plain, Point bar and other water bodies (Fig. 5b). Among all these features, Pedi plains and alluvial plains show moderate infiltration properties.

Lineament

Fig. 6a illustrates the spatial distribution of lineaments in the study area. Lineament refers to the structural alignment of internal components of a rock along a one-dimensional plane. Digital elevation model images can help to get a better comprehension of the topographic elevation and assist in identifying linear features (Dasgupta and Mukherjee 2019). In this study, the region is classified as very low for lineament density falling in between 0-0.19 km/km^2), low lineament density for value in between 0.19-0.39 km/km^2, moderate value in between 0.39-0.59 km/km^2 for moderate density, high for 0.59-0.78 km/km^2 density, and very high for 0.78-0.98 km/km^2, according to occurrence of lineaments. Lineament factor has been assigned a low to moderate overall weightage because of moderate significance control over water occurrence.

Drainage density

Drainage density is a key factor that offers observations into hydrological processes. The distribution and frequency of natural drainage networks play an important role in influencing movement, recharge, and storage of water in subsurface zone within a given area. It is measured as the total length of all drainage channels per unit area.

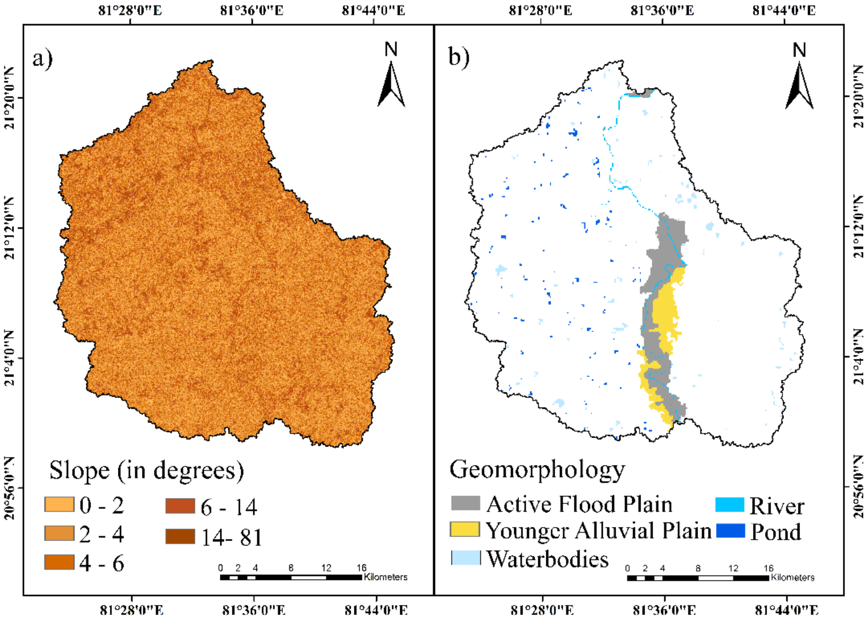

Figure 5: (a) Slope map and (b) Geomorphology map of the study region

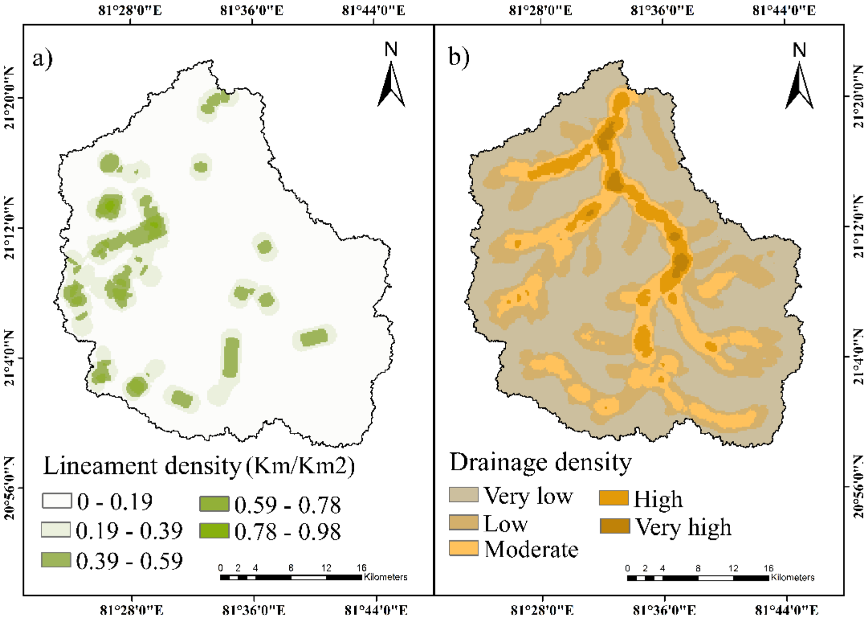

Figure 6: (a) Lineament density map and (b) Drainage density map of the study region

Lower density facilitates higher infiltration rates, whereas higher density contributes to high runoff (Tucker and Bras 1998; Sulaiman and Mustafa 2023). Fig. 6b shows five distinct zones as per drainage density.

LULC

LULC means the lands that are modified by human activities. There is a complex relationship between LULC and groundwater dynamics. Multiple land cover has different kind of control over water occurrence as it controls the infiltration rate of rainwater. In Central Kharun River basin, dominant land types are such as water bodies, forest and vegetation cover, crop land, built areas, bare ground, and range land (Fig. 7a). Rating assignments to each land type are based on their infiltration characteristics and reclassified accordingly. Increased paved land due to human settlement leads to a restriction in rainfall infiltration to the subsurface zone. Other land types somewhat more or less contribute water to the underlying zone, which helps in good recharge in that area.

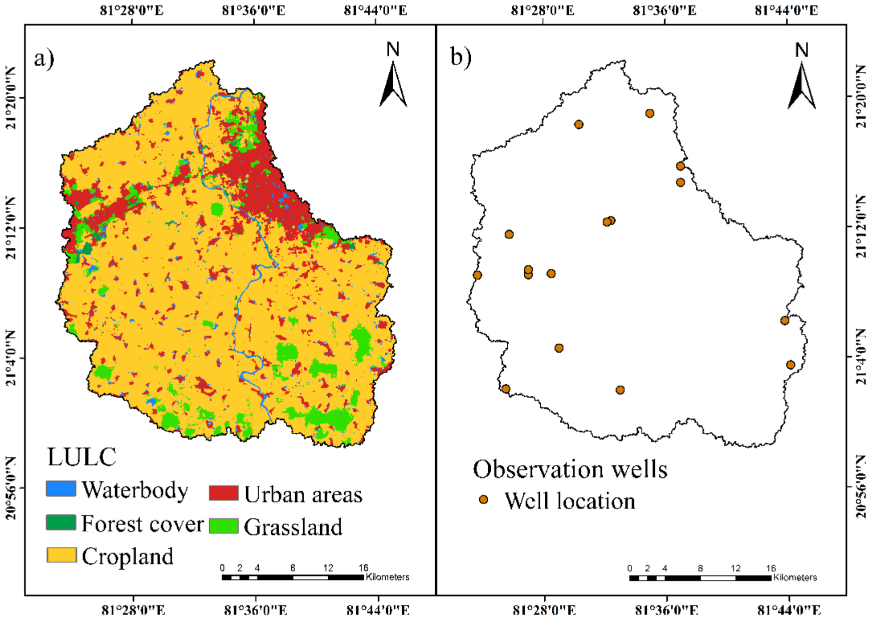

Figure 7: (a) LULC map and (b) Observation well location map of the study region

AHP based weight derivation

AHP is a decision-making process that simplifies problems in a structured manner and it requires expert knowledge to construct pair wise comparison matrix by assigning correct ranks and weights to each factor. Pairwise comparisons are a fundamental aspect of AHP (Saaty, 1987) that uses ratio scales to measure the relative strength of preferences based on discrete and continuous paired comparisons.

In the first step, a pairwise comparison matrix has been prepared by comparing relative influence of each factor with every other factor on groundwater occurrence based on hydrogeological knowledge, field understanding, and insights from previous studies. Table 2 presents matrix created for nine thematic layers such as GL, LL, RF, SL, SP, GM, LT, DD, and LULC, which have been widely considered as significant factors influencing groundwater occurrence (Indhulekha et al., 2019; Jaiswal et al., 2023; Ande et al., 2025). Groundwater level, lithology and rainfall have been given higher importance over other factors because of their more significant control over groundwater storage and movement.

Table 2: Pair-wise Comparison matrix

	GL	***LL***	***RF***	***SL***	***SP***	***GM***	***LT***	***DD***	***LULC***
GL	1	2	2.5	3	4	5	6	7	8
LL	0.5	1	1.5	1.84	2	3	4	6	7
RF	0.4	0.67	1	1.5	2	2.5	3.5	4.5	5.5
SL	0.33	0.54	0.67	1	1.8	2	3	4	5
SP	0.25	0.5	0.5	0.56	1	1.5	2	3	4
GM	0.2	0.33	0.4	0.5	0.67	1	1.5	2	3
LT	0.17	0.25	0.29	0.33	0.5	0.67	1	1.5	2
DD	0.14	0.17	0.22	0.25	0.33	0.5	0.67	1	1.5
LULC	0.13	0.14	0.18	0.2	0.25	0.33	0.5	0.67	1
Sum	3.1	5.6	7.3	9.2	12.6	16.5	22.2	29.7	37

The constructed matrix utilizes Saaty's 1 – 9 scale (Table 3) to assign relative weights to factors for delineating GWPZs. A scale value of 1 denotes equal importance between two factors, whereas a scale value of 9 denotes that one factor is extremely more important than the other. Other numeric values for relative importance are listed in the following table.

Table 3: Saatys 1 to 9 scale

Scale	**Importance**
1	Equal Importance
2	Weak importance
3	Moderate
4	Moderate plus
5	Strong Importance
6	Strong plus
7	Very strong
8	Very, very strong
9	Extreme importance

Following this, the Comparison matrix has been normalized to derive the eigenvector of each thematic layer, with the normalized matrix presented in Table 4.

Table 4: Normalized comparison matrix with eigen vector

	GL	*LL*	*RF*	*SL*	*SP*	*GM*	*LT*	*DD*	*LULC*	**Eigen vector**
GL	0.32	0.36	0.34	0.33	0.32	0.3	0.27	0.24	0.22	0.3
LL	0.16	0.18	0.21	0.2	0.16	0.18	0.18	0.2	0.19	0.18
RF	0.13	0.12	0.14	0.16	0.16	0.15	0.16	0.15	0.15	0.15
SL	0.11	0.1	0.09	0.11	0.14	0.12	0.14	0.13	0.14	0.12
SP	0.08	0.09	0.07	0.06	0.08	0.09	0.09	0.1	0.11	0.09
GM	0.06	0.06	0.06	0.05	0.05	0.06	0.07	0.07	0.08	0.07
LT	0.05	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.04
DD	0.05	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03
LULC	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.02

In AHP, principal eigenvalue (λ_{max}) and consistency are determined to account for judgemental uncertainty. To check the reliability of assigned weights and address uncertainty, λ_{max}, Consistency index (*CI)*, and Consistency ratio (*CR*) have been evaluated based on the approach proposed by Saaty (2004). *CI* can be computed by using Eq. (1):

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{1}$$

where *n* is the number of factors. The average of consistency vector determines value of λ_{max}. For the present study, 9 factors with values 9.17, 9.13, 9.13, 9.1, 9.05, 9.06, 9.05, 9.03 and 9.04, the calculated λ_{max} is 9.08. The Corresponding *CI* value is 0.0105. Calculated consistency vector and λ_{max} is presented in Table 5.

Table 5: Calculation of consistency vector

	GL	*LL*	*RF*	*SL*	*SP*	*GM*	*LT*	*DD*	*LULC*	**Consistency Vector**
GL	0.3	0.37	0.37	0.36	0.34	0.31	0.27	0.23	0.2	9.17
LL	0.15	0.18	0.22	0.22	0.17	0.19	0.18	0.2	0.17	9.13
RF	0.12	0.12	0.15	0.18	0.17	0.16	0.16	0.15	0.14	9.13
SL	0.1	0.1	0.1	0.12	0.15	0.13	0.13	0.13	0.12	9.1
SP	0.07	0.09	0.07	0.07	0.09	0.09	0.09	0.1	0.1	9.05
GM	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.07	9.06
LT	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.05	0.05	9.05
DD	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	9.03
LULC	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	9.04

Further, *CR* has been determined using following Eq. (2).

$$CR = \frac{CI}{RI} \tag{2}$$

where, *RI* denotes Random consistency index.

The *RI* value corresponding to each *n* number of factors is represented in Table 6. In this case, $n = 9$, the *RI* is 1.45 and the resulting *CR* is 0.007. The *CR* value has been compared against the commonly accepted threshold ($CR \leq 0.10$) as recommended in previous studies (Malczewski 1999; Thanh et al., 2022). Since the calculated value of *CR* (0.007), which is well below this threshold value, the comparison matrix is considered consistent and suitable for further analysis, thereby confirming the reliability of the derived AHP weights.

Table 6: Random consistency Index

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

Overlay Analysis

After deriving the eigenvector using AHP, an overlay analysis is carried out to demarcate GWPZs in the Central Kharun River basin. This process begins with the preparation and reclassification of nine thematic layers of nine factors, each representing a key parameter influencing groundwater occurrence and movement. The factors include *GL*, *LL*, *RF*, *SL*, *SP*, *GM*, *LT*, *DD*, and *LULC*. In several studies (Agarwal et al., 2016; Shailaja et al., 2019; Saranya and Saravanan 2020; Kubingwa et al., 2023), *GL* and *LL* have been selected as key thematic layers for GWP assessment. The study area exhibits unconfined aquifer conditions within limestone dominated terrain, where groundwater occurrence is primarily controlled by lithological characteristics and developed secondary porosity, such as fractures and solution cavities. Under such hydrogeological setup, groundwater level and lithological conditions serve as direct indicators of groundwater availability. Further, rainfall is commonly integrated as a thematic layer because it significantly influences groundwater occurrence. Higher rainfall generally enhances recharge, leading to good potential of groundwater occurrence, whereas lower rainfall reduces recharge and consequently results in low groundwater potential. In addition to *GL*, *LL*, and *RF*, other factors such as *SL, SP, GM, LT, DD*, and *LULC* (Das et al., 2019; Chaudhry et al., 2021; Golla et al., 2022) are widely used as thematic layers within the AHP model for the assessment of GWPZs. These factors collectively influence surface runoff, infiltration, storage characteristics, resulting in spatial distribution of GWPZs.

Each thematic layer is reclassified and assigned a rating value based on a scale value ranges from 1 to 5, where 1 denotes the least influence and 5 denotes the highest influence on groundwater potential. These ratings are determined based on the relative importance of each factor, derived from field observations, published literature, and expert judgment.

The assigned rating values for each class within the thematic layers are presented in Table.7.

Table 7: Thematic layers classification and scale value

Thematic Layers	Classification	Scale Value	Normalized Weight
Groundwater level	4-6 m	5	0.3
	6-7 m	4	
	6-9 m	3	
	9-10 m	2	
	>10 m	1	
Lithology	Dolomitic limestone with sandstone	5	0.18
	Dolomitic Limestone	4	
	Shale	1	
	Laterite	4	
	Ferruginous Sandstone	3	
Rainfall	Very Low rainfall	1	0.15
	Low rainfall	2	
	Moderate rainfall	3	
	High rainfall	4	
	Very High rainfall	5	
Soil	Sandy loam	5	0.12
	Sandy clay Loam	4	
Slope	0-2.0	5	0.09
	2.0-4.0	4	
	4.0-6.0	3	
	6.0-14.0	2	
	14.0-81.0	1	
Geomorphology	Waterbody	5	0.07
	River	5	
	Point Bar	4	
	Pediplain	5	
	Alluvial Plain	5	
Lineament	Very low *LT*	1	0.04
	Low *LT*	2	
	Moderate *LT*	3	
	High *LT*	4	
	Very high *LT*	5	
Drainage density	Very low *DD*	5	0.03
	Low *DD*	4	
	Moderate *DD*	3	
	High *DD*	2	
	Very high *DD*	1	
LULC	Waterbody	3	0.02
	Trees	4	
	Vegetation cover	4	
	Crops ground	4	
	Built up Area	1	
	Bare Ground area	2	
	Range Land area	2	

Once reclassification is complete, the eigenvector values derived from the AHP are assigned to each layer. These eigenvectors provide normalized weights. These values serve as weights that reflect relative influence of each factor in the overall analysis (Fig. 8). The weighted overlay analysis is then performed in a GIS environment, where each thematic layer is the result of multiplication of corresponding normalized weight, and the products are summed to generate the final GWPZs map. Eq. 3 is the mathematical expression for GWPZs assessment.

$$GWPZ = \Sigma\left(GL_W \times GL_r\right)+\left(LL_W \times LL_r\right)+\left(RF_W \times RF_r\right)+\left(SL_W \times SL_r\right)+\left(SP_W \times SP_r\right)+ \left(GM_W \times GM_r\right)+\left(LT_W \times LT_r\right)+\left(DD_W \times DD_r\right)+\left(LULC_W \times LULC_r\right) \quad (3)$$

Where, *GL*= Groundwater level, *LL*= Lithology, *RF*= Rainfall, *SL*= Soil, *SP*= Slope, *GM*= Geomorphology, *LT*= Lineament, *DD*= Drainage Density, *LULC*= Land use land cover. The weight and rate of influencing factors are denoted by subscripts *w* and *r* respectively.

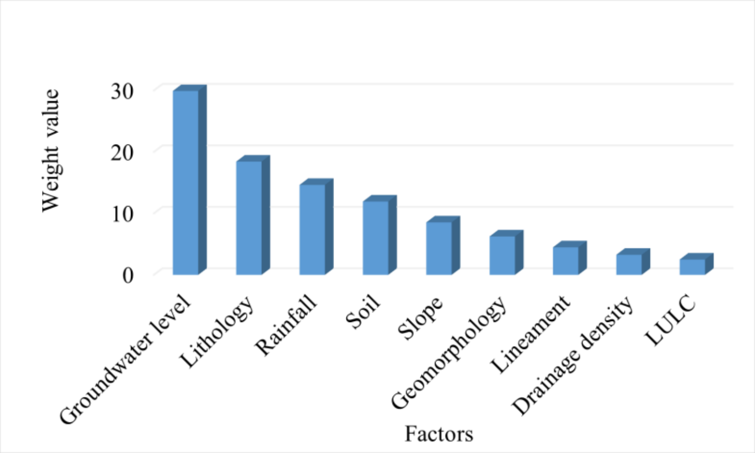

Figure 8: Weightage of various factors

Sensitivity analysis

Sensitivity analysis (SA) is a process in which model input parameters are varied to assess their impact on model output (Crosetto et al., 2000; Bagheri et al., 2013). SA helps in evaluating the impact of individual thematic layers that influence the groundwater potential. Map removal sensitivity analysis (Lodwick et al., 1990) is a commonly used method that involves systematic exclusion of a single thematic layer at a time from the weighted overlay model, followed by the recalculation of the GWPZs using normalized weights for the remaining layers (Babiker et al., 2005). The sensitivity of the model was quantified using the sensitivity Index (*SI*), calculated as the mean absolute difference between the original and modified GWPZ maps Eq. (4).

$$SI = 1/n\sum_{i=1}^{n} | GWPZ_i - GWPZ_i^{'} | \quad (4)$$

Where, SI denotes the sensitivity index, n is the total number of cells, $GWPZ_i$ and $GWPZ_i'$ represents the GWP value at cell i in the original GWPZ map and value at the same cell after removal of a thematic layer, respectively. A higher value of the SI indicates that the corresponding thematic layer has a greater influence on GWP and produces more visible changes in the GWPZ map. Similarly, lower value of SI demonstrates that the corresponding thematic layer has a low impact on GWPZ map.

RESULTS AND DISCUSSION

Groundwater Potential Zone Identification and Validation

The integration and weighted overlay analysis of several thematic layers, each of which represents unique hydrogeological and environmental features that affect groundwater occurrence, are used to define GWPZ. The study region is divided into three groundwater potential classes: low, moderate, and high GWPZs based on the cumulative groundwater potential index, as shown in Fig. 9 (a). Each zone covers a specific area of 335.8 km^2 (29.72%), 298.5 km^2 (26.42%), and 495.8 km^2 (43.87%), respectively, and has its own characteristics. This observed heterogeneous distribution of GWP throughout the basin is due to the combined effects of all hydrogeological and geomorphological factors. GWPZ map reveals that the high GWPZ covers a major portion of the study area, indicating favorable zones for groundwater availability, as these areas are underlain by favorable lithological formations and experience good natural recharge conditions due to higher infiltration and suitable geomorphological settings. Unfavorable controlling factors such as higher slope gradients, lower infiltration rates, and restricted development of weathered or fractured zones may be responsible for low GWP in the northwestern and southern regions. These various subsurface characteristics are reflected through uneven spatial distribution of GWPZs.

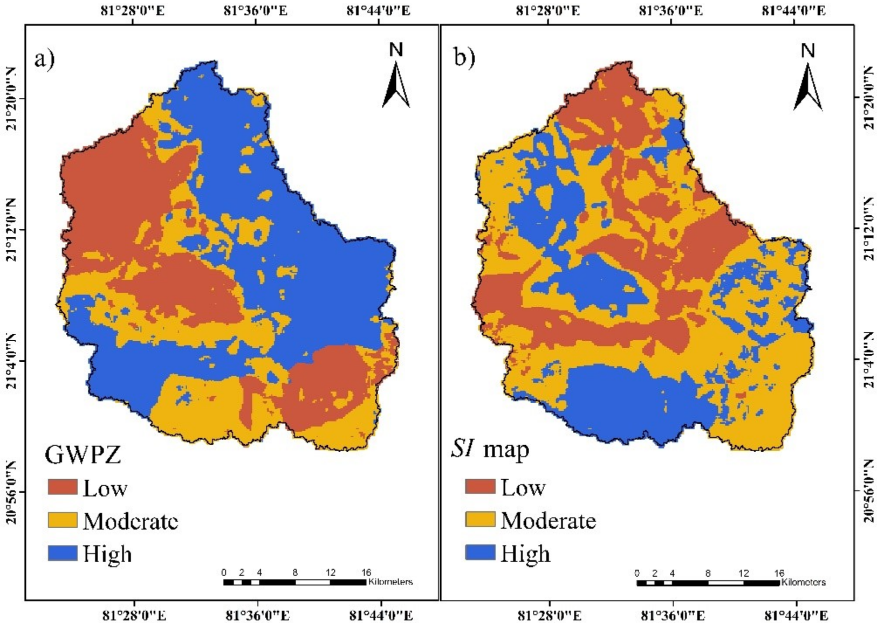

Figure 9: (a) Groundwater potential zone (GWPZ) map and (b) *SI* map showing spatial variation after removal of GL layer

Table 8: Validation and comparison of assessed GWP with the observed well yield

SL. No	Longitude	Lattitude	Observed well yields (lps)
1	81.6167	21.2458	3.5
2	81.73	21.1037	0.8
3	81.6167	21.2625	2.1
4	81.5833	21.3167	1.75
5	81.7361	21.0583	3
6	81.3944	21.1514	0.27
7	81.5056	21.3056	3.15
8	81.5403	21.2069	0.5
9	81.55	21.0333	3.5
10	81.4292	21.1931	3
11	81.475	21.1528	0.5
12	81.45	21.1517	4
13	81.4833	21.0764	0.5
14	81.5361	21.2056	3
15	81.45	21.1569	3.3

There are multiple approaches for validating the GWPZ map created using AHP method. Among these, receiver operating characteristic (ROC) curve analysis and area under curve (AUC) are the most widely used statistical tools for evaluating the accuracy of predictive models (Pourtaghi et al., 2014; Al-Shabeeb et al., 2018; Das 2019; Rajasekhar et al., 2019). In the present study, ROC analysis was carried out using groundwater well yield data by comparing observed values with predicted GWPZs. A total of 15 observation wells (Table 8), sourced from CGWB, are located throughout the study region (Fig. 7b). The well yields are classified as low (<0.92 lps), medium (0.92-3.55 lps), and high (>3.55 lps). The ROC curve was created by plotting the True Positive Rate (TPR) against the False Positive Rate (FPR) at different threshold levels (Fig. 10). Here, TPR represents the proportion of high-yield wells correctly identified as high groundwater potential zones, whereas FPR represents the proportion of low-yield wells incorrectly classified as high potential zones. To construct the ROC curve, different threshold values were applied to convert groundwater potential classes into binary categories.

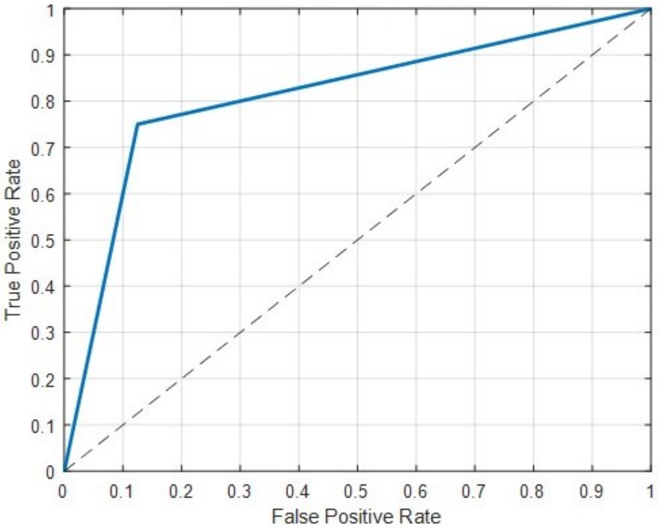

Figure 10: Micro-average ROC curve of AHP model (AUC = 0.812)

AUC value of the ROC curve was found to be approximately 0.812, indicating good predictive performance of the groundwater potential model. Based on previous studies (Razandi et al., 2015, Ramesh and Iqbal 2022), category of AUC value corresponding to predictive accuracy is presented in Table 9. As per the accuracy classification, AUC value of 0.812 falls within the very good category. It suggests that AHP weight-based model has good predictive capability.

Table 9: Accuracy classification of AUC

AUC value	Accuracy category
0.5-0.6	Poor
0.6-0.7	Average
0.7-0.8	Good
0.8-0.9	Very good
0.9-1	Excellent

Sensitivity analysis of GWPZs

SA was performed by using Raster calculator tool in the ArcGIS environment to evaluate the most significant factors that influence the GWPZs. Recalculated GWPZ map was prepared by removing individual thematic layer. The statistical parameters, such as minimum, maximum, mean, and standard deviation (SD) were derived for each removed thematic layer. The results of this analysis are presented in Table 10. Based on mean *SI*, the statistical results of SA reveal that groundwater level (*SI*=0.39*)* is the most influential factor, followed by lithology (*SI*=0.24) and rainfall (*SI*=0.15). Fig. 9 (b) illustrates that noticeable changes in potential zones were observed after removal of groundwater level thematic layer.

Table 10: Statistics of sensitivity analysis

Removed thematic layer	***SI***			
	Min	Max	Mean	SD
GL	0	1.08	0.39	0.24
LL	0	0.52	0.24	0.13
RF	0	0.48	0.15	0.09
SL	0	0.36	0.06	0.05
SP	0	0.29	0.12	0.07
GM	0	0.18	0.04	0.04
LT	0	0.17	0.07	0.03
DD	0	0.14	0.05	0.03
LULC	0	0.12	0.02	0.02

CONCLUSION

A comprehensive collection of data from various sources is gathered and analyzed to demarcate potential zones of groundwater occurrence in the Central Kharun River basin. AHP, GIS-based approaches have been employed in the present study to categorize distinct GWPZs within study region. Application of AHP technique enabled a systematic integration of thematic layers of all influencing factors to assess GWPZs. Final outcome demarcates three distinct zones, such as low, moderate, and high GWPZs as per groundwater availability. Most parts of the study region fall under the high category of groundwater potential, which demonstrates a favorable scope for utilization of groundwater for various purposes sustainably. On the other hand, north-western and southern regions are reflecting low groundwater availability, pointing towards the need for water management strategies and recharge structure interventions. GWPZ map highlights that, areas receiving a sufficient amount of rainfall and underlain by highly porous and permeable rocks exhibit high GWP within the study area. In contrast, low GWPZs primarily stem from unfavorable lithological conditions, particularly regions dominated by shale and shale with sandstone, which are less porous and less permeable, impeding groundwater storage and movement. These areas also receive less amount of rainfall, further limiting infiltration and percolation processes. Sensitivity analysis in the current work highlights that most influential factors are depth to groundwater level, lithology and rainfall. The findings of this present research can be considered as a foundation for the sustainable utilization and management of groundwater resources, enabling planners and managers of water resources to make decisions. The identified GWPZs can help policymakers prioritize locations for groundwater development and control that are sustainable. While low potential zones need immediate attention through artificial recharge, rainfall storage, and conservation techniques, high potential zones can be implemented for controlled extraction. The created geographic database can facilitate the development of groundwater management strategies tailored to a given area and encourage effective water resource distribution. Additionally, government organizations can use the scientific and repeatable foundation that the integration of AHP and GIS offers for long-term sustainability and evidence-based groundwater planning. Although the identified GWPZs in the study region is validated with the available well yield in the regions, there are certain limitations of this study which may be the source of uncertainties. The weight calculated in the AHP analysis is based on the expert hydrological knowledge which is one of the sources of uncertainty in the weight calculation. These weights may be calculated by using the advanced optimization techniques. Another avenue for the uncertainties in analysis is the smaller number of wells in the current study and the process would have better validated in the region where the number of wells is more in number. It is hoped that future research will be focused towards few of these limitations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

ACHU A.L., THOMAS J., REGHUNATH R. (2020). Multi-criteria decision analysis for delineation of groundwater potential zones in a tropical river basin using remote sensing, GIS and analytical hierarchy process (AHP), Groundwater for Sustainable Development, Vol. 10, pp. 100-365.

ADJA M.G., ASSANDE A.A., DJEMIN E.J., SORO S.I., JOURDA J.P. (2021). Contribution of a GIS to mapping and spatial-temporal characterization of rainfall variability: case of the northern part of Ivory Coast, Larhyss Journal, No 47, pp. 119-132.

AGARWAL, R., GARG, P.K. (2016). Remote sensing and GIS based groundwater potential & recharge zones mapping using multi-criteria decision-making technique, Water Resources Management, Vol. 30, pp. 243-260.

AL-SHABEEB, A.A.R., AL-ADAMAT, R., AL-FUGARA, A. K., AL-AMOUSH, H., ALAYYASH, S. (2018). Delineating groundwater potential zones within the Azraq Basin of Central Jordan using multi-criteria GIS analysis, Groundwater for Sustainable Development, Vol. 7, pp. 82-90.

ANDE, R., BIRBAL, P.Y., KANNAN, S., MEHTA, D., NIGAM, M. (2025). Assessment of Groundwater Storage and Urban Temporal Variations using GRACE Satellite Data: Case Study of Cooum river basin, India, Journal of Environmental Informatics Letters, Vol. 14, pp. 1-19.

AROUA N. (2018). Water resources in SNAT 2030. between economic needs and ecological requirements, Larhyss Journal, No 35, pp. 153-168. (In French)

AROUA N. (2022). Long term city development versus water strategy in Al-Maghreb, Larhyss Journal, No 50, pp. 173-197.

AROUA N. (2023). Setting out urban water issues examples from Algeria and worldwide, Larhyss Journal, No 56, pp. 309-327

BABA HAMED S. (2021). Impact of water pollution on public health and the environment in Oran, Larhyss Journal, No 45, pp. 203-222.

BABIKER, I.S., MOHAMED, M.A., HIYAMA, T., KATO, K. (2005). A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan, Science of the Total Environment, Vol. 345, pp. 127-140.

BAGHERI, M., SULAIMAN, W.N.A., VAGHEFI, N. (2013). Application of geographic information system technique and analytical hierarchy process model for land-use suitability analysis on coastal area, Journal of Coastal Conservation, Vol. 17, pp. 1-10.

BAHIR M., EL MOUKHAYAR R., CARREIRA P. SOUHEL A. (2015). Isotopic tools for groundwater management in semi-arid area: case of the wadi Ouazzi basin (Morocco), Larhyss Journal, No 23, pp. 23-39.

BELHADJ M.Z., BOUDOUKHA A., AMROUNE A., GAAGAI A., ZIANI D. (2017). Statistical characterization of groundwater quality of the northern area of the basin of Hodna, M'sila, southeastern Algeria, Larhyss Journal, No 31, pp. 177-194. (In French)

BEMMOUSSAT A., ADJIM M., BENSAOULA F (2017). Use of the ZYGOS model for the estimation of groundwater recharge in Sikkak watershed (Northen west of Algeria), Larhyss Journal, No 30, pp. 105-119. (In French)

CGWB (Central Groundwater Board). (2022). Annual Report on Dynamic Ground Water Resources of India, Ministry of Jal Shakti, Government of India, New Delhi, pp. 1-303.

CHABOKPOUR J., AZAMATHULLA H.M.D., NAMPALLI R.C.R., SYED S. (2025). Unraveling complex discharge-water quality dynamics, Larhyss Journal, No 62, pp. 107-128.

CHAUDHARI, A.N., MEHTA, D.J., SHARMA, D.N.D. (2021). An assessment of groundwater quality in South-West zone of Surat city, Water Supply, Vol. 21, pp. 3000-3010.

CHAUDHARI, A.N., MEHTA, D.J., SHARMA, N.D. (2022). Coupled effect of seawater intrusion on groundwater quality: study of South-West zone of Surat city, Water Supply, Vol. 22, pp. 1716-1734.

CHAUDHRY, A.K., KUMAR, K., ALAM, M.A. (2021). Mapping of groundwater potential zones using the fuzzy analytic hierarchy process and geospatial technique, Geocarto International, Vol. 36, pp. 2323-2344.

CHIBANE B., ALI-RAHMANI S.E. (2015). Hydrological based model to estimate groundwater recharge, real- evapotranspiration and runoff in semi-arid area, Larhyss Journal, No 23, pp. 231-242.

CHOWDHURY A., JHA M.K., CHOWDARY V.M. (2010). Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques, Environmental Earth Sciences, Vol. 59, pp. 1209-1222.

CROSETTO, M., TARANTOLA, S., SALTELLI, A. (2000). Sensitivity and uncertainty analysis in spatial modelling based on GIS, Agriculture, Ecosystems & Environment, Vol. 81, pp. 71-79.

DASGUPTA S., MUKHERJEE S. (2019). Remote sensing in lineament identification: examples from western India, Developments in Structural Geology and Tectonics, Vol. 5, pp. 205-221.

DAS, B., PAL, S.C., MALIK, S., CHAKRABORTTY, R. (2019). Modeling groundwater potential zones of Puruliya district, West Bengal, India using remote sensing and GIS techniques, Geology, Ecology, and Landscapes, Vol. 3, pp. 223-237.

DAS S. (2017). Delineation of groundwater potential zone in hard rock terrain in Gangajalghati block, Bankura district, India using remote sensing and GIS techniques, Modeling Earth Systems and Environment, Vol. 3, pp. 1589-1599.

DEB S. (2024). Optimizing hydrological exploration through GIS-based groundwater potential zoning in Gomati district, Tripura, India, Larhyss Journal, No 60, pp. 231-256.

EL MOUKHAYAR R., BAHIR M., CARREIRA P. (2015). Estimation of groundwater recharge in arid region through hydrochemistry and isotope: a case study Kourimat basin Morocco, Larhyss Journal, No 23, pp. 87-104.

FAMIGLIETTI J.S. (2014). The global groundwater crisis, Nature Climate Change, Vol. 4, pp. 945-948.

FAREGH W., BENKHALED A. (2016). GIS based SCS-CN method for estimating runoff in Sigus watershed, Larhyss Journal, No 27, pp. 257-276. (In French)

FASHAE O.A., TIJANI M.N., TALABI A.O., ADEDEJI O.I. (2014). Delineation of groundwater potential zones in the crystalline basement terrain of SW-Nigeria: An integrated GIS and remote sensing approach, Applied Water Science, Vol. 4, pp. 19-38.

FATEMI S.M., MOLAVI A. (2025). Comparative study of machine learning models in predicting water table fluctuations in Azarshahr Plain, Iran, Larhyss Journal, No 61, pp. 343-369.

GAALOUL N. (2015). Modeling of underground flows in unsaturated porous medium: application to artificial recharge by treated wastewater - Korba coastal water table (cap-bon, Tunisia), Larhyss Journal, No 21, pp. 181-190. (In French)

GIORDANO M. (2006). Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: A first-cut assessment, Hydrogeology Journal, 14, 310-318.

GLEESON T., WADA Y., BIERKENS M.F.P., VAN BEEK L.P.H. (2012). Water balance of global aquifers revealed by groundwater footprint, Nature, Vol. 488, pp. 197-200.

GOLLA, V., BADAPALLI, P.K., TELKAR, S.K. (2022). Delineation of groundwater potential zones in semi-arid region (Ananatapuram) using geospatial techniques, Materials Today: Proceedings, Vol. 50, pp. 600-606.

HOUNTONDJI B., CODO F.P., AINA M.P. (2020). Characterization of hydrogeological conditions from the Monzoungoudo groundwater reservoir in Benin, Larhyss Journal, No 41, pp. 223-232. (In French)

IHSAN T., DEROSYA V. (2024). Drinking water problems in rural areas: review of point-of-use methods to improve water quality and public health, Larhyss Journal, No 58, pp. 55-71.

INDHULEKHA, K., CHANDRA MONDAL, K., JHARIYA, D.C. (2019). Groundwater prospect mapping using remote sensing, GIS and resistivity survey techniques in Chhokra Nala Raipur district, Chhattisgarh, India, Journal of Water Supply: Research and Technology Aqua, Vol. 68, pp. 595-606.

JAISWAL T., JHARIYA D., SINGH S. (2023). Identification and mapping of groundwater potential zone using analytical hierarchy process and GIS in lower Kharun basin, Chhattisgarh, India, Larhyss Journal, No 53, pp. 117-143.

JAYASENA H.A.H., RATHNAYAKE R.D.D.P., CHANDRASENA M.G.P.N., RANATHUNGA B.P.D.W. (2021). A classic example of urban-rural linkages through ancient Voda Ela in Sri Lanka - symbiosis of total environment on efficient water management, Larhyss Journal, No 47, pp. 59-82.

JHA M.K., CHOWDARY V.M., CHOWDHURY A. (2010). Groundwater assessment in Salboni Block West Bengal (India) using remote sensing, geographical information system and multi-criteria decision analysis techniques, Hydrogeology Journal, Vol. 18, pp. 1713-1728.

KALIRAJ S., CHANDRASEKAR N., MAGESH N.S. (2014). Identification of potential groundwater recharge zones in Vaigai upper basin, Tamil Nadu, using GIS-based analytical hierarchical process (AHP) technique, Arabian Journal of Geosciences, Vol. 7, pp. 1385-1401.

KEZZAR M., SOUAR A. (2024). The water management system in the village of Menades in Algeria between past and present, Larhyss Journal, No 57, pp. 55-79.

KRISHNAMURTHY J., MANAI A., JAYARAMAN V., MANIVEL M. (2014). Groundwater resources in hard rock areas using remote sensing and GIS, International Journal of Applied Earth Observation and Geoinformation, Vol. 7, pp. 45-58.

KUBINGWA, J.N., MAKOBA, E.E., MUSSA, K.R. (2023). Integrated geospatial and geophysical approaches for mapping groundwater potential in the semi-arid Bukombe District, Tanzania, Earth, Vol. 4, 241-265.

KUMAR T., GAUTAM A.K., KUMAR T. (2014). Appraising the accuracy of GIS based multi-criteria decision-making technique for delineation of Groundwater potential zones, Water Resources Management*,* Vol. 28, pp. 4449-4466.

LACHACHE S., DERDOUR A., MAAZOUZI I., AMROUNE A., GUASTALDI E. (2023). Statistical approach of groundwater quality assessment at Naama region, South-West Algeria, Larhyss Journal, No 55, pp. 125-144.

LAKSHMI S.V., REDDY Y.V.K. (2018). Identification of groundwater potential zones using GIS and remote sensing, International Journal of Pure and Applied Mathematics, Vol. 119, pp. 3195-3210.

LODWICK, W.A., MONSON, W., SVOBODA, L. (1990). Attribute error and sensitivity analysis of map operations in geographical information systems: suitability analysis, International Journal of Geographical Information System, Vol. 4, pp. 413-428.

MAGESH N.S., CHANDRASEKAR N., SOUNDRANAYAGAM J.P. (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques, Geoscience Frontiers, Vol. 3, pp. 189-196.

MALCZEWSKI J. (1999). GIS and multi-criteria decision analysis, Book, 1st Edition, John Wiley & Sons, Burnaby, Canada, 392p.

MEHTA, D., PATEL, P., SHARMA, N., ESLAMIAN, S. (2024). Comparative analysis of DRASTIC and GOD model for groundwater vulnerability assessment, Modeling Earth Systems and Environment, Vol. 10, pp. 671-694.

MITRA R., ROY D. (2023). Delineation of groundwater potential zones through the integration of remote sensing, geographic information system, and multi-criteria decision-making technique in the sub-Himalayan foothills region, India, International Journal of Energy and Water Resources, Vol. 7, pp. 581-601.

MOHAMAD N.D., ABDUL HAMID N.S., RAMLI R.R., AHMAD KAMAL N., ABDUL ADIS A.A. (2024). Water quality assessment at royal Belum state park, Perak, Malaysia, Larhyss Journal, No 57, pp. 101-120.

MUKHERJEE P., SINGH C.K., MUKHERJEE S. (2012). Delineation of groundwater potential zones in arid region of India: A remote sensing and GIS approach, Water Resources Management, Vol. 26, pp. 2643-2672.

MURMU P., KUMAR M., LAL D., SONKER I., SINGH S.K. (2019). Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India, Groundwater for Sustainable Development, Vol. 9, pp. 100-239.

NAG S.K., CHAKRABORTY S. (2003). Influence of rock types and structures in the development of drainage network in hard rock area, Journal of the Indian Society of Remote Sensing, Vol. 31, pp. 25-35.

NGOUALA M.M., MBILOU U.G., TCHOUMOU M., SAMBA-KIMBATA M.J. (2016). Characterization surface water - groundwater aquifer in coastal watershed of the republic of Congo Loémé, Larhyss Journal, No 28, pp. 237-256. (In French)

NITHYA C.N., SRINIVAS Y., MAGESH N.S., KALIRAJ S. (2019). Assessment of groundwater potential zones in Chittar basin, Southern India using GIS based AHP technique, Remote Sensing Applications: Society and Environment, Vol. 15, pp. 100-248.

OUATTARA D., DIAWARA H., SOUMAORO L., KONE A.B., GAIDUKOVA E.V. (2022). Realization of a layout and management plan for the Sadiola bottomland in the Koutiala cercle in southern Mali, Larhyss Journal, No 52, pp. 61-76.

OUIS S. (2012). Impact of climatic fluctuations on the quantity and quality of groundwater in a semi-arid region: case of the Ghriss plain (northwest Algeria), Larhyss Journal, No 11, pp. 119-131. (In French)

PANDEY P., MISHRA R., CHAUHAN R.K. (2022). Future prospects in the implementation of a real-time smart water supply management and water quality monitoring system, Larhyss Journal, No 51, pp. 237-252.

PATEL, P., MEHTA, D., SHARMA, N. (2022). A review on the application of the DRASTIC method in the assessment of groundwater vulnerability, Water Supply, Vol. 22, pp. 5190-5205.

PATRA S., MISHRA P., MAHAPATRA S.C. (2018). Delineation of groundwater potential zone for sustainable development: A case study from Ganga Alluvial Plain covering Hooghly district of India using remote sensing, geographic information system and analytic hierarchy process, Journal of Cleaner Production, Vol. 172, pp. 2485-2502.

PAULO MONTEIRO J., COSTA MANUEL S. (2004). Dams' groundwater modelling and water management at the regional scale in a coastal mediterranean area (the southern Portugal region – Algarve), Larhyss Journal, No 3, pp. 157-169.

POURTAGHI, Z.S., POURGHASEMI, H.R. (2014). GIS-based groundwater spring potential assessment and mapping in the Birjand Township, southern Khorasan Province, Iran, Hydrogeology Journal, Vol. 22, pp. 643-662.

PRASAD R.K., MONDAL N.C., BANERJEE P., NANDAKUMAR M.V., SINGH V. S. (2008). Deciphering potential groundwater zone in hard rock through the application of GIS, Environmental Geology, Vol. 55, pp. 467-475.

QURESHI H.U., ABBAS I., SHAH S.M.H., TEO F.Y. (2024). Hydrologic evaluation of monthly and annual groundwater recharge dynamics for a sustainable groundwater resources management in Quetta city, Pakistan, Larhyss Journal, No 60, pp. 27-53.

RAHMATI O., NAZARI SAMANI A., MAHDAVI M., POURGHASEMI H.R., ZEINIVAND H. (2015). Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS, Arabian Journal of Geosciences, Vol. 8, pp. 7059-7071.

RAJASEKHAR, M., RAJU, G.S., SREENIVASULU, Y., RAJU, R.S. (2019). Delineation of groundwater potential zones in semi-arid region of Jilledubanderu river basin, Anantapur District, Andhra Pradesh, India using fuzzy logic, AHP and integrated fuzzy-AHP approaches, Hydro-Research, Vol. 2, pp. 97-108.

RAJPUT D.C., MISTRY K.P., BHORANIYA J.K., UMRIGAR J.N., WAIKHOM S.I. (2023). Assessing the decadal groundwater level fluctuation-a case study of Gujarat, India, Larhyss Journal, No 54, pp. 175-191.

RAMESH, V., IQBAL, S.S. (2022). Urban flood susceptibility zonation mapping using evidential belief function, frequency ratio and fuzzy gamma operator models in GIS: a case study of Greater Mumbai, Maharashtra, India, Geocarto International, Vol. 37, pp. 581-606.

RAZANDI, Y., POURGHASEMI, H.R., NEISANI, N.S., RAHMATI, O. (2015). Application of analytical hierarchy process, frequency ratio, and certainty factor models for groundwater potential mapping using GIS, Earth Science Informatics, Vol. 8, pp. 867-883.

REMINI B. (2019). The Oasis of El Guerrara (Algeria): irrigation and recharge of the aquifers ensured by the floods, Larhyss Journal, No 40, pp. 135-163. (In French)

REMINI B. (2020). Algeria: the climate is changing, the water is becoming scarce, what to do? Larhyss Journal, No 41, pp. 181-221. (In French)

REMINI B. (2025). Algeria's groundwater: an untapped strategic resource for water security, Larhyss Journal, No 61, pp. 401-431.

RUSLI S.R., BENSE V.F., MUSTAFA S.M., WEERTS A.H. (2024). The impact of future changes in climate variables and groundwater abstraction on basin-scale groundwater availability, Hydrology and Earth System Sciences, Vol. 28, Issue 22, pp. 5107-5131.

SAIDI S., AMMAR S., JLASSI F., BOURI S. (2016). Urban expansion and its impact on water resources using remote sensing and GIS: Case of great Tunis, Larhyss Journal, No 28, pp. 87-101. (In French)

SAATY R.W. (1987). The analytic hierarchy process, what it is and how it is used, Mathematical Modelling, Vol. 9, Issues 3-5, pp. 161-176.

SAATY T.L. (2004). Fundamentals of the analytic network process, multiple networks with benefits, costs, opportunities and risks, Journal of Systems Science and Systems Engineering, Vol. 13, pp. 348-379.

SAHU S., SUPE J., RATHORE K., VERMA S., MEHTA D. (2024). An integrated approach for evaluating water quality, Larhyss Journal, No 60, pp. 213-230.

SARANYA, T., SARAVANAN, S. (2020). Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India, Modeling Earth Systems and Environment, Vol. 6, pp. 1105-1122.

SHAILAJA, G., KADAM, A.K., GUPTA, G., UMRIKAR, B.N., PAWAR, N.J. (2019). Integrated geophysical, geospatial and multiple-criteria decision analysis techniques for delineation of groundwater potential zones in a semi-arid hard-rock aquifer in Maharashtra, India, Hydrogeology Journal, Vol. 27, pp. 639-654.

SHAO Z., HUQ M.E., CAI B., ALTAN O., LI Y. (2020). Integrated remote sensing and GIS approach using Fuzzy-AHP to assess and identify groundwater potential zones in semi-arid Shanxi Province, China, Environmental Modelling and Software, Vol. 134, pp. 104-868.

SINGH K., PANDEY P., PANDEY S., MISHRA A.R., TRIPATHI R. (2022). AI-based water quality monitoring of the river Ganga using fuzzy, Larhyss Journal, No 51, pp. 67-85.

SOUROGOU R.M., HOUNTONDJI F.C.C., ZAKARI S., AKOSSOU A.Y.J. (2021). Water quality in Batran, Karakoudarou, Nawari and Tissarou dam reservoirs in the department of Alibori in the northern Benin, Larhyss Journal, No 48, pp. 29-47.

SULAIMAN W.H., MUSTAFA Y.T. (2023). Geospatial multi-criteria evaluation using AHP–GIS to delineate groundwater potential zones in Zakho Basin, Kurdistan Region, Iraq, Earth, Vol. 4, Issue 3, pp. 655-675.

THAKUR J.K., SINGH S.K., EKANTHALU V.S. (2017). Integrating remote sensing, geographic information systems and global positioning system techniques with hydrological modeling, Applied Water Science, Vol. 7, pp. 1595–1608.

THANH N.N., CHOTPANTARAT S., TRUNG N.H., NGU N.H., VAN MUOI L. (2022). Mapping groundwater potential zones in Kanchanaburi Province, Thailand by integrating of analytic hierarchy process, frequency ratio, and random forest, Ecological Indicators, Vol. 145, pp. 109-591.

TODD D.K., MAYS L.W. (2004). Groundwater hydrology, Book, 3rd Edition, John Wiley & Sons, Hoboken, USA, 638p.

TUCKER G.E., BRAS R.L. (1998). Hillslope processes, drainage density, and landscape morphology, Water Resources Research, Vol. 34, Issue 10, pp. 2751-2764.

VAN DER GUN J. (2021). Groundwater resources sustainability, Global Groundwater, pp. 331-345.

WIND Y., SAATY T.L. (1980). Marketing applications of the analytic hierarchy process, Management Science, Vol. 26, pp. 641-658.

YING B., KE L., ZHU F., HE N. (2023). Towards differentiated development policies for mountainous areas: A spatial analysis of mountain distribution and characteristics in a geographic region, Land Degradation and Development, Vol. 34, pp. 5071-5082.