



Groundwater recharge potential zone modeling in the Wadi Al-Lith Basin, Saudi Arabia

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Abstract

The management of groundwater resources is crucial in arid and semi-arid regions such as Al-Lith Basin, and therefore, the identification of suitable areas for groundwater recharge is important in solving the problem of water scarcity and ensuring the long-term sustainability of aquifers. In this study, the Analytic Hierarchy Process (AHP) technique, in conjunction with GIS, was applied to locate potential zones for groundwater recharge in the Al-Lith basin. The research methodology includes collecting the essential data, including lineament density, slope, rainfall, drainage density, LU/LC, soil, elevation, and TWI. AHP is used to assign relative weights to different qualities, considering their significance in influencing groundwater recharge. The ArcGIS was employed to process and analyze the weighted layers, which resulted in the creation of a comprehensive map illustrating the potential for groundwater recharge. The study results suggested that the Al-Lith Subbasin has several zones that exhibit different levels of groundwater recharge capability. The results obtained from this study indicated that 12.83% of the basin area has significant groundwater recharge potential zones (GWPZ), ranging from high to very high levels. The groundwater recharge potential zones in the basin are categorized as very poor to poor, covering 19.4% of the area, while the moderate groundwater recharge potential zones represent 67.77% of the basin area. The groundwater protection zones were validated using 19 wells distributed across the basin. The validation findings indicate there is an overlap between the GWPZ classes and the wells in the specified location. Overall, the findings of this study can enhance groundwater resource management and inform policy development for targeted interventions aimed at enhancing groundwater recharge.

Keywords AHP · GIS · Groundwater recharge · Al-Lith · Saudi Arabia

Introduction

One of the most important natural resources, groundwater, is found in porous spaces and fissures in rock and sediment below the earth's surface (Naghibi et al. 2015). It significantly contributes to ecological harmony, economic development, and human well-being (Prentice et al. 2001). Approximately 30% of the Earth's freshwater resources are stored below as groundwater, whereas surface water, in the form of lakes, marshes, reservoirs, and rivers, constitutes only 0.3%

(Senanayake et al. 2016). The major supply of groundwater is derived from precipitation and snowmelt, which infiltrate into the soil and run through the aquifer via interconnected soil pores. Groundwater utilization is deemed to be a more dependable and potable alternative in contrast to surface water, owing to its enhanced convenience and less susceptibility to contamination (Mallick et al. 2019).

In Saudi Arabia, the country's water requirements from diverse sources are satisfied by a combination of desalinated water, processed water, renewable water resources, and non-renewable fossil water (Rajmohan et al. 2021). The flash flood and rainfall both contribute to the process of recharging the shallow aquifer, which plays an important part in total water use. Similarly, precipitation is one of the primary factors that contributes about 2045 million cubic meters to the country's water storage (Masoud et al. 2018). The agricultural sector uses 84% of groundwater in this nation (Chowdhury and Al-Zahrani 2015). Over-abstraction of groundwater has led to a decline in the amount of water

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stored in shallow aquifers (Zaidi et al. 2015). The storage of groundwater in the shallow aquifer has been reduced as a result of over-abstraction, which has a negative impact on the quantity (Zaidi et al. 2015).

It is crucial to acknowledge that groundwater exploration methods in arid and semi-arid locations have both advantages and constraints. Geophysical surveys, which are traditional procedures, provide an ineffective means to gather data on groundwater potential. However, they need expert staff and may be expensive, and there is a possibility of mistakes of interpretation. On the other hand, the combined method of using remote sensing, GIS, and the Analytical Hierarchy Process (AHP) addresses some drawbacks and provides a more effective and precise evaluation of areas with high potential for groundwater (Kpiebaya et al. 2022).

The determination of the Groundwater Recharge Potential Zone (GRPZ) spatial distribution is contingent upon the accurate mapping and identification of several influencing elements. Hence, the integration of numerous datasets enables the utilization of Geographic Information System (GIS) techniques for the purpose of conducting spatial analysis (Mishra and Sinha 2020). An approach often used for the assessment of several possibilities is the AHP (Rajasekhar et al. 2019; Vahidnia et al. 2009).

Groundwater recharge is influenced by several factors, including lineament density, slope, rainfall, drainage density, Land Use Land Cover (LULC), soil, elevation, and Topographic Wetness Index (TWI) (Khan et al. 2023). The Area of Potential Zone (APZ) was calculated by assigning weights to the factors mentioned before according to their respective contributions to groundwater potentiality. Remote sensing (RS) and geographic information systems (GIS) were used as methodologies for assessing the potentiality of aquifers. The distribution of geographic, hydrogeological, and geological data was facilitated by the use of Geographic Information Systems (GIS). Remote sensing (RS) methods are used to identify land use and land cover (LULC), soil types, and fractures. Subsequently, they transitioned to Geographic Information Systems (GIS) for the purpose of conducting analysis and overlaying data. The Analytic Hierarchy Process (AHP) was used to delineate the APZ (Adiat et al. 2012; Echogdali et al. 2022; Machiwal et al. 2011). The system effectively handles the outputs, and streamlines intricate viewpoints into pairwise series comparisons. In recent times, there has been an increasing use of GIS methods in combination with Multi-Criteria Decision-Making (MCDM) technologies, namely the analytic hierarchy process (AHP), to allocate weights to thematic layers (Saranya and Saravanan 2020). The use of these strategies has been shown to be beneficial in integrating structure, appropriateness, and accuracy into the process of decision-making (Kumar and Krishna 2018; Machiwal et al. 2011). The use of Analytic

Hierarchy Process (AHP) methodologies in the field of environmental problem-solving and management has become more prevalent. Several researchers have used the Analytic Hierarchy Process (AHP) in various applications such as ecological impact assessments (Memarbashi et al. 2017), flood risk mapping (Siddayao et al. 2014; Kazakis et al. 2015; Gigović et al. 2017; Wang et al. 2019; Elsebaie et al. 2023), and solid waste management (Khoshand et al. 2018). One of the most often used and well-executed applications of AHP technology (Arumugam et al. 2023; Dar et al. 2021; Ikirri et al. 2023; Khan et al. 2021, 2022; Radulović et al. 2022; Rajasekhar et al. 2019) pertains to the mapping of prospective groundwater resources and the identification of appropriate locations for recharge.

The main objective of this study is to identify groundwater potential zones (GRPZ) in the Al-Lith Basin using the AHP technique and a GIS method. The research presented a novel approach for managing and making decisions about water resources in a sustainable way by integrating GIS and AHP approaches. The study is organized as follows: Sections 2 and 3 present the case study and data sets, respectively. The methodology is described in Section 4. Section 5 presents the findings, and the discussion is shown in Section 6. The conclusions are reported in Section 7.

Study area

The Wadi Al-Lith Basin is located near the As-Sarawat mountains to the east and north, as well as the Red Sea coast to the west (Fig. 1). The basin of Wadi Al-Lith spans an area of 3089 square kilometers and is estimated to possess a length of 109 kilometers. The geographical coordinates of the location in question fall within the latitudinal range of 20°70'54" to 21°7'7" and the longitudinal range of 40°11'26" to 40°48'44". Al-Laith City, located in Western Saudi Arabia, around 180 km to the southwest of the Holy City of Mecca, is a small urban settlement that benefits from convenient access to prominent international transportation networks. It is located at the end of Wadi Al-Lith farther downstream. The Wadi Al-Lith area is known for its dry environment, ranging from arid to hyperarid conditions. In terms of potential evaporation, the month of July has the greatest monthly average of 200 mm, while February has the smallest potential evaporation at 111 mm (Bashir and Alsalman 2023). There are just a few occasions of precipitation throughout the winter season, which lasts from November to March. During summer, the wind usually moves from the west to southwest, while in winter, it blows from northwest to west. In the month of September, the highest average wind speed recorded is 39 km/h, while the lowest average wind speed is seen to be 17.3 km/h in the month of December.

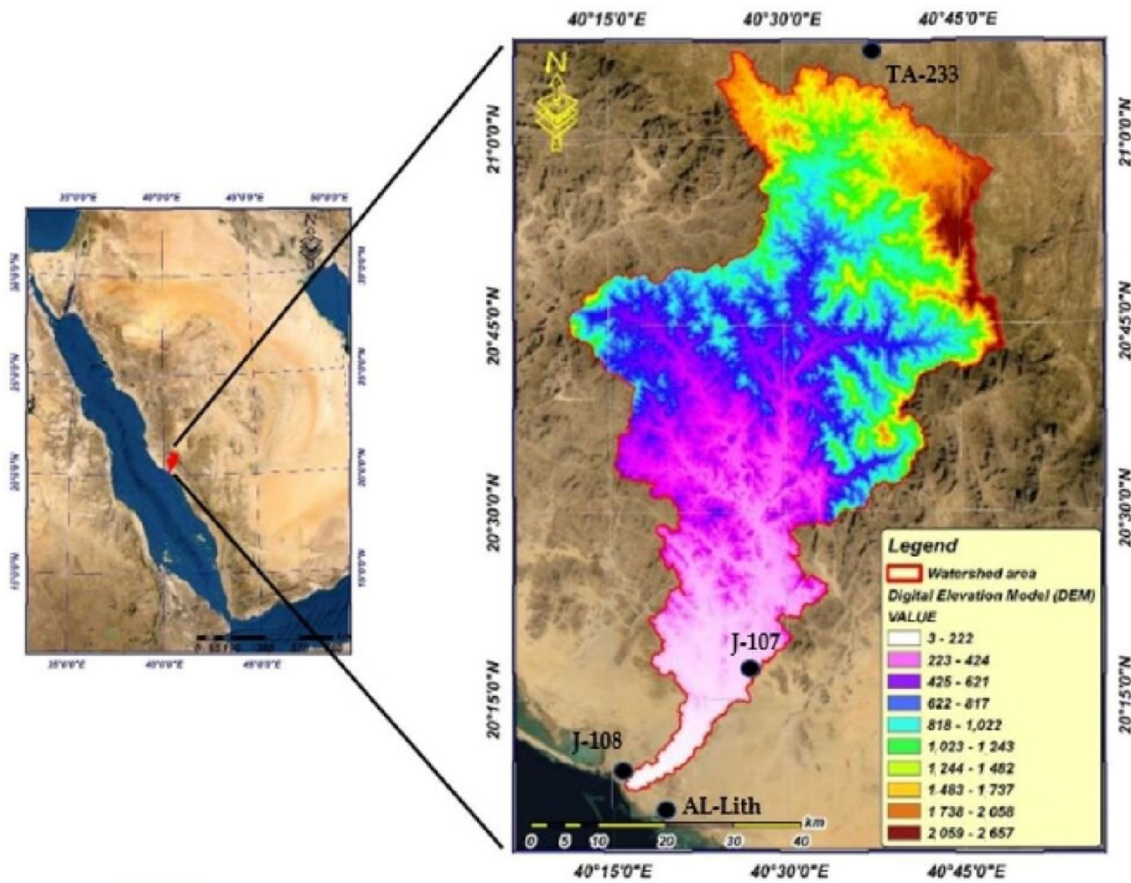


Fig. 1 Coordinates and digital elevation model of Wadi Al-Lith (Elsebaie et al. 2022)

Database

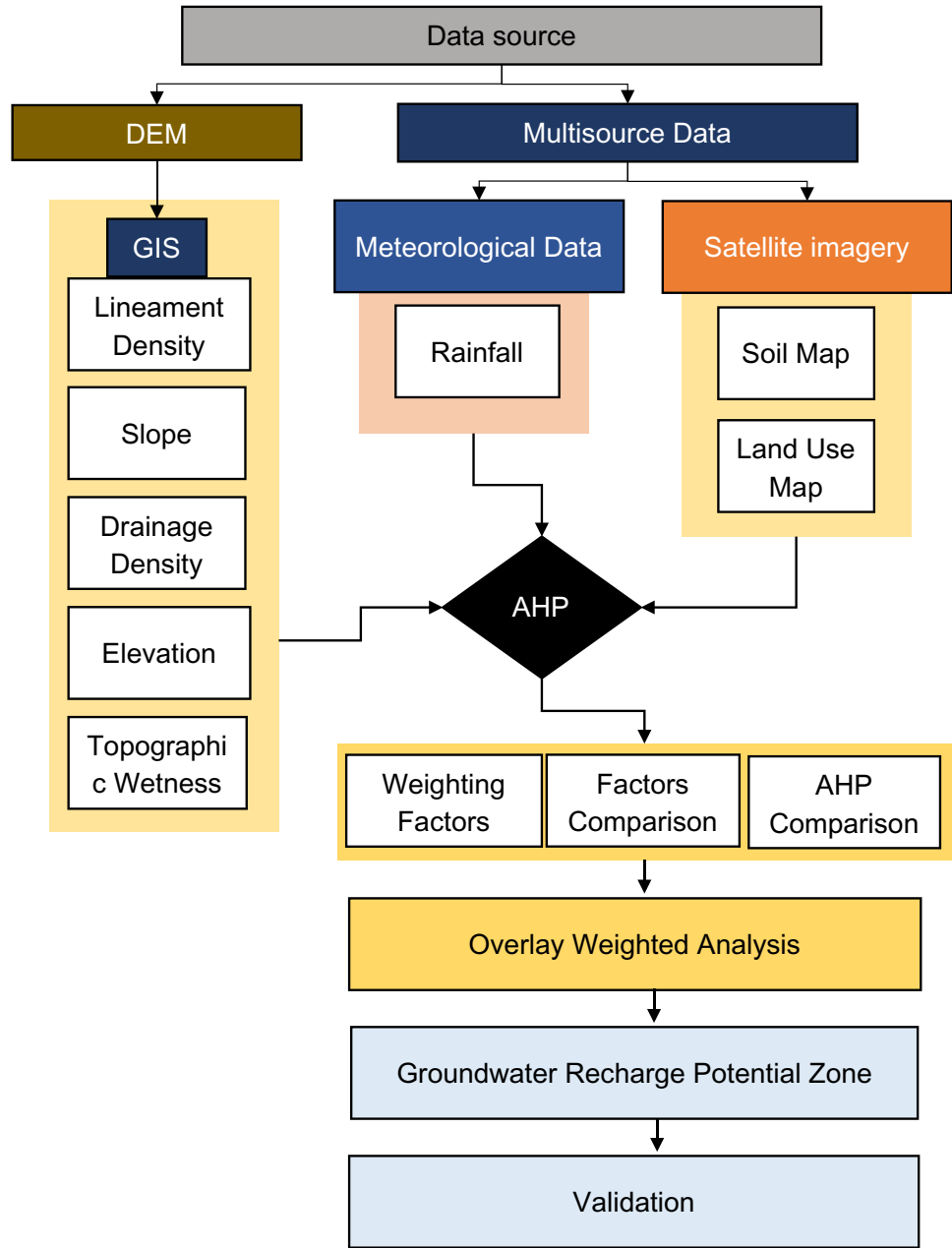
The process of data preparation is an essential and proactive measure in the development of a map that determines the prospective zones for groundwater recharge. The data pertaining to the research region were collected from many sources, as seen in Fig. 4. King Abdulaziz City for Science and Technology provided 10-m-resolution Digital Elevation Model (DEM) data. DEM was analyzed using ArcGIS software to generate many layers, including lineament density, slope, rainfall, drainage density, LULC, soil type, elevation, and TWI (see Fig. 4). The Ministry of Agriculture, Water, and Environment database provided daily precipitation statistics. The Inverse Distance Weighting (IDW) approach was used to interpolate the mean daily maximum rainfall data for the years 2000 to 2020 over the specified study area. The data pertaining to soil types were obtained by accessing a digital soil map of the globe, which can be found at the following URL: <https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/446ed430-8383-11db-b9b2-000d939bc5d8>. Satellite images were downloaded from the USGS earth explorer website (<https://earthexplorer.usgs.gov/>) and

analyzed for LULC information. The LULC map was created in ArcGIS 10.8 utilizing satellite imagery, image classification methods, and a maximum likelihood algorithm. A unified database was achieved by resampling the geographical layers into a raster format.

Methodology

The assessment of groundwater recharge potential involves merging and preprocessing geodata sets from GIS, meteorological, and satellite sources to create a comprehensive dataset. The AHP method is used to determine the relative importance and assign weights to several elements that affect groundwater recharge, including land use, soil type, plant cover, slope. Subsequently, overlay-weighted analysis is used to locate possible recharging zones. Additionally, 19 wells are located where the total suspended solids (TDS) are measured to validate the identified potential zone. Figure 2 presents an overview of the research methodology that was used for this study. The GRPZ determination may be attributed to these eight elements, which were identified as being

Fig. 2 Flowchart illustrating the approach used in the current research



essential to the process. Using the AHP technique, we compared factors, weighted them, and made a comparison matrix to see how they stack up against one another. After performing an analysis based on many factors, the GRPZ map that was ultimately produced was crafted with the assistance of the AHP weightage combination approach. In the following sections, an AHP model overview as well as a short discussion of the chosen elements are presented.

Influential factors

Eight factors have been used to identify the GRPZ. Satellite imaging, geomorpho-logical mapping, soil mapping,

and hydrogeological data were used to derive these parameters. Thematic maps are established for each parameter as follows:

Lineament factor

Lineaments are geological features seen on the Earth's surface that exhibits linear or curved patterns. These features are believed to reflect the underlying lithological structure, which includes faults, fractures, and cleavages. They may be studied and analyzed using satellite imaging. The methodology used for the calculation of lineament density was the utilization of a grid-based technique. The authors (Ghosh et al.

2022) provided a definition for a metric known as lineament density, which is calculated by dividing the total length of lineaments in a grid by the area of the grid.

$$\text{Lineament Density} = \sum_{i=1}^{i=n} \frac{L_i}{A} (\text{km}^{-1}) \quad (1)$$

The equation provided represents the relationship between $\sum L_i$, which denotes the cumulative length of

lineaments inside the grid in kilometers, and A, which represents the size of the grid in square kilometers. Areas with high to extremely high lineament density have significant potential for groundwater development. Figure 3a displays the results of the lineament density calculation performed using Eq. (1) and the GIS toolbox. Figure 3 shows that the eastern and central regions of the study area have a high density of lineaments, while the southern and southwestern areas have a lower density.

Fig. 3 GRPZ factors: **a** lineament density; **b** slope; **c** mean annual rainfall; **d** drainage density

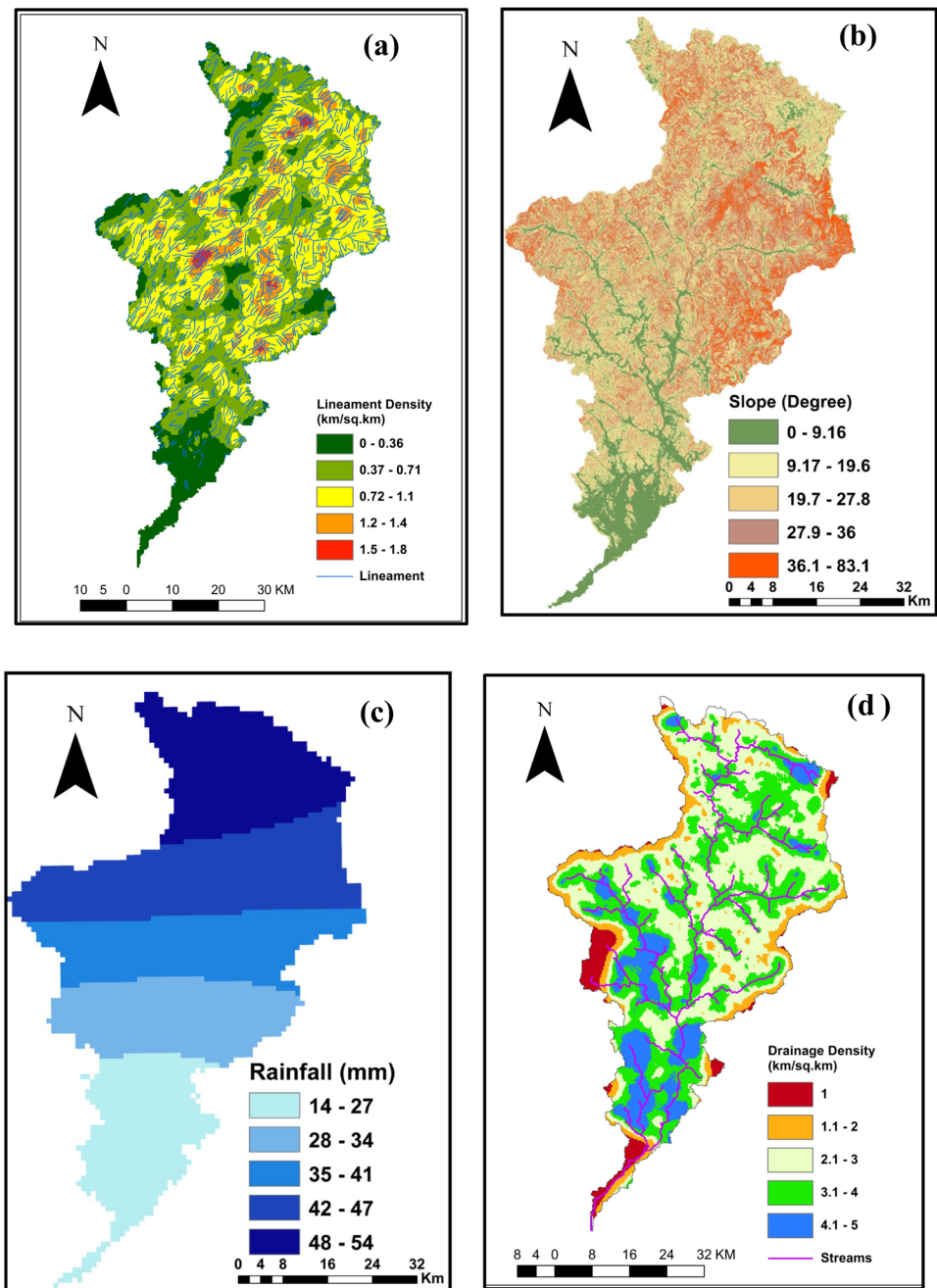
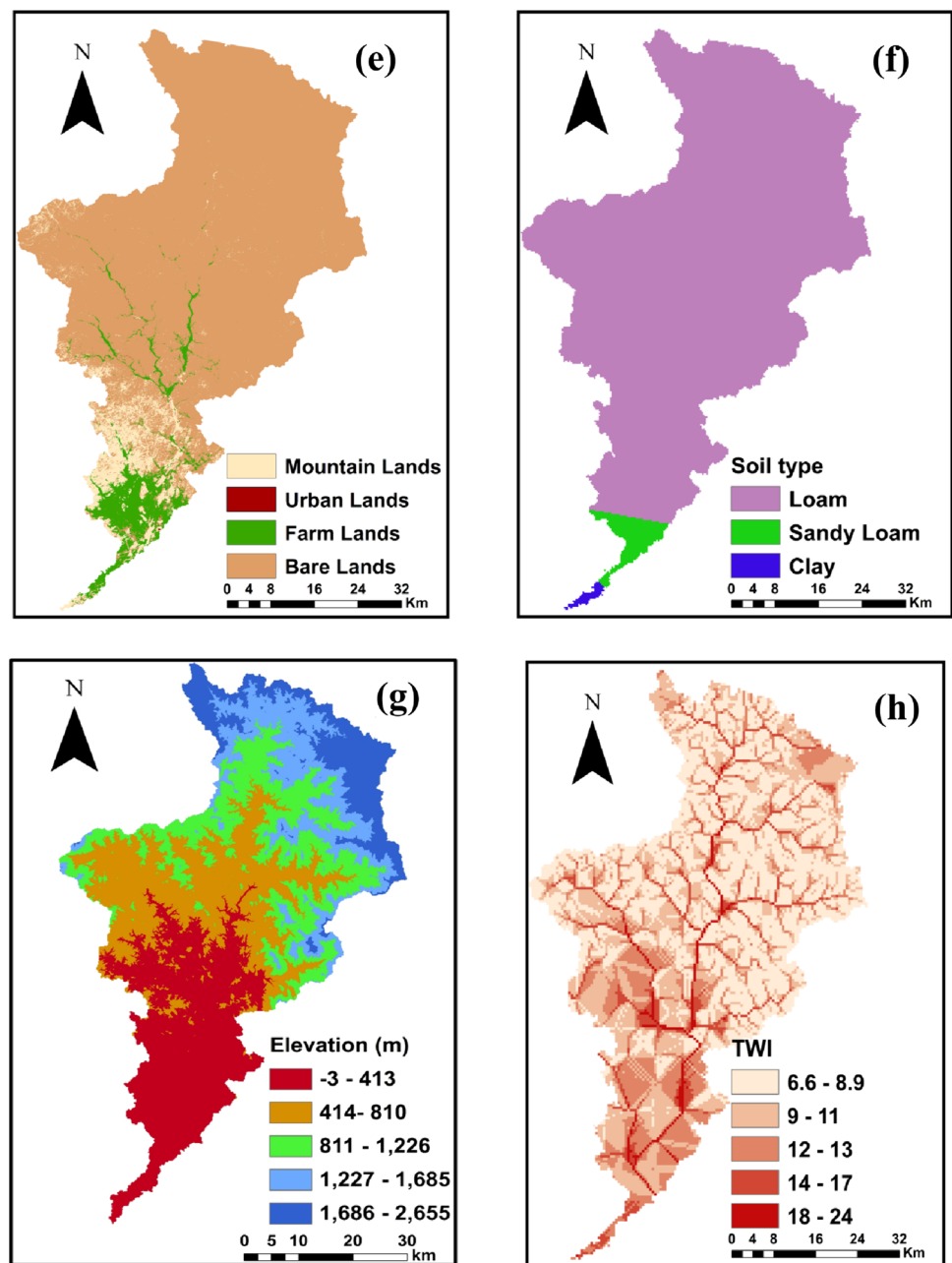


Fig. 4 GRPZ factors: e land use; f soil type; g elevation; h TWI



Slope factor

The slope is a quantitative representation of the degree of inclination of an item relative to a horizontal plane, indicating the steepness or obliqueness of the object (Rimba et al. 2017).

The locations characterized by steep slopes exhibited high surface runoff, limited infiltration of water into the aquifer, and a poor potential for aquifer recharging (Khan et al. 2023). Conversely, mild inclines were characterized by less surface runoff, increased infiltration, and a heightened possibility for aquifer recharge. The slope map is split into five classes, with the lowest class corresponding to a slope of

0° – 9.16° and the highest class corresponding to a slope of 36.1° – 83.1° . The slope map was created using DEM (10 m resolution), as shown in Fig. 3b.

Rainfall factor

Most of the groundwater is replenished by precipitation. Rainfall amount, duration, and intensity all influence the rates of infiltration and surface runoff. Low precipitation over an extended period causes significant surface runoff and poor penetration (Senapati and Das 2022). Precipitation throughout the course of a year has a role in groundwater recharge. A themed map of precipitation information was

generated using the ArcGIS platform and the IDW technique of spatial interpolation. As can be seen in Fig. 3c, the study area is broken down into five distinct categories based on its average precipitation. Overall, the quantity and duration of rainfall determine the amount of infiltration. To illustrate, when it rains lightly for a long time, more water infiltrates into the ground than flows off, but when it rains heavily for a short time, less water infiltrates into the ground and more runoff.

Drainage density factor

The concept of drainage density has significant importance in the field of hydrology, serving as a basic principle. It is determined by dividing the total length of drainage channels by the size of the basin.

The measurement of drainage density serves as a significant indication for assessing the rate of infiltration. The relationship between drainage density and permeability is inversely proportional (Bera et al. 2020). A higher drainage density is indicative of more surface runoff and less water infiltration, resulting in diminished groundwater recharge. Conversely, a lower drainage density signifies greater penetration of precipitation and a more substantial contribution to groundwater recharge (Barua et al. 2021; Bhunia 2020; Senapati and Das 2021).

The determination of drainage density is conducted using the following equation:

$$D = L/A \quad (2)$$

In the given context, D represents the drainage density of the watershed, L denotes the whole length of the drainage channel within the watershed measured in kilometers, and A represents the entire area of the watershed measured in square kilometers. The calculation of drainage density was performed using Eq. (2) and the Geographic Information System (GIS) toolbox, as seen in Fig. 3d. From a geographical perspective, it has been found that the southern region and some areas in the western section of the research area are very suitable for recharging groundwater. Conversely, the central areas were not suitable for replenishing groundwater.

Land use/land cover factor

LULC has a crucial role in governing soil moisture, penetration, and surface runoff rate, hence directly influencing groundwater recharge (Senapati and Das 2021). This particular LULC category effectively regulates the storage of groundwater by means of very complicated geological mechanisms occurring at the Earth's surface. The phenomenon of urban land development has led to a corresponding increase in impermeable cover and a reduction in forest

cover inside urban areas. These changes together lead to a decline in the process of infiltration. The LULC map was generated from satellite images using image classification methods and a maximum likelihood algorithm implemented in ArcGIS 10.8. The LULC map shown in Fig. 4e revealed the presence of four distinct types. The categorized land use and land cover (LULC) categories consist of urban areas, agricultural land, mountains, and barren terrain. Senapati and Das (2022) showed that classified water bodies and forest land can have great and good potential for groundwater recharge, respectively. As a result, urban land was categorized as having low levels of groundwater. The bare lands were the most prevalent type, accounting for 85.7% of the total area. Farm fields constituted 6.5% of the area. The mountain region included 7.7% of the land, while urban areas made up 0.1%. The dense agricultural fields were given a significant weight. The lightweight item was designated for use in the metropolitan environment.

Soil factor

The properties of different soil types have an impact on the process of groundwater recharge. The soil has a discernible characteristic that necessitates investigation in terms of its capacity to facilitate the infiltration of surface water into the aquifer system. The soil with a coarse texture exhibits a higher degree of permeability, whereas the soil with a fine texture demonstrates lower permeability. The very porous soil enables quick subsurface infiltration of surface water (Mandal et al. 2016). Soil with a high clay content has limited infiltration capacity, resulting in comparatively low groundwater potential inside clay formations. Soils containing a combination of sand particles have a greater rate of infiltration, indicating the presence of substantial potential for groundwater. Three distinct soil classes were identified and obtained from satellite pictures within the research region. These classes include loam, sandy loam, and clay, as seen in Fig. 4f. The soil type greatly influences the infiltration of water into underground formations and has a considerable impact on groundwater recharge. An increase in the rate at which surface water seeps underground is associated with soil porosity. Soils with a mixture of sand particles have a greater infiltration rate, which means that there is a lot of groundwater potential.

Elevation factor

The elevation of the terrain plays a crucial role in the process of replenishing groundwater resources. According to previous research (Ajay Kumar et al. 2020; Priya et al. 2022), regions characterized by lower heights on plains have a tendency to exhibit prolonged water retention, leading to increased groundwater recharge. The

management of stream gradients is influenced by elevation, which plays a significant role in determining the capacity for groundwater within a drainage basin across varying altitudes per unit area (Ghosh et al. 2022; Patra et al. 2018). The digital elevation model (DEM) was categorized into five distinct groups using ArcGIS 10.8 software, as seen in Fig. 4g. The elevation range in the study area was divided into five categories: 1686–2655 m (11.2%), 1227–1685 m (14.4%), 811–1226 m (20.6%), 414–810 m (25.5%), and – 3 to 413 m (28.3%).

TWI factor

The use of TWI is often utilized to evaluate the influence of topography on the generation of overflow and the accumulation of flow within a stream watershed (Das 2018; Khosravi et al. 2016). TWI was first developed by Beven and Kirkby (1979) as an integral component of a runoff model. The technique known as TWI is used to analyze and assess the spatial arrangement of wetness circumstances inside a given regional topographic setting. In more technical terms, it defines the relationship between the specified catchment area and the slope. TWI was derived using the following basic formula:

$$TWI = \ln \left[\frac{A_s}{\tan(\beta)} \right] \tag{3}$$

The upstream contributing zone is denoted as A_s , while the slope gradient is represented by the symbol β . The determination of TWI was conducted using GIS techniques by analyzing DEM, as seen in Fig. 4h. Overall, Aquifers are mostly located in areas with greater topographic wetness indices. High weights have been allocated for high TWI, and conversely.

Analytical hierarchy process (AHP)

The AHP methodology consists of four distinct stages: constructing the decision hierarchy, determining the relative importance of features and sub-attributes, evaluating each choice and calculating its overall weight for each attribute, and verifying the coherence of subjective judgments (Ouma and Tateishi 2014). Parameter layers are created with the purpose of demarcating the areas that display the potential for groundwater recharge. The weight is then ascertained via the process of reclassifying the classes that meet the criteria.

Table 1 presents the hierarchical arrangement of the weighted parameters. The GRPZ map was developed using MCDM techniques, with the AHP used as the specific MCDM tool. As part of the AHP, a pairwise comparison was conducted for all possible criteria. A total of twenty-eight pairwise comparisons were established to evaluate eight criteria. The values located outside the diagonal of the matrix show the relative weight of a component in comparison with the other elements.

The reason for the equality of the diagonal values to one is due to the comparison of a component with itself. Table 2 displays the matrix that has been normalized. The priority vector and weight for each factor have been computed. In the event that the consistency ratio (CR) falls below the permissible threshold for inconsistency, it may be concluded that all pairwise comparisons are deemed genuine. The AHP permits a maximum inconsistency threshold of 10%. The computation of the CR was performed using Eq. (4).

$$CR = CI/RI \tag{4}$$

The consistency index (CI) and the random consistency index (RI) are denoted in the given context. The random consistency index, as shown in Table 3, is equal to 1.41 for eight components (Saaty 1988).

The calculation of CI was performed using Eq. (5):

Table 1 Watershed groundwater potential pairwise comparison matrix

Factors	Line-ament density	Slope	Rainfall	Drainage density	LULC	Soil	Elevation	TWI
Lineament density	1	2	3	4	5	5	7	8
Slope	0.5	1	2	3	4	5	5	7
Rainfall	0.33	0.5	1	2	3	4	5	5
Drainage density	0.25	0.33	0.5	1	2	3	4	5
LULC	0.2	0.25	0.33	0.5	1	2	3	4
Soil	0.2	0.2	0.25	0.33	0.5	1	2	3
Elevation	0.14	0.2	0.2	0.25	0.33	0.5	1	2
TWI	0.13	0.14	0.2	0.2	0.25	0.33	0.5	1
Total	2.75	4.62	7.48	11.28	16.08	20.83	27.5	35

Table 2 Weighted comparison

Factors	Lineament Density	Slope	Rainfall	Drainage density	LULC	Soil	Elevation	TWI	Weightage	Weightage (%)
Lineament density	0.36	0.43	0.40	0.35	0.31	0.24	0.25	0.23	0.32	32
Slope	0.18	0.22	0.27	0.27	0.25	0.24	0.18	0.20	0.23	23
Rainfall	0.12	0.11	0.13	0.18	0.19	0.19	0.18	0.14	0.16	16
Drainage density	0.09	0.07	0.07	0.09	0.12	0.14	0.15	0.14	0.11	11
LULC	0.07	0.05	0.04	0.04	0.06	0.10	0.11	0.11	0.07	7
Soil	0.07	0.04	0.03	0.03	0.03	0.05	0.07	0.09	0.05	5
Elevation	0.05	0.04	0.03	0.02	0.02	0.02	0.04	0.06	0.04	4
TWI	0.05	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.02	2
Total	1.00	1	1	1	1	1	1	1	1.00	100

Table 3 Random index (RI) (Saaty 1988)

Number of criteria (N)	1	2	3	4	5	6	7	8	9	10
Random index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$CI = (\lambda_{max} - n) / (n - 1) \tag{5}$$

where *n* denotes the number of factors, and λ_{max} is the sum of the weights assigned to each column in the comparison matrix. Tables 1 and 2 are used to compute the maximum for watershed variables to locate GRPZ, as shown below:

$$\begin{aligned} \lambda_{max} = & 2.75 * 0.32 + 4.62 * 0.23 + 7.48 * 0.16 \\ & + 11.28 * 0.11 + 16.08 * 0.07 + 20.83 \\ & * 0.05 + 27.5 * 0.04 + 35 * 0.02 = 8.347. \end{aligned}$$

The CR is 4.96%, when comparing it to the standard 10%. As a result, the ranking of the pairwise matrix is considered acceptable.

Results

Table 4 presents a list of parameters selected for analysis along with their weights and ranks. The parameters are Lineament density, Slope, Rainfall, Drainage density, land use, soil, elevation, and TWI. The pairwise contrast matrix and factor map are used to establish the relative importance and ranking of each parameter. The priority factor is expressed as a relative weight value ranging from 0 to 100%. A relative weight of 0% implies the lowest relevance, while a weight of 100% indicates the most relevant parameter. For example, the lineament density and slope are the most relevant parameters, with 32% and 23%, respectively. The lowest

parameters are elevation and TWI, with 4% and 2%, respectively (Table 4). The range for the ranking starts from 1 to 5. Five represents the highest degree of influence, and 1 represents the lowest degree of influence.

Figure 5 illustrates the potential groundwater recharge zones in the Al-Lith Basin. The figure identifies various levels of groundwater recharge potential in basin, classified as very high, high, moderate, low, and very low. These categories represent 0.01%, 12.82%, 67.77%, 19.37%, and 0.03% of the total basin area, respectively. Additionally, it is clear that the northern part of the basin offers more options for groundwater potential zones compared to the middle and southern sections. This may be due to higher mean annual rainfall, lineament density, and flat slope in the northern section as compared to the southern and middle regions. In fact, a flat or a small sloping terrain has a slower surface runoff and a greater capacity to retain water, which can result in an improved groundwater recharge.

To validate the groundwater potential zones identified using the AHP method, 19 wells were located in the study area and total dissolved solids (TDS) were measured in each of them (Table 5). High levels of total suspended solids in these wells may indicate high salinity. Therefore, such zones are not considered potential groundwater zones. For instance, the lowest TDS value was recorded in well 12 with a value of 392 ml/s, and the developed model identified this area as a high-potential zone. On the other hand, the other measured TDS values in the wells were rated as moderate to poor potential zones (Fig. 5).

Table 4 Ranking of the weighted GROZ of the catchment

Parameters	Relative weight (%)	Reclassified parameter	Ranking	GRPZ
Lineament density	32	0–0.36	1	Very low
		0.37–0.71	2	Low
		0.72–1.1	3	Moderate
		1.2–1.4	4	High
		1.5–1.8	5	Very high
Slope	23	37–83	1	Very low
		28–38	2	Low
		19–27	3	Moderate
		7.9–18	4	High
		0–7.8	5	Very high
Rainfall	16	14–27	1	Very low
		28–35	2	Low
		36–41	3	Moderate
		42–47	4	High
		48–55	5	Very high
Drainage Density	11	2.2–2.9	1	Very low
		1.8–2.1	2	Low
		1.3–1.7	3	Moderate
		0.52–1.2	4	High
		0–0.52	5	Very high
LULC	7	Urban area	2	Low
		Bare land	3	Moderate
		Mountains	4	High
		Farmland	5	Very high
Soil	5	Clay	2	Low
		Loam	3	Moderate
		Sandy Loam	4	High
Elevation	4	1686–2655	1	Very low
		1227–1685	2	Low
		811–1226	3	Moderate
		414–810	4	High
		–3–413	5	Very high
TWI	2	6.6–9	1	Very low
		9.1–11	2	Low
		12–14	3	Moderate
		15–17	4	High
		18–25	5	Very high

Discussion

The present study aimed to accurately identify the areas with the potential for groundwater recharge in the AI-Lith basin watershed, even under challenging conditions. This was achieved by employing the AHP technique, which has been successfully utilized in various watersheds, as evidenced by previous research (Ajay Kumar et al. 2020; Arumugam et al. 2023; Dar et al. 2021; Echogdali et al. 2022; Elsebaie et al.

2023; Ghosh et al. 2022; Ikirri et al. 2023; Khan et al. 2022, 2023; Khoshand et al. 2018; Mallick et al. 2019; Memar-bashi et al. 2017; Priya et al. 2022; Radulović et al. 2022; Saranya & Saravanan 2020; Senapati and Das 2021, 2022). AHP is widely used by researchers for the identification of probable zones for recharging groundwater due to its proven reliability. The chosen watershed was influenced by eight significant parameters, namely lineament density, slope, rainfall, drainage density, land use/land cover (LU/LC),

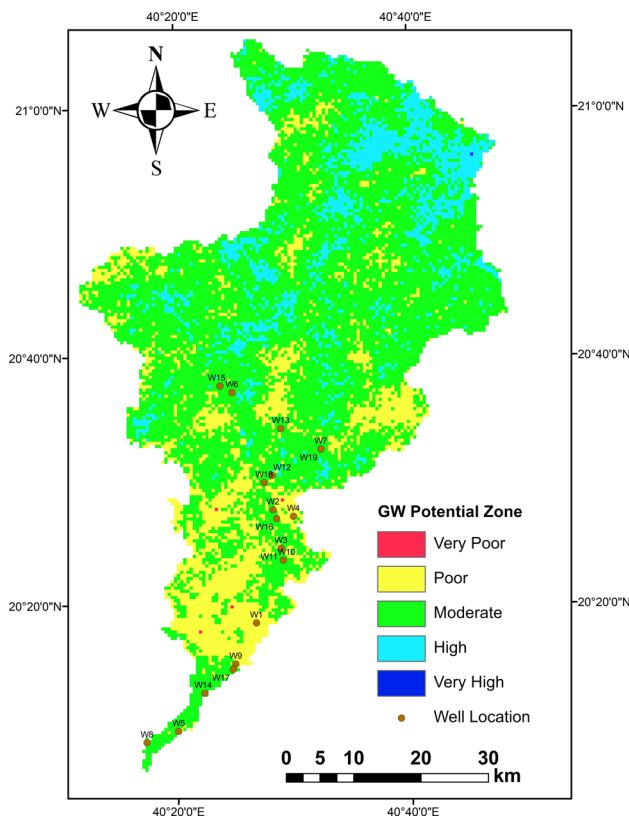


Fig. 5 Al-Lith basin groundwater recharge potential zone map

Table 5 Locations and TDS values of groundwater wells in case study

Well ID	Latitude	Longitude	Total dissolved solid (mg/l)
W1	20.309	40.446	1037.5
W2	20.461	40.471	2079
W3	20.409	40.482	831.5
W4	20.452	40.5	766.6
W5	20.164	40.334	1577.4
W6	20.619	40.414	842
W7	20.542	40.54	434
W8	20.149	40.289	3845
W9	20.254	40.416	1195
W10	20.393	40.485	1771
W11	20.409	40.482	981
W12	20.507	40.47	392
W13	20.57	40.483	400
W14	20.215	40.372	2481
W15	20.628	40.397	741
W16	20.449	40.476	4781.7
W17	20.24652	40.41242	–
W18	20.4975	40.4587	–
W19	20.54178	40.53993	–

soil composition, elevation, and topographic wetness index (TWI). The AHP was used to assign weights to the components involved in mapping. These weights were determined to be 32%, 23%, 16%, 11%, 7%, 5%, 4%, and 2%, respectively. This suggests that the lineament density has the highest weight percentage, while the TWI has the lowest weight percentage in comparison with the other major variables.

Lineament density is an important factor in groundwater recharge for any location (Mallick et al. 2019; Mukherjee et al. 2012). It is important to note that lineament density has the most significance among the eight selected parameters in this research, and this result agrees with the results of Priya et al., (2022) who found the biggest weight was attributed to lineament density, while Ghanim et al., (2023) found lineament density to have the second highest weight.

The slope of the land has a direct influence on how water flows over the surface, which therefore plays an important role in recharging groundwater (Berhanu and Hatiye 2020). It is worth noting that slope has the second highest degree of importance among the eight variables included for this research, with a relative weight of 23%. This conclusion is consistent with those of earlier investigations on similar watersheds. Mallick et al. (2019) investigated the Aseer Region of Saudi Arabia to identify and characterize groundwater potential zones. The second biggest weight among the twelve evaluated characteristics was slope, followed by rainfall. Ghanim et al. (2023) conducted a study in the Habawnah basin in southern Saudi Arabia, and slope was the third-ranked metric in identifying groundwater potential zones.

Geographically, the Central and Northern parts of the study area were classified as good and moderate areas for groundwater recharge potential zone due to the existence of a gentle slope, sandy loam soil texture, well soil drainage, high-lineament density, and moderate drainage density. However, the Southern part of the study area was considered a low and poor groundwater potential zone of the study area (Fig. 5).

The analysis captures that the majority of the study area which represents the North and Northern East lies in the moderate GWPZ. Some patches in the northern part of the study were observed to have high GWPZ. But it can also be observed that there was expansion in the poor GWP category toward the southwestern part of the study area. Kumar et al. (2020) showed similar results while investigating GWPZ in the Deccan Volcanic Province watershed located in Katol and Kalmeshwar. They found that around 33% of the watershed experienced poor GWPZ.

The presence of flat terrain with a minimal incline is associated with a reduced velocity of surface runoff and an increased capacity for retaining water, facilitating the process of groundwater recharge. The findings indicate that about 12.83% and 67.77% of the research region were

categorized as having good and moderate GRPZ, respectively. In addition, it should be noted that the remaining 19.4% of the research area falls under the classification of a zone with low potential for groundwater resources. The findings indicate that about 85 square kilometers (2.75%) of the designated research area were categorized as an excellent groundwater recharge zone, mostly owing to the prevalence of sandy soil texture. Similarly, approximately 2980 km² (96.49%) of the area was covered with sandy loam soil and a zone with moderate potential for groundwater recharge. Nevertheless, a mere 0.76% of the research area, equivalent to 24 km², was characterized by clay soil texture, which is deemed to have a low capacity for recharging groundwater.

The research additionally verified the existence of prospective groundwater zones by comparing them with data obtained from observational wells. Out of the 19 wells examined, none were found to be in a very poor zone. Three wells were located in a zone with poor potential, while 15 wells were placed in zones with moderate potential. One well was found to be in a zone with high potential. Most of the wells were located in moderate potential zones that corresponded to their proximity to heavy agricultural activities.

By comparing the groundwater potential map to the locations of operational wells in the study area, its accuracy was confirmed; this method was frequently employed in previous studies (Ghanim et al. 2023; Mallick et al. 2019; Naghibi et al. 2015).

Also, the validation involves comparing the measured total dissolved solids (TDS) in the borehole with the groundwater protection zones (GWPZs) and establishing a correlation between them. The validation outcomes indicate that the wells exhibiting satisfactory water quality are mostly situated in areas with high and moderate potential. The concentration of Total Dissolved Solids (TDS) varied between 392 and 4781.7 mg/l. The lowest TDS value, which was 392 mg/l, was found in the high-potential zone which is seen as a good outcome.

Overall, policymakers and competent authorities gain from the GRPZ maps. They are useful for figuring out how to improve watershed groundwater quality and supply. In addition, the AHP technique provides a methodical strategy to reduce urban growth in recharge regions, ensuring that the best options are consistently chosen. Having several construction projects and expanding urban areas in the floodplain might cut into recharged groundwater regions. This is what has happened throughout the last ten years on the subject of research. The findings demonstrated that urbanization has a negative impact on hydrological processes, leading to less groundwater penetration and more surface water runoff.

The findings of this study might be used by authorities and land developers to better replenish groundwater. The GRPZ map may be used to determine the best locations for new dams, reservoirs, and other infrastructure.

Conclusions

Over the last twenty years, the increasing climate change and conversion of green regions into cities have endangered the natural water supply. This would directly affect the unregulated water use by the enormous urban population in various cities. Identifying the possible zones for groundwater recharge was crucial in order to determine the most suitable management strategies for preserving groundwater supplies. The land suitability for groundwater recharge in the research region was determined by combining data from eight factors. We used the ArcGIS environment to reclassify all of the desired metrics, and then, we used the spatial analyst tool's weighted overlay to overlay them.

This study presents the construction of a GRPZ map for the Al-Lith basin in Saudi Arabia. The map was developed using the AHP approach, integrated with GIS methodology. In this research, a total of eight factors were assessed, taking into consideration the topographical features, climatic conditions, soil characteristics, and land use data. The use of multi-criteria analysis has been recognized as imperative for doing risk analysis, particularly in situations where there is a dearth of data. The final map depicting the possible zones for groundwater recharge was generated by the use of the ArcGIS program after the computation of the respective weights.

According to the findings of the research, the region of Al-Lith seems to have many zones that demonstrate varying degrees of groundwater recharge potential. The regions that are ideal for groundwater recharge were ranked as follows: very high (0.01%), high (12.82%), moderate (67.77%), poor (19.37%), and very poor (0.03%).

The final GWPZ map, derived from the integration of thematic layers, was validated by comparing well locations and TDS values within the research area. The cross-validation findings demonstrated that the AHP methodology is a good one for extracting groundwater potential maps in the region. Nevertheless, GWPZ results provide a potential opportunity to solve the problem of insufficient groundwater supply in areas with a low fraction of appropriate zones by using artificial recharge for groundwater management and planning.

The findings may assist decision-makers, water resource management authorities, and other stakeholders in effectively using and managing the identified groundwater recharge potential zone in the study area for long-term sustainability. Furthermore, in order to better understand the groundwater recharge potential in the study area, it is beneficial that future research expand the metrics used and incorporate both economic and social data, and conduct further examination of the bore wells. Additionally,

it is important to note that this study only accounts for the spatial variability that can impact the identification of potential groundwater zones. For future studies, it is recommended that temporal variability be considered.

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Data Availability The data are available on request from authors.

Declarations

Conflicts of interest The authors declare no conflicts of interest.

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