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Research article

Mapping coastal groundwater potential zones using remote sensing based AHP model in Al Qunfudhah region along Red Sea, Saudi Arabia

Fahad Alshehri [a], Hazem T. Abd El-Hamid [b,*], Ahmed Mohamed [c]

[a] *Abdullah Alrushaid Chair for Earth Science Remote Sensing Research, Geology and Geophysics Department, King Saud University, Riyadh, 11451, Saudi Arabia*
[b] *National Institute of Oceanography and Fisheries, NIOF, Cairo, Egypt*
[c] *Geology Department, Faculty of Science, Assiut University, Egypt*

A R T I C L E I N F O

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A B S T R A C T

Due to the increases in agriculture and industry sector as well as high population, lack of water is becoming a major problem in the Middle East especially in arid regions. Saudi Arabia needs more groundwater research and explorations because of its higher water use and no source of freshwater. Assessing groundwater zonation in semi-arid locations is essential due to the significant degree of variation in groundwater depth, aquifer features, topographical characteristics, and insufficient precipitation. Mapping prospective groundwater zones in Al Qunfudhah region of southwestern Saudi Arabia has utilized the capability of the multi-criteria decision approaches (MCDA), and the Geographic information system (GIS). We have used the analytical hierarchy process (AHP) as one of the MCDA that is applied to achieve the objective of the current study by integrating twelve controlling factors. These factors are represented by the thematic layers; slope, precipitation, soil type, land use/cover (LULC), drainage density (DD), normalized difference vegetation index (NDVI), curvature, topographic position index (TPI), Terrain Ruggedness Index (TRI), drainage density (DD), and Lineament Density (LD). These thematic layers are combined with GIS to delineate the zones of groundwater potentialities. All factors were classified and weighted according to their importance and its effect on groundwater zones. Their normalized weights were evaluated using a pairwise comparison matrix. The present study shows that the groundwater potential zones (GWPZs) map is represented by five groups ranging between a very high zone with an area of 23781.06 Km^2 that represents 4.04 % of the studied area, and a very poor GWPZ with an area of 182944.4 Km^2 that represents 31.09 % of the studied area. The AHP model suggests that lineament density, slope, and drainage density are more important for determining the groundwater potentiality than other physiographic factors. The study's findings will be helpful in developing practical strategies for the region's groundwater supply. This analysis shows how the methodology may be used to study a broad coastal groundwater basin. The current study will give the decision makers to select suitable sites with a high groundwater potential.

* Corresponding author.
E-mail address: ht.abdelhamid@niof.sci.eg (H.T. Abd El-Hamid).

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1. Introduction

Groundwater basins along the coast are crucial for development and habitation. An important natural resource for human survivability is groundwater in arid and hyper-arid regions, where precipitation and surface water are scarce [1,2]. About 0.3 % of surface water in reservoirs, lakes, and rivers and 30% of all freshwaters in the form of groundwater underground the earth [3]. As populations and economies expand in arid places, there is a greater need to ensure reliable access to abundant water resources [4]. Mapping of groundwater is a result of high demand of water for many purposes [5]. Zonation of groundwater in dry and semi-arid areas has been the subject of numerous studies that make use of remote sensing, geophysical, and geochemical data sets [6–10]. In both urban and rural areas, groundwater is a natural resource for water supply. It aids in reducing poverty since groundwater can be piped directly to impoverished areas at a lower cost and in less time than surface water [11–14]. Data of satellite images are becoming useful in groundwater exploration because of their ability to detect variations in landforms that may function as direct or indirect indicators of the existence of groundwater [15]. Groundwater occurrence is determined by several environmental factors as geology, physiography, lithological composition, drainage patterns, land use and cover, drainage density, and lineaments [16]. An important factor in ensuring the long-term success of projects, lowering the probability of water scarcity, and decreasing the drilling expenses is the delineation and assessment of groundwater prospective zones. Given that, the traditional geophysical techniques and the borehole data are both laborious, time-consuming, and costly for the non-accessible and remote regions. In addition to the substantial time and resources required to obtain them, their results are often suspect given the paucity of the datasets required for the implementation of these methods and are challenging to apply on regional scales. Moreover, more geophysical techniques should be suggested to confirm the results [17].

However, geographic information system (GIS) integration with remote-sensing data and multi-criteria decision approaches (MCDA) techniques have been frequently utilized for delineating possible groundwater potential zones (Kumar et al., 2007; Hammouri et al., 2014). Analytic Hierarchy Process (AHP) was first proposed by Saaty (1988). It is one of the MCDA techniques, which may be used to examine and analyzing several factors. The benefits of this method are numerous for groundwater evaluation, forecasting, and long-term planning. Thematic layers such as slope, topography, geology, soil, rainfall and land use can be assessed with the help of geospatial tools to delineate groundwater potential zones [18]. AHP is a helpful tool in locating areas with promising groundwater supplies. Several research studies have been successfully used the remote sensing, GIS, and AHP for tracking and evaluating groundwater potential zones [19,20]. According to Abdel Hamid [21], the AHP is one of the geographical multicriteria studies used to determine flood-prone areas. AHP can be built in a variety of ways, one of which is by employing software that can operate and calculate automatically.

The AHP is a pairwise comparison measurement concept that relies on the expert opinion to generate priority scales. The rankings of absolute judgments used to make decisions reveal how the factors interact in relation to a particular property [22]. AHP is very adaptive since it gives a straightforward method for determining the relationship between criteria and options.

This method divides the criteria into several sub-criteria and uses a hierarchical tree with several levels. Using a series of hierarchical ordering criteria, this MCDA method has been used in several varieties of prediction studies, particularly those carried out in areas with sparse and irregular distributions of well data. This model's input data include the topography, hydrology, and land cover of the basin, as well as its slope, elevation, curvature, Terrain Roughness Index (TRI), Topographic Position Index (TPI), land use/landcover (LULC), distance density (DD), drainage density, Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and lineaments. Most of these parameters are created using the Digital Elevation - Shuttle Radar Topography Mission (SRTM) allowing morphometric and geomorphic research and ensuring the rapid and cost-effective development of consistent results. maps of LULC can be used to find water resources that are useful for agriculture and other human endeavors in addition to these requirements. The goal of this study's groundwater potential modelling for identifying groundwater-accessible areas across the study region. When governmental and non-governmental organizations manage, plan, and develop groundwater resources, this will improve accuracy and efficiency, save time, and save money.

The present study tried to cover the gap of groundwater zonation in Al Qunfudhah region along Red Sea, Saudi Arabia. The present study tried to focus on sites and places of groundwater to cover the demand of people for freshwater. Also, the present study will present a final map of ground water to help decision maker and stakeholders for good planning. Stakeholders and governmental institutes will benefit from groundwater mapping which be a guide for future planning and suitable exploration. Using satellite data, this research aims to define and characterize groundwater potential zones for the domestic, manufacturing, and farming water supply of the Al Qunfudhah population. The methodology incorporates remote sensing and Geographic Information System within the AHP framework. Multiple theme layers are constructed for the most important characteristics that govern groundwater potentiality in this region, and these levels are incorporated into the AHP model. The map of groundwater potential zones (GWPZs) was constructed by combining the theme layers with a raster calculator, employing the AHP approach, and assigning a rating. This study would provide a simple approach to better managing and preparing for water use, making it critically significant for environmental management. The main aim of the present study is to focus on the sensitive areas to groundwater using integrated approach of remote sensing and GIS techniques. This aim was applied using different data acquired from satellites and images.

2. Materials and methods

2.1. Study area

Al-Qunfudhah is one of the most significant cities in the Makkah Al-Mukarramah region of the Kingdom of Saudi Arabia, as depicted in Fig. 1. It is the ninth-largest province in the region, with an estimated size of 7032 km^2, or around 3.65% of the overall land area. It is accessible by the coastal road and is situated on the western coast of the Red Sea. Due to its proximity to the Red Sea, Qunfudhah has a unique climate. Summers are typically quite hot and humid, while spring and winter are brief and wet, especially around December. Makkah Al-Mukarramah has a hot desert climate. It retains its hot temperature in winter, which can range from 18 °C at night to 30 °C in the day. Three watershed regions in the Al Qunfudhah area (Hail, Doga, and Yabah) make up the research area. Wadi Hali is situated on the coast of the Red Sea, near to the Asir region and represents as the southern gate to the region, and it is close to the heart of Kenana. Doga wadi is one of Al-Qufudhah Governorate's major valleys. The center of Doga is located approximately 90 km south of Al-Leith Governorate, 73 Km north of Al-Qunfudhah Governorate, and 270 km south of Makkah Al-Mukarramah. Wadi Yabah is one of the Tihama valleys in the western region of the Saudi Arabian Kingdom. It is located in the southern Al-Qunfudhah Governorate in the Makkah Al-Mukarramah Region, close to Juma Rabia al-Maqatrah and Al-Quoz Center and is considered one of the most important valleys in the Tihama, the Saudi Arabian region.

2.2. Methodology

Numerous variables have been employed to determine potential groundwater zones. Raster maps of the variables were generated using GIS (10.6) and Envi (5.3) from remote sensing datasets. These thematic layers are land use/land cover, slope, NDVI, lineament density, vegetation indices, drainage density, curvature, TPI, and TRI. Atmospheric and radiometric corrections were applied using Semi-Automatic Classification Plugin. The SRTM DEM data, which is downloaded from the NASA website with a spatial resolution of 12.5 × 12.5 m, was used to create the elevation, slope, and drainage density maps as shown in Table 1. In a GIS environment, several processing techniques, including conversion, interpolation, categorization, reclassification, augmentation, and filtering, were applied to the used satellite data. Lineament map was extracted using satellite image. It was made according to visual interpretation from various satellite images and aerial photographs. In recent years, high resolution of satellites is used as a good technique for mapping groundwater in arid and semi-arid regions [23]. Using visual interpretation, lineament map was mapped with the aid of relief map. The details of the image processing and methods are visualized in Fig. 2. Our results were compared with previous data for validation using Landsat 8 data and Google Earth.

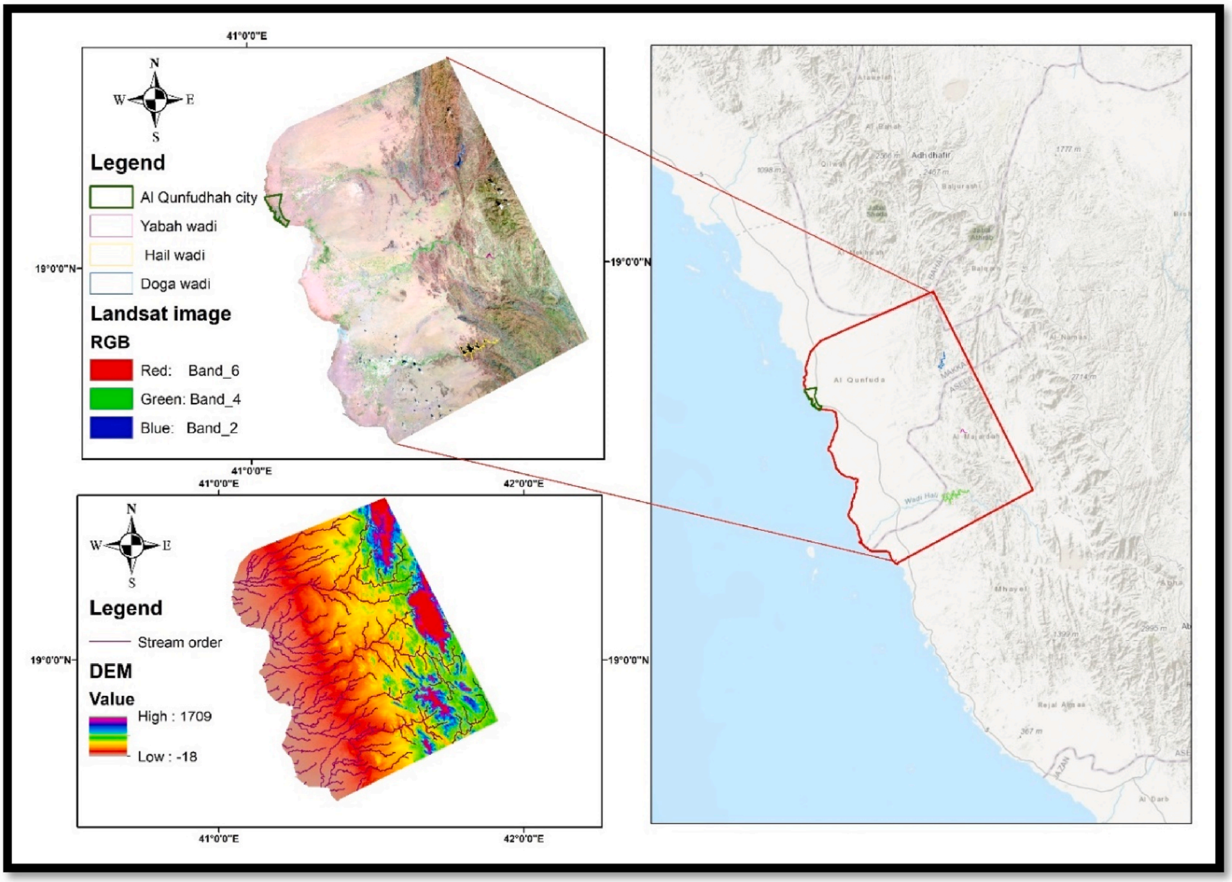

Fig. 1. The location map of the study area.

Table 1
Dataset source and resolution.

Data	Spatial	Resolution (m)	Source
DEM, slope, drainage density	Raster	30	https://earthexplorer.usgs.gov/
Landsat 8 OLI (LD & LULC)			https://earthexplorer.usgs.gov/
Soil data			https://www.fao.org/soils-portal/data-hub/soil-classification/en/
Rainfall data			https://gpm.nasa.gov/missions/GPM

Using fill, flow accumulation, and flow direction, the order of the stream was determined. Equation (1) was used the Line Density tool and stream network to compute drainage density (km/km^2).

$$\mathrm{DD} = \sum\nolimits_{i=1}^{n} \frac{Di}{A} \quad \text{Eq. (1)}$$

Where D_i is the total stream length in stream order i (km). A is the basin area (km$^{2)}$. TRI is characterized by equation (2):

$$\mathrm{TRI} = \sum_{k=0}^{n} (Z_C - Z_i)2)2 \quad \text{Eq. (2)}$$

Where z_i is one of the eight nearby cells' elevation and z_c is the elevation of the central cell.

The following equation (3) was utilized to determine TPI.

$$\mathrm{TPI} = \frac{M_{o-}\sum_{n-1M_n}}{\mathrm{n}} \quad \text{Eq. (3)}$$

Where M_o is the elevation of the evaluated model point, M_n is the elevation of the grid, and n is the total number of surrounding points used for evaluation. TPI of 0 values indicate a fatty ground surface. Low TPI values are assigned a higher weight, and vice versa. Also, lineament extraction was calculated using random lines in different areas according to hill shade. After that, lineaments were extracted using Arc map 10.6. Manual extraction of lineament is more reliable than other automatic methods [24].

The NDVI evaluates how green the vegetation is and is an excellent indicator of how the vegetation in one zone has changed over time using the following equation (4).

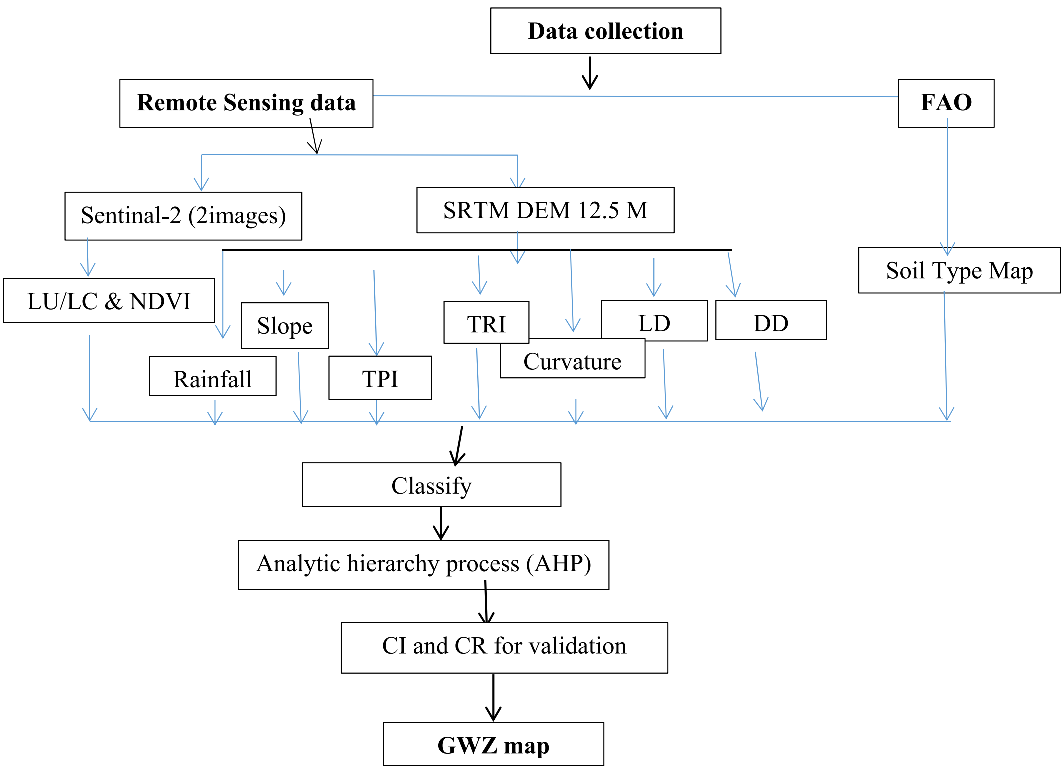

Fig. 2. Flow chart of the method for obtaining flood hazard map.

$$NDVI = \frac{B4 - B5}{B4 + B5} \quad \text{Eq. (4)}$$

To begin mapping the groundwater potential zone, all data layers were originally converted to raster data with the same 30 m × 30 m spatial resolution. Using a pair-wise comparison of all the characteristics, the relative significance of each factor used for groundwater potentiality was determined. Using the weights that were calculated, each map was classified. The weightage overlay module in Arc GIS 10.8 was then utilized to construct a map of groundwater potential by combining all thematic layers.

2.3. Weight calculation using AHP

The approach of [25], also known as the AHP, is frequently used to assess spatial choice problems in the management of natural resources, especially groundwater difficulties [26]. To evaluate the weight of multiple layers, the AHP method is utilized [27]. When employing Saaty's scale of relative importance, the first step is to build a Pairwise Comparison Matrix (PCM), as described by Saaty [28]. Normalized weights were removed after ranking each layer in order of significance as shown in Table 2. The algorithm for calculating the consistency index was used to find the maximum values (max) of the normalized main Eigen vectors for each parameter.

2.4. Calculation of the CI and CR

The reliability of groundwater zonation was assumed using consistency index (CI) and consistency ratio (CR). The CR was computed using equation (5), whether the weights given to each component were suitable. When the CR is less than 0.10, the weight is considered constant.

$$\boldsymbol{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (5)$$

CI: the consistency index. RI: the random index. The **CI** was computed in equation **(6):**

$$\boldsymbol{CI} = \frac{\boldsymbol{\lambda_{max-n}}}{\mathbf{n-1}} \quad \text{Eq.(6)}$$

Where n is the total number of parameters used in this study, and max is the main eigenvalue of the comparison matrix. The CR was computed to see if the weights assigned to each factor were appropriate. When the consistency ratio is less than 0.10, the weight is considered constant. The calculation yielded a CI value of 0.075. The specified weights for each parameter are adequate for future investigation because the consistency ratio (CR) result is less than 0.1 and less than 0.0538. Following the evaluation of the weights using the AHP technique and the standardization of each raster using the geometric mean criteria, each feature class was assigned a rating value of 1–5; very low, low, medium, high, and very high [29]. The rating scores indicated the suitability of the groundwater potential. All data were mentioned in Table 3 and in **Figure** (2) illustrates the methods of this study. Standardized Principal Eigen Vectors was calculated as shown in Table 4. Ranking of all parameters were determined using comparison matrix of AHP that provides an overall ranking of the outputs. The alternative with the highest value is the first choice (Muralitharan and Palanivel 2015) as shown in Table 5.

2.5. Mapping of GWPZs

After the ranking and weighting of the components and their subcategories in thematic maps as detailed below, the weighted overlay method was utilized to integrate all of the inputs using equation (7).

$$\mathbf{GWPZ} = S_W\, S_{wi} + LD_W\, LD_{wi} + DD_W\, DD_{wi} + L_W\, L_{wi} + V_W\, V_{wi} + LD_W\, LD_{wi} + T_W\, T_{wi} + S_W\, S_{wi} + F_W\, L_{wi} \quad \text{Eq. (7)}$$

Where: DD: Drainage Density, S: soil type, LD: Lineament Density, T: Index of Topographic Position, F: rainfall, and the letters V, L, and W all stand for the weighted average of a theme's constituent elements. The model's weights were initially determined for each thematic map and its subclasses using ArcGIS's reclassification and raster calculator features. The raster calculator application also

Table 2
Saaty's relative significance scale.

Scale	Definition	Explanation
1	Equal significance	The goal is equally benefited by the two activities.
2	moderate priority between one thing and another	One activity is greatly preferred over another by experience and judgment.
3	Important or very important	One activity is clearly superior to another based on experience and judgment.
5	Extremely important	Strong support is given to one activity, and it is shown to be dominant in actual practice.
7	Very extremely significant	The strongest potential order of affirmation can be found in the data supporting one activity over another.
9	The values that fall between the two adjacent judgments	When to make a compromise

Table 3
Relative weight for selected thematic layers.

Factor	Slope	LD	LULC	TPI	TRI	DD	NDVI	Rainfall	Soil type
Slope	**1**	2.2	0.04	0.18	0.009	0.241	0.212	1.47	0.40
LD	2.29	**1**	0.04	0.74	0.27	0.85	0.0008	0.60	0.04
LULC	0.04	0.04	**1**	0.42	0.096	0.5	0.06	0.99	0.17
TPI	0.18	0.746	0.42	**1**	0.57	0.20	0.04	1.96	0.008
TRI	0.009	0.27	0.0096	0.57	**1**	0.97	0.29	0.043	0.13
DD	0.24	0.85	0.5	0.20	0.97	**1**	0.43	2.29	0.23
NDVI	0.21	0.0008	0.06	0.04	0.29	0.43	**1**	0.73	0.032
Rainfall	1.47	0.60	0.99	1.9	0.043	2.29	0.73	**1**	0.32
Soil type	0.40	0.04	0.17	0.0008	0.134	0.23	0.032	0.32	**1**

Table 4
Standardized erincipal Eigen vectors.

Parameters	Standardized Principal Eigen Vectors
Slope	21.28%
LD	12.86%
LULC	14.47%
TPI	10.68%
TRI	6.63%
DD	7.36%
NDVI	11.19%
Rainfall	6.70%
Soil type	8.82%

used to overlay the theme features. The final groundwater potential map was generated by combining and delimiting five zones: excellent, good, medium, low, and extremely low. As a result of its reliability, this strategy has been implemented in a wide variety of research ([30,31]; Alshehri et al., 2023).

3. Results and discussion

3.1. Analysis of hydrology

There are many factors that control and assess the Groundwater zonation as geological structure, topography, slope, precipitation, soil, secondary porosity, drainage pattern, LULC, hydrological conditions of a region and the inter-relationships among these factors [32,33]. In the present study, some influencing factors, such as Geology, DD, LD, LU, soil type, LC, slope, rainfall, NDVI, curvature, TPI, and TRI were used to determine the GWPZs in the current study.

3.1.1. Slope

A surface's slope is the angle formed between the surface and the horizontal. This critical factor, which also directly impacts the infiltration rate and surface runoff in any area. It effects on the process of groundwater recharge [34]. A steep slope holds water on the surface for a short period of time due to the rapid runoff, which minimizes infiltration and recharging of groundwater. In contrast, flat terrain is conducive to recharge due to its high infiltration rates and minimal runoff. Based on DEM data slope has been classified into five classes as very low (0–4%), low (4–10%), moderate (11–18%), high (19–27%) and very high (28–70 %) shown in Fig. 3. The majority of the study area is in the range 0–4%. As a result, the maximum area has

a slope that is ideal for holding and accumulating water. Nag and Ghosh (2013) mentioned that the high slope, the high groundwater retention and the lower slope, the high run off and less infiltration. Because of extremely high runoff and a low rate of infiltration, a location with a slope of more than 16″ (severe to extremely steep slope) was deemed unsuitable for the occurrence of groundwater, and the lowest possible score was given [35].

3.1.2. Lineament density (LD)

Lineament is very important factor for determining the zones of groundwater [36]. Lineaments are landforms that are straight or nearly straight and are found all across the surface of the Earth. The permeability of the ground amplifies them. Lineaments are essential for groundwater circulation and storage because they facilitate water infiltration into the subsurface [37]. LD are widely dispersed, virtually straight landforms that are made more pronounced by the ground's permeability [38]. Zones beside the lineaments are consider a good indicator of water storage and high infiltration rate [39]. In the present study, the LD is mainly along NE-SW and NW-SE directions which are represented by a rose diagram (Fig. 4). Also, the DD increase with the increase of LD. Magowe and Carr [40] stated that the higher lineament, the higher groundwater probability.

Table 5
A list of factors along with their ratings, weights, and coverage areas.

Weightage (%)	Class	Degree	Rating
Slope (Degree)			
21.3	0–4	Very high	5
	4–10	High	4
	10–18	Moderate	3
	18–27	Low	2
	27–70	Very low	1
	Lineament Density (km/km^2)		
12.9	No lineament	Very low	1
	Fractures, short lineament	Low	2
	Local faults, frequent fractures	Moderate	3
	Interconnected local faults	High	4
	Major long faults	Very high	5
	LULC		
14.5	Water bodies	Very high	5
	Vegetation	High	4
	Agriculture	Moderate	3
	Bare lands	Low	2
	Built up	Very low	1
	TPI (%)		
10.7	−49−−2.7	Very low	1
	−2.7−−0.74	Low	2
	−0.47- 0.88	Moderate	3
	0.88-3.3	High	4
	3.3–54.3	Very high	5
	TRI (%)		
6.6	0–3.6	Very low	1
	3.6–7.2	Low	2
	7.2–14	Moderate	3
	514.5–34	High	4
	34–185	Very high	5
	Drainage Density (km/km^2)		
7.4	0–21.8	Very high	5
	21.8–49.6	High	4
	49.6–81	Moderate	3
	81–118	Low	2
	118–222	Very low	1
	NDVI (Degree)		
11.2	−0.1-0.01	Very low	1
	0.01-0.07	Low	2
	0.07-0.1	Moderate	3
	0.1–0.02	High	4
	0.2-0.5	Very high	5
	Rainfall (mm)		
6.7	73.8–111	Very low	1
	112–142	Low	2
	143–169	Moderate	3
	170–224	High	4
	225–316	Very high	5
	Soil type		
8.8	Silty clay/loam	Very low	1
	Clay loam	Low	2
	Sandy loam	Moderate	3
	–	High	4
	–	Very high	5

3.1.3. DD and stream order

The DD is computed by the ratio of the drained basin's surface area to the sum of the lengths of its watercourses [41]. Low drainage density results in large GWPZs, whereas high drainage density decreases infiltration and generates smaller GWPZs. Typically, the presence of groundwater is inversely proportional to drainage system density [42]. Drainage density that acquired from satellite

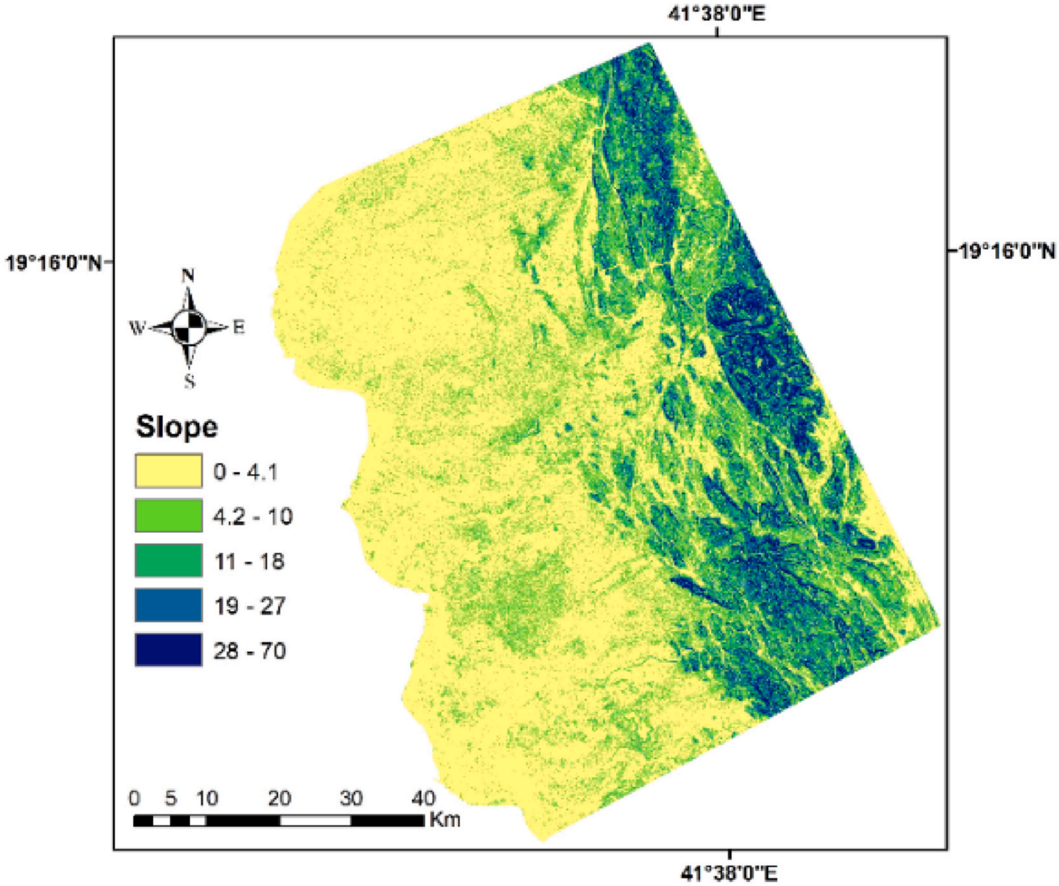

Fig. 3. Slope map of the study area.

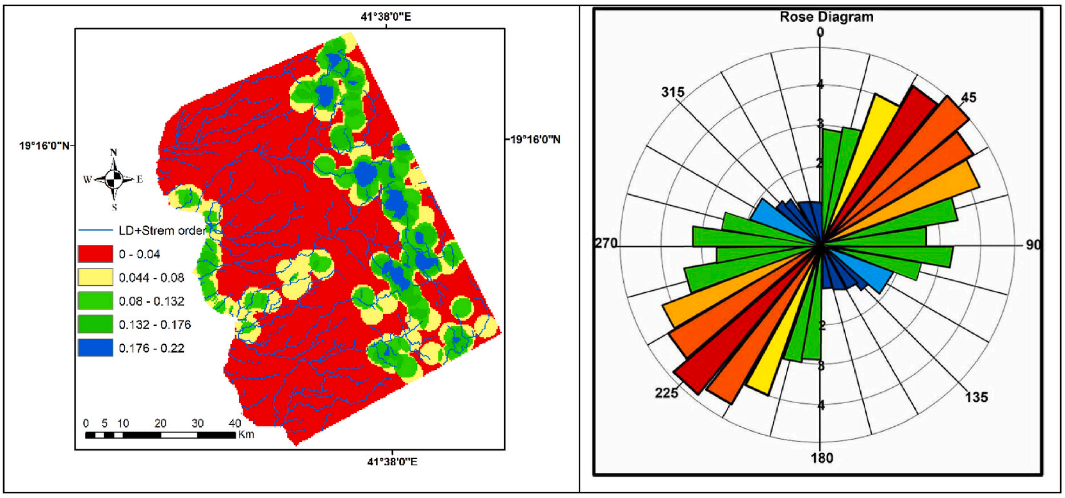

Fig. 4. Lineaments and rose diagram of the study area.

images reflects the properties of the surface as well as a subsurface formation. It reflects the characteristic of drainage pattern [43]. In the present study, DD ranged from 0 to 220 m/m^2. The higher drainage density, the higher runoff and the low drainage density reflects the recharge of groundwater zonation [43]. It was classified into five classes as follow: very low, low, moderate, high and very high (Fig. 5). To prevent the damage of flood and prepare for good planning along the study area, DD should be calculated [44].

3.1.4. TRI & TPI

Using the TRI, which is the average difference between the center of a pixel and its neighboring cells, the heterogeneities of the landscape were measured. The LU use map was created using Landsat images by the maximum likelihood and supervised classification methods. Agriculture, dry land farming, housing, and rangeland were the four main categories of land use. One of the most essential parameters for defining groundwater potential zones is lithology. TPI is frequently used to automatically categorize topographic slope areas and landforms. Several physical processes that affect the terrain, including hilltop, exposed ridges, valley bottom, fat plain, and upper and lower slope activities, are associated with TPI. It aids in the differentiation of topographic characteristics. Two factors reflect the topography of the study area as shown in Fig. 6.

3.1.5. Curvature

It provides a quantitative description of the surface profile, which could have convex or concave upward profiles. Water tends to build up and to slow down in concave and in convex surfaces, respectively. High values of curvature are linked with high values of mass, and vice versa. It was shown that most of the study area are falls under low curvature as shown in Fig. 7. An enhanced peak discharge is possible due to the high surface roughness, which is extremely susceptible to erosion [44]. Also, zones of high curvature are prone to water flow and accumulation, which increases the possibility of infiltration and groundwater replenishment [45].

3.1.6. LULC

It defines for a region as the dependence on groundwater and provides environmental information [46]. Initially, a visual inspection of the research region was conducted. Using classification algorithms, satellite image pixels can be classified into different classes. Using the built Semi-Automatic Classification Plugin, a supervised classification was performed in QGIS. The analyst decides on the training pixels that will be utilized to obtain the various LULC characteristics and enable the categorization. Since Maximum Likelihood is the most common method for analyzing satellite imagery (Fig. 8). In the present study, area without landcover has least rate of infiltration. The vegetation cover is proportional to infiltration rate. Shaban et al. [47] highlighted the various methods in which plant cover promotes groundwater recharge, including the biological breakdown of the roots, which creates a channel for water to seep into the surface of soil. Water bodies are the most important factor that effect on groundwater zonation based on type of soil [48]. The recharge of water differs from one type of soil to another; clay, sand and agriculture respectively [49]. Leduc et al [50] stated that

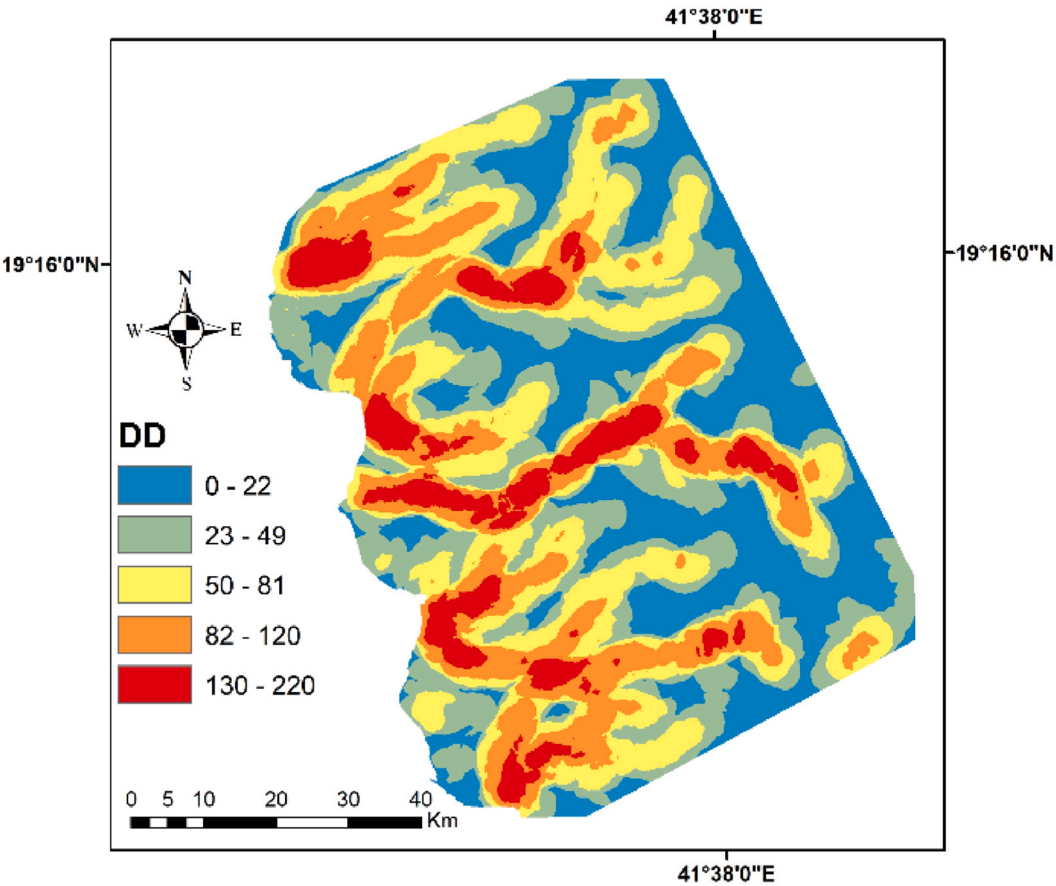

Fig. 5. Drainage density of the study area.

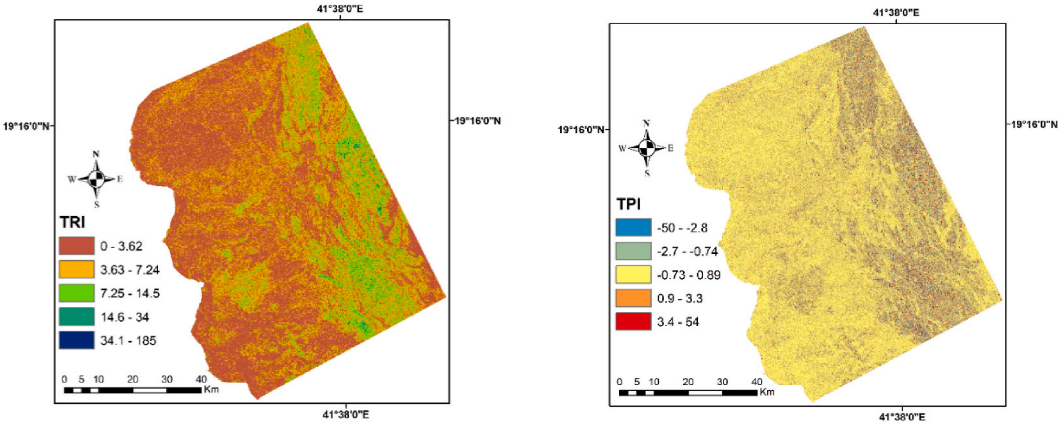

Fig. 6. TRI & TPI of the study area respectively.

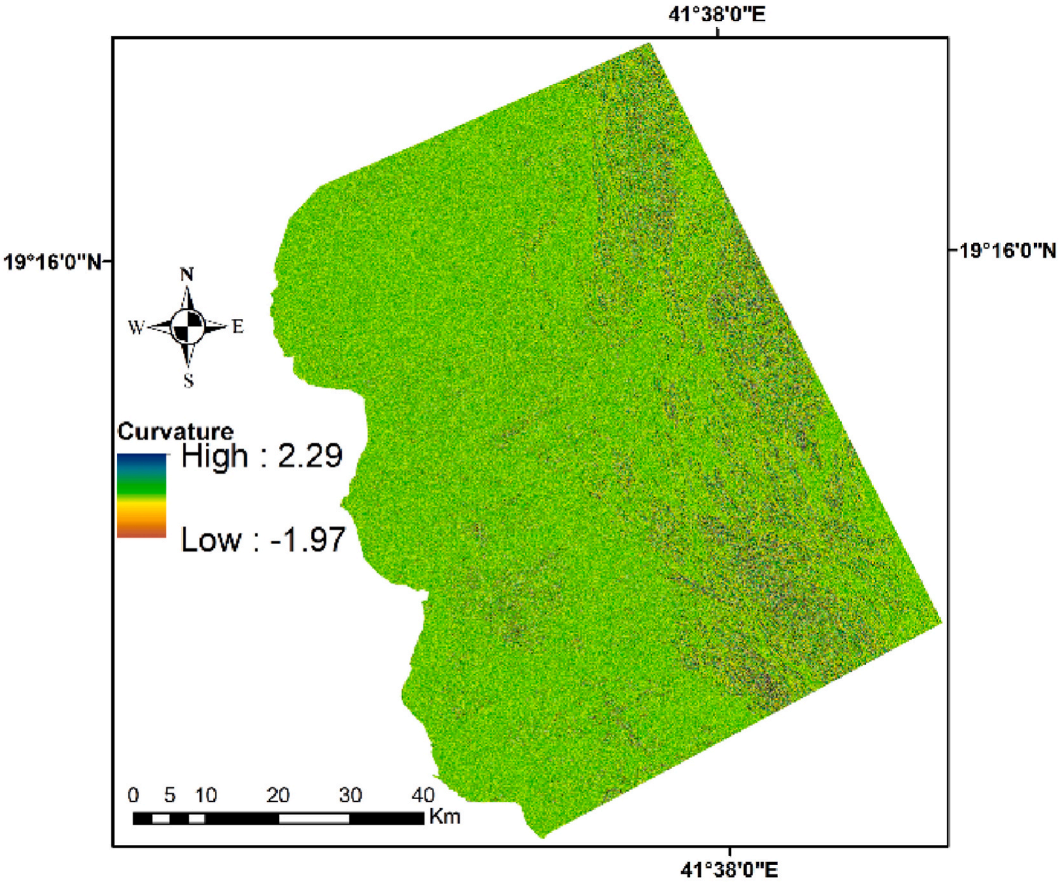

Fig. 7. Curvature map of the study area.

variation in LULC especially vegetation encourages the probability of groundwater.

3.1.7. Soil type

Three valleys in Al Qunfudhah city were analyzed, and their various soil types were classified according to the typical impact they had on groundwater recharge [51]. The permeability of a soil refers to how easily air and water can travel through it. During irrigation or rainfall, water passes rather slowly through soils with low permeability but quite readily through soils with high permeability. Large pore holes in sand-textured soils make it simple for rainfall to move through the soil. Sandy soils are said to have strong infiltration

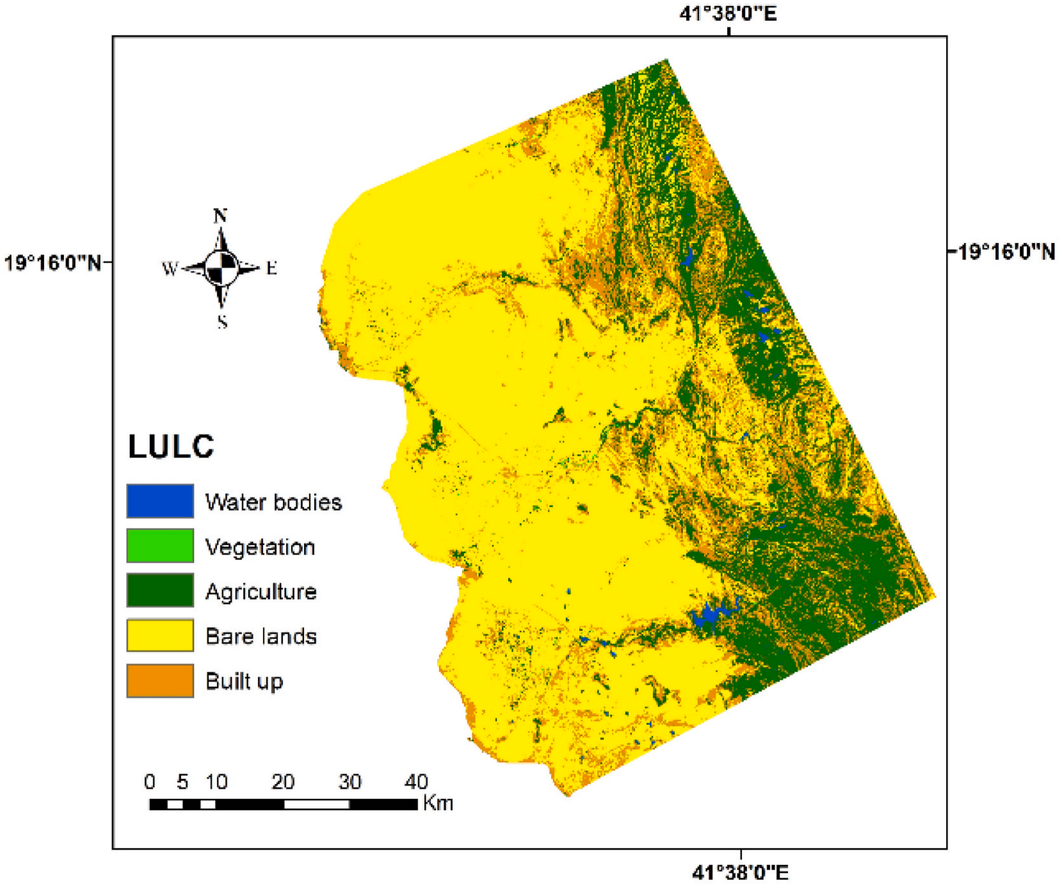

Fig. 8. LULC of the study area.

rates and good drainage due to their high permeability. Clay-textured soils have limited pore spaces, which cause water to percolate through them slowly. Clay soils are notorious for having low infiltration rates and poor drainage due to their limited permeability. When more water is absorbed into the pores, the air is driven out of them. High infiltration rate of water occurs in sandy loam soil; therefore, sandy loam soil was given as the high weight (Fig. 9).

3.1.8. *Rainfall*

There is a clear relationship between the type of slope and exposed rock units and the amount of water that is absorbed and stored underground, as stated by Arulbalaji et al. [20]. To aid in the creation of an inverse distance weighted (IDW) rainfall averaged map for the study region, random sites inside and just outside the study area's borders were chosen to collect rainfall data. In agreement with Nigussie et al. [52], the IDW approach was chosen to generate the continual raster for the measured rainfall locations. According to our findings and the rainfall distribution chart, the average winter precipitation in the study region varied between 73.8- and 316-mm. High weight has been assigned since high rainfall is more favorable for high groundwater potential. Recharge of water depends on the amount of rainfall [53]. Data of the present study showed arrange of rainfall from 73.8 to 316 mm as shown in Fig. 10. Random points were taken along the study area for rainfall calculation. Rainfall and groundwater have a strong beneficial association, according to several studies [23].

3.1.9. *NDVI*

Owing to the improved surface storage element, vegetation is able to collect rainfall on its leaves and branches, which increases evapotranspiration and prolongs the time required for the soil to recharge. The NDVI, a vegetation index, is often used to explain the growth cycle of plants. Five NDVI classes were obtained during our analysis (Fig. 11). The lowest NDVI values (−0.13–0.01) were found in small parts of the study area where built area is found while the highest NDVI values (0.21–0.53) were found mostly in inland areas.

3.2. *Validation of groundwater zonation*

Models lack scientific value in the absence of a validation mechanism [54]. Data on water depth/water table from several wells

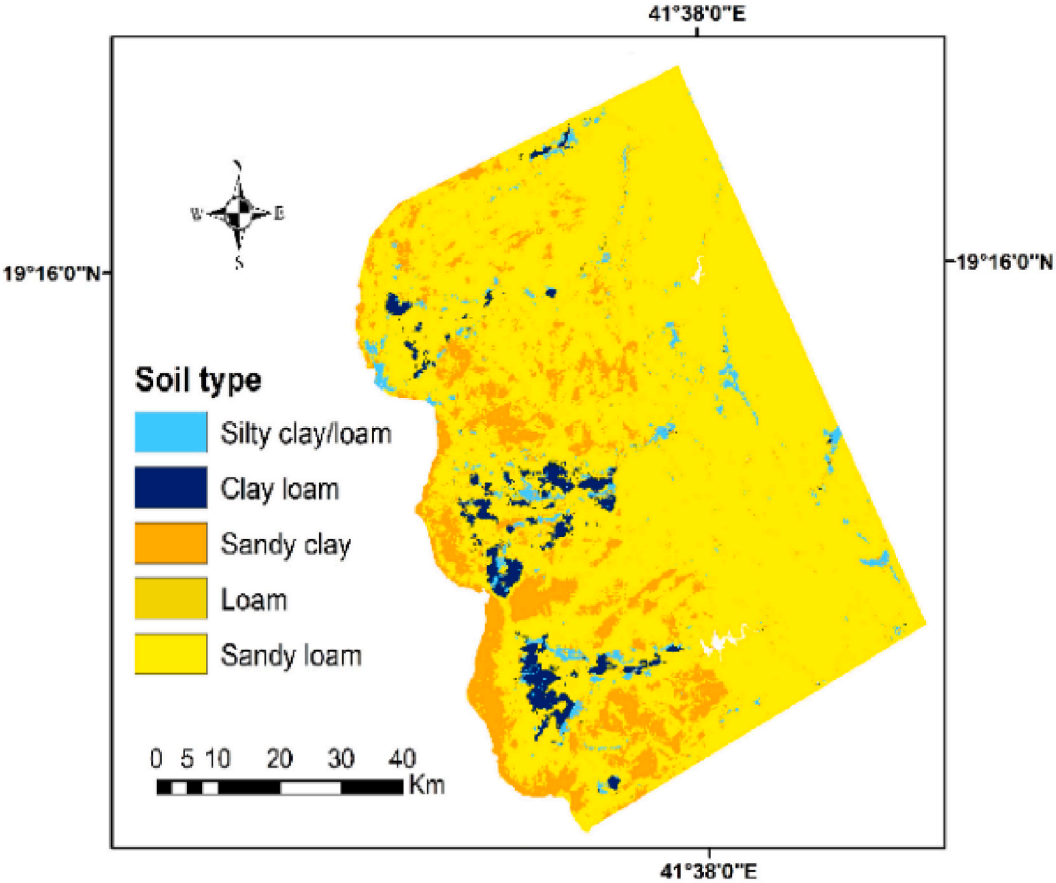

Fig. 9. Soil type of the study area.

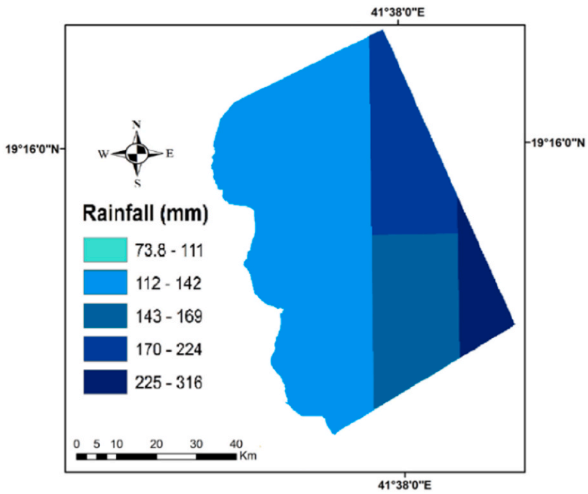

Fig. 10. Average rainfall of the study area.

were acquired with their global positioning system (GPS) locations in order to verify the study's findings. As seen in, the research area's water depth ranged from 0 to 66 m as shown in Fig. 12. The accurate data from the field study were overlaid with the delimited GWPZ data. The majority of the wells with high and medium groundwater depths were found inside GWPZs with extremely high and high occurrence of groundwater, according to the overlay analysis. The Join and Relate tool were used to geographically join the groundwater table data to the shape file.

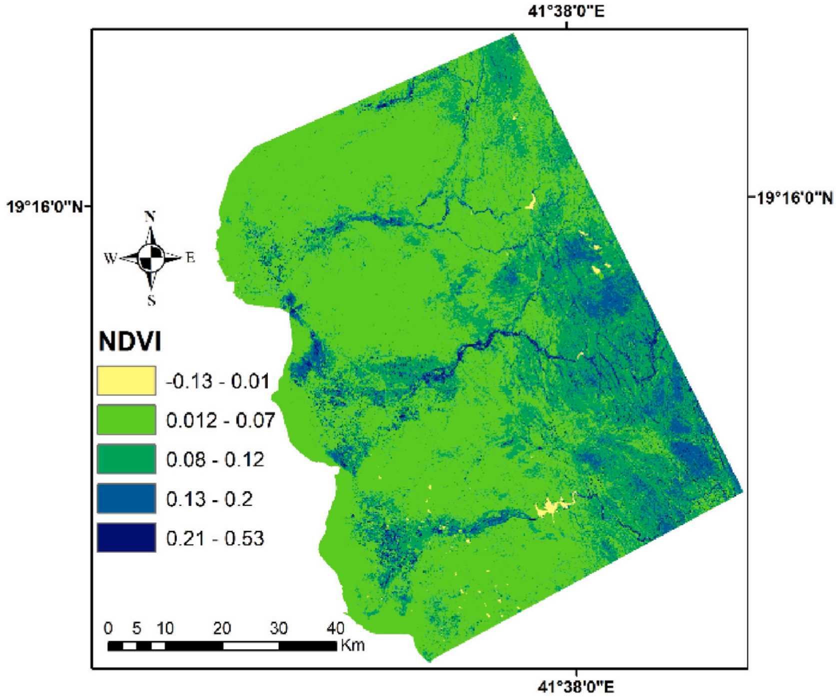

Fig. 11. NDVI of the study area.

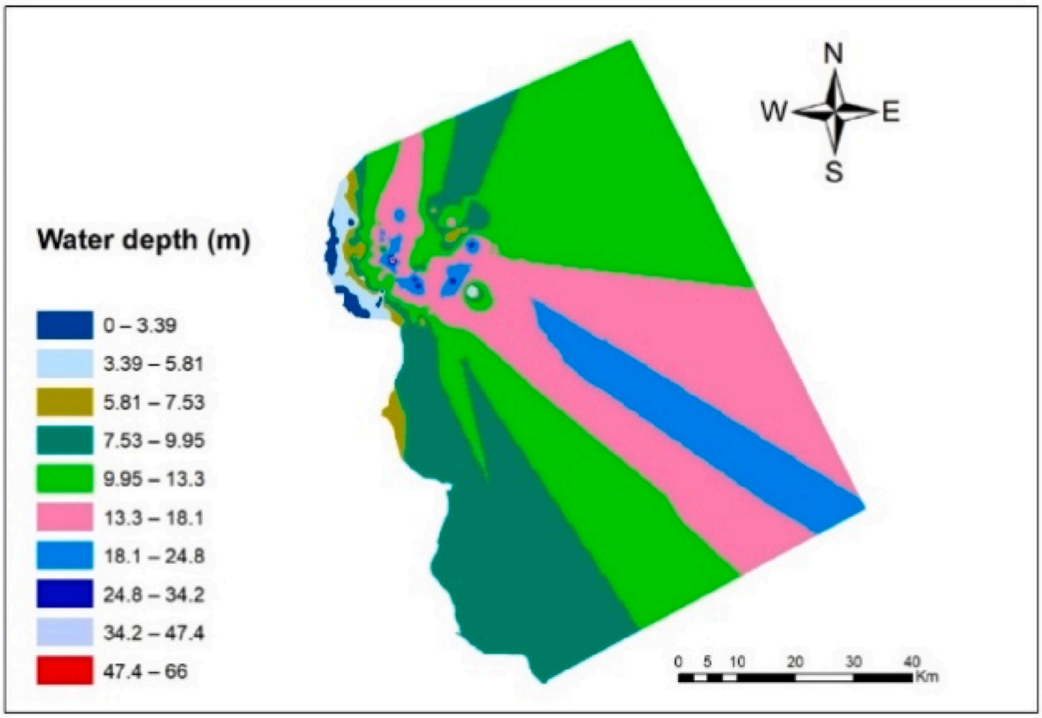

Fig. 12. Water depth (m) of different wells along the study area.

3.3. Groundwater potential zones

Management and continuous production of a region rely greatly on a deeper understanding of groundwater potential. This type of knowledge is required for the long-term groundwater management. A comprehensive evaluation of the resource is necessary due to the temporal and spatial variability of groundwater supply. GWPZs were identified for this study by incorporating several parameters, including the NDVI, rainfall, soil type, curvature, LD, slope, DD, altitudes and LULC. Furthermore, the AHP was used to determine percentages and rankings for each category [28]. These results agree with those applied by Ref. [45]. Classifications of natural breaks (Jenks) state that natural groupings present in the data serve as the basis for classes. Class splits are designed to maximize the distinctions between classes while grouping similar values together in the best possible way. The final GWPZs map (Fig. 13) indicated one of the categories in a qualitative form, such as (1) Very poor, (2) Low, (3) Medium, (4) High, and (5) Very high. Findings indicated that 31.09% (182944.4 km^2) of the area had very poor groundwater potential, while 32.77% (192838.1 km^2) of it had poor groundwater potential, 21.12% (124273.5 km^2) had medium groundwater potential, 10.95% (64446.8 km^2) had low groundwater potential, and 4.04% (23781.06 km^2) had a very high groundwater potential zone as shown in Table 6. According to Fig. 13, the northernmost region of the study region has a relatively low potential due to its low permeability, higher elevation, and moderate slopes. Low heights, lower slopes, and high drainage densities are where the watershed's good and excellent GWPZs are situated. Additionally, zones with high groundwater potential are associated with high penetration rates [55]. This study's finding of heterogeneity is Funding by the fact that groundwater potential varies across space and time even within the same basin on scales of only a few meters. The model results reveal that geology and slope, which are the primary factors, have a stronger impact on the occurrence of groundwater in the studied area. In order to predict groundwater potentiality, comparable research for identifying GWPZs have been carried out all throughout the world [56]. Arumugam et al. (2023) demonstrates that the GWPZ map applied by the geospatial approach is a reliable and cost-effective technique and can be adopted to any part of the world. Nevertheless, the current study had very little access to these data. Therefore, it is exceedingly difficult to validate the GWPZ results. As agreed with Azande et al., 2015, who conducted a study in Iran using the same model (AHP) with 10 factor maps. Both investigations were conducted in a very plain location with a large number of bore wells providing data on the water table, yield, and aquifer in-depth information. Remote sensing and geographic information systems (GIS) are crucial when combined with the AHP technique to give access to potentially significant advanced analytics for mapping and simulating groundwater resources [57]. Ehsan et al [58] stated that using AHP and data of remote sensing improve groundwater

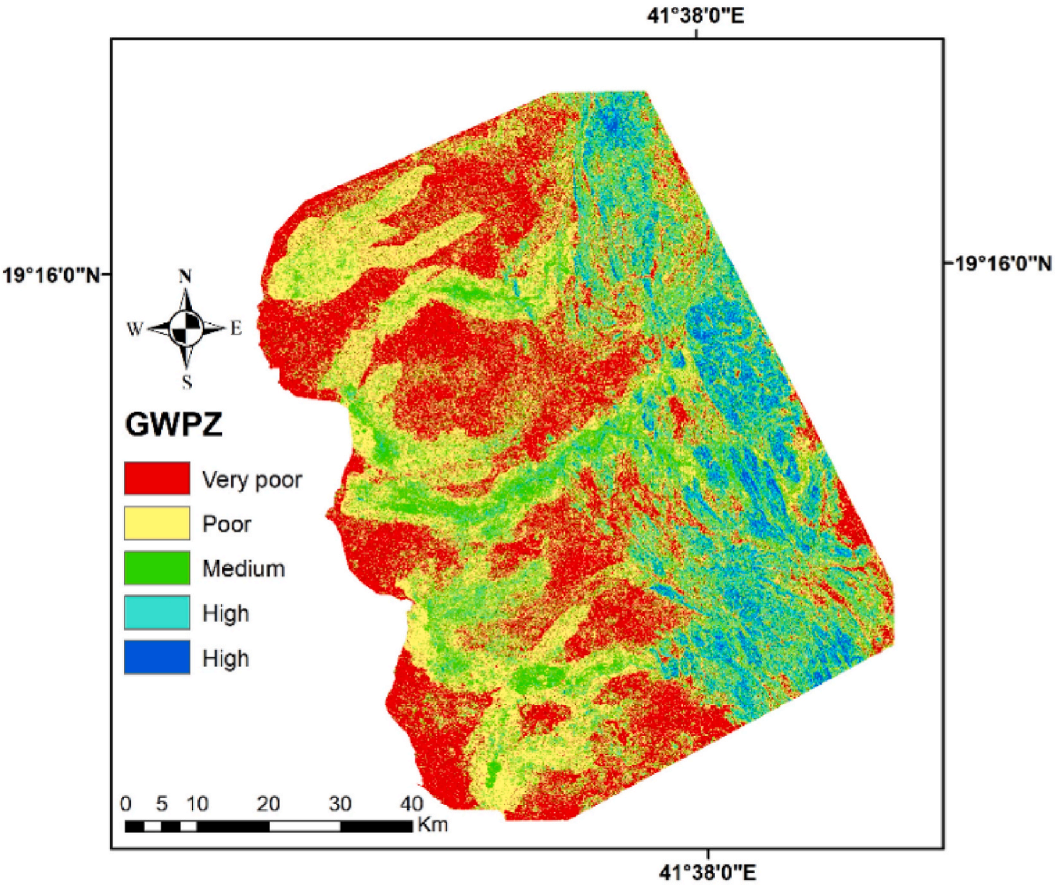

Fig. 13. Groundwater potential zones map.

Table 6
The coverage of the different GWPZs.

Class (Possibility)	Area in (Km^2)	Area in (%)
Very poor	182944	31.097
Poor	192838	32.77
Medium	124273	21.124
High	64446	10.95
Very high	23781	4.0424

management for the future practices. An effective methodology for the spatiotemporal monitoring and evaluation of groundwater resource potential zones combines the application of RS and GIS with AHP. Suitability maps help to understand the behavior to environmental problems, which funded environmental planners with the necessary baseline [59,60].

4. Conclusion

One of the biggest worries in many regions especially in arid is the rising demand for fresh water, therefore zonation of groundwater using cost effective technology is necessary to fulfil the requirements of fresh water. Using RS, GIS, and AHP, the main aim of this work was to build a simple and accurate method for detecting the groundwater potential zone in Al Qunfudhah city, Saudi Arabia. Some environmental factors were extracted from remote sensing data; NDVI, LD, DD, TRI, rainfall, TPI, soil type, slope, and LULC as a significant variable. Satty AHP model is one of the best approaches for determining the relative importance of different groundwater research. CI and CR were then used to determine whether the methods were valid. The results revealed that approximately 0.062% of the investigated area has a very high groundwater potential, with the other 66.51% falling between poor and high zones. The present study's groundwater potential zone map provides information to help local government officials, decision-makers, and water stakeholders better water sustainability management in the study region for different uses. This information can save costs, time, and labor with more precision. The absence of field survey data is one of the most restricting limitations of this method. Although groundwater has generally been regarded as a national issue, international cooperation is becoming increasingly important. People's ignorance of a resource's full potential often leads to the onset of conflicts. It is necessary and of the utmost importance to manage the groundwater resources in bordering states. The current level of groundwater efforts is insufficient; in fact, national and regional policies and development goals give groundwater comparatively little consideration. Finally, the present approach of remote sensing data and GIS is very suitable for coastal basin.

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Data availability statement

Data will be made available on request. CRediT authorship contribution statement.

CRediT authorship contribution statement

Fahad Alshehri: Validation, Supervision, Software, Funding acquisition. **Hazem T. Abd El-Hamid:** Visualization, Methodology, Investigation, Conceptualization. **Ahmed Mohamed:** Writing – review & editing, Visualization.

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.

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