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ORIGINAL ARTICLE

GIS-based multi-criteria decision making for delineation of potential groundwater recharge zones for sustainable resource management in the Eastern Mediterranean: a case study

Hazem Ghassan Abdo[1] · **Dinesh Kumar Vishwakarma**[2] · **Karam Alsafadi**[3] · **Ahmed Ali Bindajam**[4] · **Javed Mallick**[5] · **Suraj Kumar Mallick**[6] · **Karikkathil C. Arun Kumar**[7] · **Jasem A. Albanai**[8] · **Alban Kuriqi**[9,10] · **Artan Hysa**[11]

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Abstract

In light of population growth and climate change, groundwater is one of the most important water resources globally. Groundwater is crucial for sustaining many vital sectors in Syria, including industrial and agricultural sectors. However, groundwater exploitation has significantly escalated to meet different water needs especially in the post-war period and the earthquake disaster. Therefore, the goal was this study delineation of the groundwater potential zones (GPZs) by integrating the analytic hierarchy process (AHP) method in a geographic information systems (GIS) within the AlAlqerdaha river basin in western Syria. In this study, ten criteria were used to map the spatial distribution of GPZs, including slope, geomorphology, drainage density, land use/land cover (LU/LC), lineament density, lithology, rainfall, soil, curvature and topographic wetness index (TWI). GPZs map was validated by using the location of 74 wells and the Receiver Operating Characteristic Curve (ROC). The findings suggest that the study area is divided into five GPZs: very low, 21.39 km^2 (10.87%); low, 52.45 km^2 (26.65%); moderate, 65.64 km^2 (33.35%); high, 40.45 km^2 (20.55%) and very high, 16.90 km^2 (8.58%). High and very high zones mainly corresponded to the western regions of the study area. The conducted spatial modeling indicated that the AHP-based GPZs map showed a remarkably acceptable correlation with wells locations (AUC = 87.7%, n = 74), demonstrating the precision of the AHP–GIS as a rating method. The results of this study provide objective and constructive outputs that can help decision-makers to optimally manage groundwater resources in the post-war phase in Syria.

Keywords AlAlqerdaha river basin · Water resources · Analytical hierarchy process · Groundwater potential zones · Receiver operating characteristic curve

Abbreviations

GPZs	Groundwater potential zones
MCM	Million cubic meters
GIS	Geographic information systems
AHP	Analytic hierarchy process
RS	Remote sensing
ROC	Receiver operating characteristic curve
AUC	Area under the curve
MCDA	Multicriteria decision analysis
WoE	Weights of evidence
WoA	Weighted overlay approach

Extended author information available on the last page of the article

Introduction

Groundwater is a vital and finite resource, crucial for life on Earth (Dentico and Ghribi 2023; Baghel et al. 2023). It serves various uses on a large scale, such as domestic, industrial and agricultural. Groundwater demand has significantly escalated in developed and developing countries over recent years to meet the water requirements of domestic, industrial, and agricultural needs (Rajendran et al. 2023; Biswas et al. 2020; Melese and Belay 2022). Continuously increasing groundwater consumption due to massive population density, a growing area of irrigated farming and less environmentally significant economic advancement has put enormous stress on its prudent utilization (Lecart et al. 2024; Elvis et al. 2023; Sherif et al. 2023; Alsafadi et al. 2023). Globally, domestic, industrial and agricultural applications account for approximately 36, 27, and 42% of total groundwater use, respectively (Taylor et al. 2013; Bera et al. 2020; Genjula et al. 2023; Ahmad et al. 2023).

Groundwater occurrence is primarily controlled by geological, climate-related, physiographic, and ecological factors (Pagano et al. 2023). The underlying strata's lithology and the aquifer's permeability are the primary determinants of groundwater movement (Rezaie-Boroon et al. 2014; Barua et al. 2021; Moodley et al. 2023). Underground water levels have dropped in recent decades as a result of overuse and ineffective management measures (Uc Castillo et al. 2023; Nosrati and Eeckhaut 2012). As a result, One of the most important tactics in this field is managing groundwater resources by exploring and using them in accordance with aquifer potential (Haghizadeh et al. 2017; Ikirri et al. 2023; Rahmati et al. 2015; Muavhi et al. 2023). Thus, the consideration of effective approaches for evaluating locations with a high potential for groundwater exploitation has become an urgent need, using contemporary data preparation and integration methodologies and innovative decision-making processes in this scope (Allafta et al. 2020; Das et al. 2022; Arun Kumar et al. 2021).

Delineation of groundwater potential zones (GPZs) is one of the most important and most modern tools used in groundwater management on the river basin scale. Importantly, the conventional methods for delineating GPZs are uneconomical, time-consuming, highly expensive, sometimes ineffective, and have some limitations. As such, different studies have been published on the delineation of GPZs map with thematic layer data such as drainage patterns, lithology, topography, and soil types using GIS and RS techniques (Ikirri et al. 2023; Rather et al. 2022). Recently, multicriteria decision analysis (MCDA), modeling of weights of evidence (WoE) and probabilistic models were applied to the delineation of GPZs (Bhuyan and Deka 2022; Islam et al. 2023). Other analyzes that used machine-learning models, including decision trees, fuzzy logic, and numerical models, yielded more sophisticated results (Kordestani et al. 2019). Attempts have been made to integrate RS and geophysical surveys with GIS to extract additional thematic layers (Magaia et al. 2018). The efficiency of the formulation differs from one study to another, some are more effective, accurate, time-saving, and cost-effective, whereas the traditional methods are time-consuming (Bhuyan and Deka 2022; Baba et al. 2022).

The analytic hierarchy process (AHP), developed by Saaty (1980), is considered a commonly utilized approach with MCDA for solving socioeconomic decision-making problems (Alsafadi et al. 2020; Sarkar et al. 2022; Rendana et al. 2023). The AHP model simplifies complicated judgments by creating several pair-wise comparisons, and then combining the findings (Saaty 2001). The integration between the AHP model and Geographic Information Systems (GIS) technologies is a valuable tool for developing GPZs maps worldwide. However, Several studies have utilized this tool to map GPZs (Abrar et al. 2022; Kumar and Krishna 2018; Rahmati et al. 2015; Roy et al. 2022; Golla et al. 2022; Ki et al. 2023).

Groundwater in Syria is one of the crucial foundations for supporting the process of economic and social development, especially in the post-war phase (Baba et al. 2021; Alrawi et al. 2022). The development of a multi-criteria spatial model that enables reliable demarcation of regions constitutes an urgent research gap at the level of creating flexible and sustainable groundwater management strategies in Syria in the face of current and future challenges. Further, the western region of Syria received thousands of internal refugees during the war, which led to an increase in demand for more groundwater resources. Thus, the novelty of the current assessment is the use of integration between AHP and GIS in mapping the western region of Syria, which has witnessed shocking social and economic changes as a result of the war (Abdo and Richi 2024). Furthermore, the method of providing and deriving the spatial data needed to develop a GPZs map represents a constructive approach to applying this assessment in other areas of Syria. The novelty presented in this assessment constitutes a unique aspect that provides a more comprehensive understanding of the groundwater system that contributes to recovery from the consequences of the war in Syria. This evaluation assumes that the combination of AHP and GIS will enable accurate and reliable delineation of the GPZs map in an area that has undergone significant spatial changes. Furthermore, the availability of remote sensing (RS) data provides an objective alternative to most of the missing data needed to complete this assessment.

The ultimate goal of this study is to develope a GPZs map utilizing geospatial technologies and the AHP approach. The environmental causal factors were used to interpret GPZs in the current investigation. The results of this assessment will provide important values to decision-makers in the water sector, specifically in the post-war stage in Syria.

Study area settings

The AlAlqerdaha River is located in the coastal region of western Syria between latitudes of 35°0.50′0.48″ and 35°0.38′0.33″ N and 35°0.54′0.47″' and longitude of 36°0.21′0.59″ E, with an area of 196.8 km^2 (Fig. 1). The study area is delimited to the north by Al-Maddike river basin, to the south by Al-Porghool river basin, to the east by the Orontes River basin, and to the west by the Mediterranean. The territory consists of various and complex geological formations, including *Jurassic*, *Cretaceous* and *Quaternary*. *Cretaceous* and *Cretaceous* formations, which cover the most extensive distribution in the study area, consist of limestone, dolomite, marls and limy marl. These

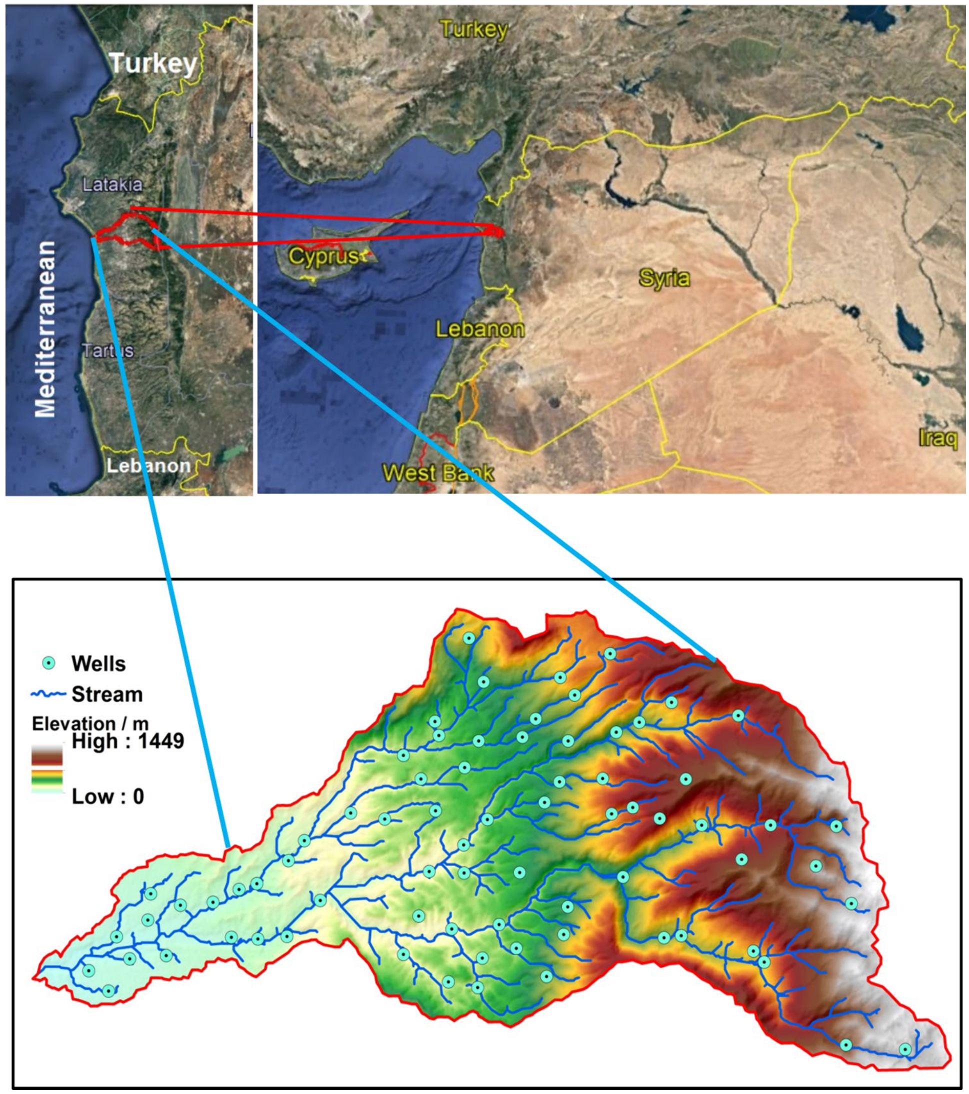

Fig. 1 Study area location

structures are exposed to an accelerated superficial and implicit karstification dissolution process and are subject to severe tectonic shearing (Abdo 2020; Younes et al. 2023). Moreover, there is spatial variation in the permeability of these formations due to the varying lithological properties. *Quaternary* covers the western parts, especially the floodplain and along the courses of the river network. These formations fundamentally consist of fluviatile gravels, boulders, sandstones, marine sandstones and deposits. These formations are considered the most permeable as compared to the *Jurassic*, *Cretaceous* formations. The study area belongs to the mass of the Syrian coastal mountains which witnessed many tectonic activities, forming many regional faults, folds, grabens and catchments (Abdo and Salloum 2017). Geological lineaments form paths for groundwater. Hydrologically, the AlAlqerdaha river basin belongs to the Syrian coastal basin Unit on the eastern Mediterranean coast. The AlAlqerdaha River is classified as a seasonal river due to the prevailing geographical conditions. It consists of two main tributaries known as the Al-Shihawi and Al-Jour rivers. Al-Thawra Dam was built on the Shehawi River, mainly with the aim of securing irrigation water. Meanwhile, the groundwater system consists of an expansive amount of groundwater in three sedimentary hydrogeological aquifers, including: *Jurassic*, *Cretaceous* and *Quaternary* aquifers.

The study basin can be divided into three main geomorphological sectors. The flat sector (0–100 m) is characterized by wide floodplains and high sedimentation values. While the hilly (100–400 m) and mountainous (400–1449 m) sectors are characterized by steep slopes and instability of slopes. The Alqerdaha River basin is primarily sited in a moist climate *Csa* according to the Köppen – Geiger climate category (Mohammed et al. 2020a, b). The average summer temperature is 24.7° while in the winter is 9.8°. The annual rainfall is between 1100 and 1457 mm. The vegetation system mainly consists of both agricultural and wild vegetation. Agricultural vegetation includes field crops, olive trees, and citrus fruits While the wild vegetation consists of scattered forest systems with great diversity. Wild trees include *Cypress*, *Pine*, *Elm* and *Acacia* (Abdo 2018).

The population of the Madros Basin is 81,746 according to national statistics carried out in 2022. Agricultural activity is considered the most important economic sector in the region.The depths of the aquifer range from 5 m in the western plain areas to 266 m in the mountainous eastern parts. The process of pumping groundwater is subject to complex obstacles, especially the availability of electrical power carriers in the study area. The daily pumping rate reaches about 5000 m^3/day in the various monitored wells. All residents of the basin depend on groundwater resources for their lives and economic activities. The use of the groundwater supply in the study area is determined for the purposes of domestic use and drinking, in addition to other economic activities, including agriculture, tourism, and industry.

Methodology

Data collection and processing

Data are employed and acquired from diverse sources to analyze the GPZs. Table 1 lists all the satellite images and acquired data in precise detail. During field surveys, the handheld GPS is used to collect soil samples and locate existing wells at various locations within the basin. The laboratory tested these samples for particle size distribution and water permeability. The entire study used ArcMap v. 10.4.1 applications to process the data. In Fig. 2, all the procedures employed in this study are listed.

In a GIS context, data was derived and analyzed at a resolution of 12.5 m using the following spatial analysis tools: Resample, Resize, Euclidean Distance, Interpolation, Tabulation, Conversion, Raster Calculator, and Reclassification tools. Similarly, slope angle and curvature layers were derived utilizing Digital elevation model (DEM) depending on *Surface Analysis* tools in ArcMap v. 10.4.1 software. The maps of the geomorphology and geology of the AlAlqerdaha River were prepared using the general geomorphological and geology maps in Lattakia Governorate by clipping method. Also, geological lineaments were digitizing from the general geological map. Landuse/landcover (LULC) layer of 2021 was produced by the supervised classification method (maximum likelihood classifier). Topographic wetness index (TWI) and drainage density (DD) layers were derived by processing DEM with surface analysis and hydrology tools. The soil map was derived from the general soil types map (1/50.000) produced by Al-Hanadi Center for Agricultural Research–Directorate of Agriculture in Lattakia Governorate. In this regard, the inverse distance weighted (IDW) method was used to produce the spatial distribution of precipitation values map. Moreover, the distance from the faults was investigated by using the Euclidean distance tool.

Criteria selection

The selection of criteria affecting the delineation of GPZs map is one of the controversial stages in such studies. With the aim of objective analysis, a set of methodological considerations were relied upon in selecting conditioning

Table 1 Thematic data layers of environmental factors to interpret GPZs and sources of data

Parameter	Data source	Data format
Slope	Digital elevation model: Alaska Satellite Facility (ASF), ALOS, 12.5 m Spatial Resolution (https://vertex.daac.asf.alaska.edu/)	Spatial raster grid data (.tif)
Geomorphology	Geomorphological map 1/50,000 scale (Ministry of Oil and Mineral Resources (MOMR)—Geology Directorate, Lattakia Governorate	Spatial vector data (.shp)
Lithology	Geological maps 1/50.000 MOMR, Geology Directorate, Lattakia Governorate	Spatial vector data (.shp)
Topographic wetness index	Digital elevation model: Alaska Satellite Facility (ASF), ALOS, 12.5 m Spatial Resolution (https://vertex.daac.asf.alaska.edu/)	Spatial raster grid data (.tif)
Lineament density	Geological maps 1/50.000 MOMR, Geology Directorate, Lattakia Governorate	Spatial vector data (.shp)
Land use/land cover	Landsat OLI-TIRS, 2021 (USGS Earth explorer)	Spatial vector data (.shp)
Drainage density	Digital elevation model: Alaska satellite facility (ASF), ALOS, 12.5 m Spatial Resolution (https://vertex.daac.asf.alaska.edu/)	Spatial raster grid data (.tif)
Soil	Soil maps 1/50.000 (Al-Hanadi Center for Agricultural Research–Directorate of Agriculture in Lattakia Governorate)	Spatial vector data (.shp)
Rainfall	General Directorate of Meteorology–Damascus Governorate	Spatial vector data (.shp)
Curvature	Digital elevation model: Alaska satellite facility (ASF), ALOS, 12.5 m Spatial resolution (https://vertex.daac.asf.alaska.edu/)	Spatial raster grid data (.tif)

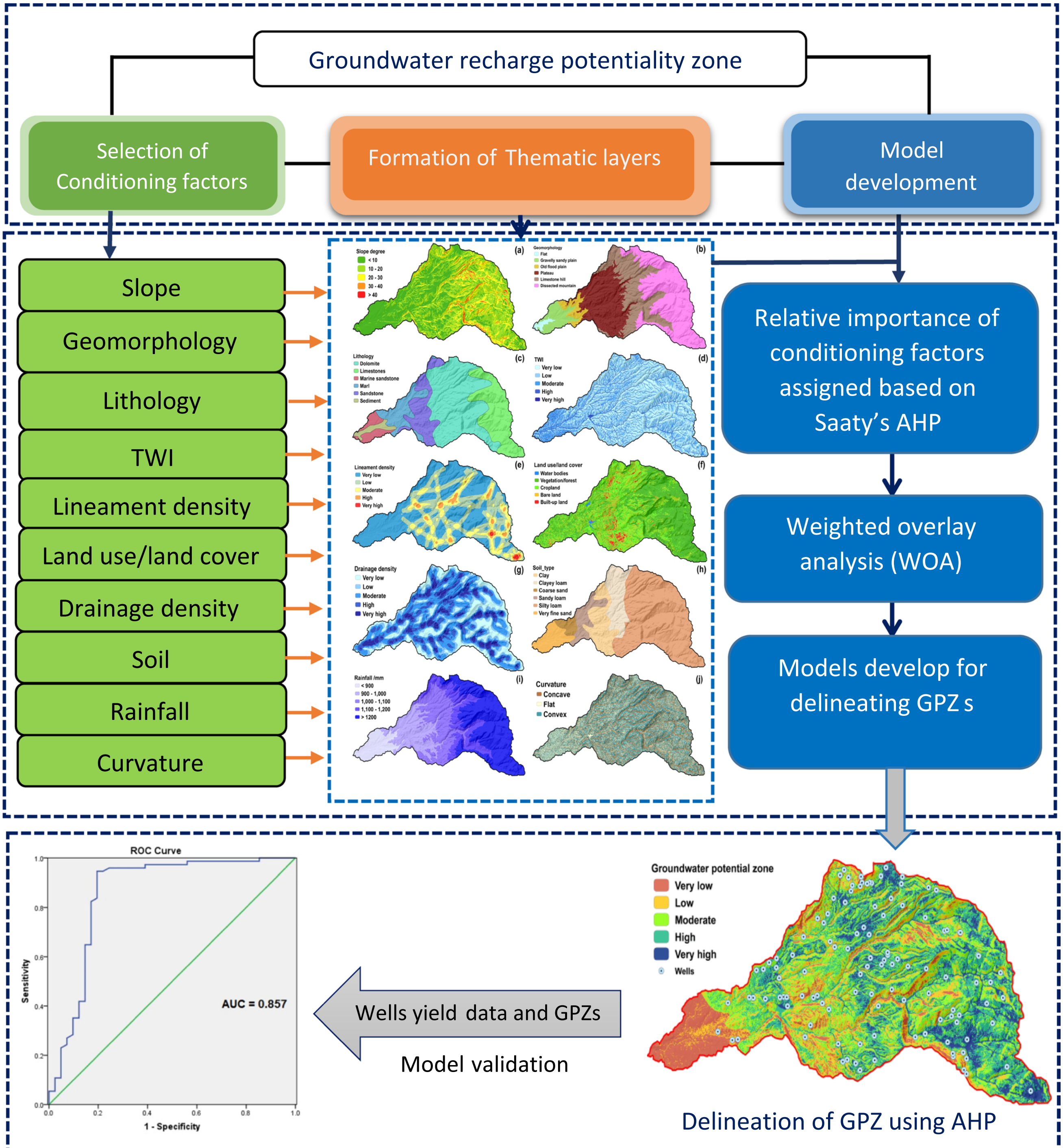

Fig. 2 Schematic representation of workflow showing the methodology

factors, including the geographical characteristics of the AlAlqerdaha River, and it's related database (Benjmel et al. 2020). Satellite imagery is essential to depict the basin physiographic conditions, i.e., LULC, slope, drainage density, fractures, faults, and cleavages, at large spatial scales. Ten thematic maps, including curvature (CV), drainage density (DD), slope (Sl), geomorphology (Ge), lithology (Li), lineament density (LD), LU/LC, rainfall (RF), soil type (So), and topographic wetness index (TWI) layer were created using conventional and geospatial environment that helps to assess the GPZs of the western part of Syria. Several researchers used characteristics such as these to assess and evaluate groundwater resources for GPZs delineation (Table 2).

Table 2 Methods and parameters used for GPZs mapping

Parameters	Methods	References
Drainage, drainage density, geology, lineaments density, LULC, and soil type	AHP	Panahi et al. (2017)
Drainage density, lineament density, lithology, LULC, rainfall, slope, and soil type	AHP	Al-Shabeeb et al. (2018)
Distance to the river, drainage density, geomorphology, lineament density. lithology, LULC, rainfall, slope, and soil type	AHP	Allafta et al. (2020)
Drainage density, elevation, geology, geomorphology, lineament density, LULC, rainfall, slope, and soil type	AHP	Saranya and Saravanan (2020)
Curvature, drainage density, geomorphology, lineament density, LULC, rainfall, slope, soil type, and TWI	AHP	Bera et al. (2020)
Lithology, rainfall, geomorphology, slope, drainage density, soil, LULC, distance to the river, and lineament density	AHP	Allafta et al. (2020)
Drainage, drainage density, geology, geomorphology, lineaments, LULC, and soil type	AHP	Golla et al. (2022)
Drainage density, geology, geomorphology, lineament density, LULC, rainfall, slope, soil type	AHP	Roy et al. (2022)
Drainage density, fault density, geomorphology, lineament density, lithology, LULC, rainfall, slope, and soil type	AHP	Aykut (2021a, b)
Drainage density, geomorphology, lineament density, lithology, LULC, rainfall, slope, and soil type	AHP	Zghibi et al. (2020)
Drainage density, geology, geomorphology, lineament density, LULC, and slope	AHP	Sadek et al. (2021)
Drainage density, geology, geomorphology, LULC, runoff, slope, and soil type	AHP	Kadam et al. (2020)
Drainage density, geology, lineaments density, LULC, rainfall, and slope	AHP	Kessar et al. (2020)
Drainage density, geology, lineaments density, LULC, rainfall, slope, and soil type	AHP	Ndhlovu and Woyessa (2021)
Drainage density, geology, geomorphology, LULC, rainfall, runoff, slope, soil type, and TWI	AHP	Yıldırım (2021)

Calculation of AHP weightage

The thematic layer weights are identified using the AHP (Saaty 1977) which is considered one of the most extensively used MCDA strategies for GPZs and environmental management. Surprisingly, the GIS-based weighted overlay approach (WOA) with AHP has been lauded by MCDA scholars as a viable manner for investigating geo-problems (Alsafadi et al. 2020).

Mathematically, we determined the score of the sub-criteria X_i for each thematic layer on a 0–5 scale (Table 7), and then combined it with the AHP weights W_i. Hence, the GIS-based weighted overlay approach (WoA) was utilized to produce a GPZ final layer as:

$$GPZscore = \left[\sum_{i=1}^{n} X_i \times W_i\right] \quad (1)$$

$$\begin{aligned} GPZs = {} & (X_{Sl} * W_{Sl}) + (X_{Ge} * W_{Ge}) + (X_{Li} * W_{Li}) \\ & + (X_{TWI} * W_{TWI}) + (X_{LD} * W_{LD}) \\ & + (X_{LULC} * W_{LULC}) + (X_{DD} * W_{DD}) \\ & + (X_{So} * W_{So}) + (X_{RF} * W_{RF}) \\ & + (X_{CV} * W_{CV}) \end{aligned}$$

W_i = weightage of criterion, and X_i = score of sub-criteria i, as shown in Table 8, for each thematic layer on a 0–5 scoring scale.

A hierarchical approach creates the problem, including the study's goal and criteria. Second, assuming all the criteria are weighted, we must obtain the weighted criteria. Each thematic map and its sub-features are given weights based on previous knowledge of factor characteristics, local field experience, personal judgment and expert opinion (Halder et al. 2022). Thus, the judgment fundamental scale varying between 1 and 9 was used based on Saaty's table (Saaty 1990) to assign a pair-wise comparison matrix (PWCM) (Table 3).

The basic input is components of the PWCM, matrix A, which may be acquired as a matrix of $n \times n$ factors produced based on Saaty's scale ratios and obtained as

$$A = [a_{ij}], i, j = 1, 2, 3 \ldots \ldots, n \quad (2)$$

As a fundamental rule, matrix A with its components a_{ij} possesses the property of reciprocity, i.e., $a_{ii} = 1$, $a_{ij} = 1/a_i$.

Following that, A is determined as total values per column as follows:

$$\left[\sum_{i=1}^{n} a_{ij} = 1, 2, 3 \ldots \ldots, n\right] \quad (3)$$

Then we normalized the principal matrix (A) after setting its components as matrix B Table 7, which may be characterized as:

$$B = [b_{ij}], i, j = 1, 2, 3 \ldots \ldots, n \quad (4)$$

Table 3 The fundamental scale of absolute numbers for AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance is demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	
Rationales	Ratio arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Each element is given a relative weighting, where matrix B is the normalized matrix A, and its components (b_{ij}) can be calculated as follows:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij} = 1,2,3\ldots\ldots,n} \quad (5)$$

The weight of single criteria was acquired by dividing the sum values of the b_{ij} inside the matrix B's row by the total number of criteria ($n=10$) (Table 4):

$$W_i = \frac{\sum_{i=1}^{n} b_{ij}}{\sum_{i=1}^{n} \cdot \sum_{j=1}^{n} b_{ij}}, i,j = 1,2,3\ldots\ldots,n \quad (6)$$

In which the total weights are equal to 1, i.e., $\sum_{i=1}^{n} W_i = 1$.

It is critical in the AHP approach that the weights produced by PWCM be constant, as well as the judgment matrix consistency, which is defined based on the consistency ratio (CR) coefficients: the consistency index (CI), the random consistency index (RCI) from Saaty's table (Saaty 1980) and eigenvector technique-based maximum eigenvalue (λ), as presented in recent studies (Alsafadi et al. 2022; Kumar and Krishna 2018).

Afterward, the judgment matrix was shaped using PWCM (Table 5). Following that, the relative weights (W) of the factors were computed, i.e., the normalized pair-wise comparison matrix (NPWCM) (Table 6). In order to accept the consistency of the matrix, there must be a CR of less than 0.1.

GIS weighted overlay analysis

After obtaining the final weights for the criteria using the AHP method based on creating pairwise comparisons, making a comparison matrix and providing the acceptable consistency proportion. The weight overlay analysis (WOA) in GIS platform has been implemented to map the GPZs map. Weighted overlay analysis is a method for developing a comprehensive investigation, by allocating a typical scale of values to input elements depending on AHP analysis (Nowreen et al. 2021). This stage included assigning the weights calculated using AHP for each thematic layer. Moreover, a sub-weighting of 1–5 was given to the classes of each thematic layer according to its impact on the groundwater potential, with 1 implying a very low effect, and 5 implying a very important impact. Utilizing the WOA of ArcMap v. 10.4.1 software, the reclassified layers of slope, geomorphology, drainage density, LU/LC, lineament density, lithology, rainfall, soil, curvature and topographic TWI, and their related ratio effect on groundwater potentially, were composed to generate the GPZs map within the study area. The sum

Table 4 The random inconsistency value

Number of criteria	1	2	3	4	5	6	7	8	9	10
Random inconsistency	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 5 PWCM using by AHP method

Factors	SL	GE	GL	TWI	LD	LULC	DD	SO	RF	CV
SL	1	3	4	6	3	4	5	4	7	9
GE	0.33	1	3	4	3	4	6	4	6	9
GL	0.25	0.33	1	3	2	5	6	4	5	6
TWI	0.17	0.25	0.33	1	2	3	3	4	3	3
LD	0.33	0.33	0.5	0.5	1	3	2	3	2	6
LULC	0.25	0.25	0.2	0.33	0.33	1	2	3	2	4
DD	0.2	0.17	0.17	0.33	0.5	0.5	1	2	2	4
SO	0.25	0.25	0.25	0.25	0.33	0.33	0.5	1	2	3
RF	0.14	0.17	0.2	0.33	0.5	0.5	0.5	0.5	1	5
CV	0.11	0.11	0.17	0.33	0.17	0.25	0.25	0.33	0.2	1

Table 6 NPWCM and computation of factor weightage

	Sl	Ge	Li	TWI	LD	LULC	DD	So	RF	CV	Weights	Rank
Slope (Sl)	0.330	0.512	0.407	0.373	0.234	0.185	0.190	0.155	0.232	0.180	**0.280**	1
Geomorphology (Ge)	0.109	0.171	0.305	0.249	0.234	0.185	0.229	0.155	0.199	0.180	**0.202**	2
Lithology (Li)	0.083	0.056	0.102	0.187	0.156	0.232	0.229	0.155	0.166	0.120	**0.148**	3
Topographic wetness index (TWI)	0.056	0.043	0.034	0.062	0.156	0.139	0.114	0.155	0.099	0.060	**0.092**	4
Lineament density (LD)	0.109	0.056	0.051	0.031	0.078	0.139	0.076	0.116	0.066	0.120	**0.084**	5
Land use/land cover (LU/LC)	0.083	0.043	0.020	0.021	0.026	0.046	0.076	0.116	0.066	0.080	**0.058**	6
Drainage density (DD)	0.066	0.029	0.017	0.021	0.039	0.023	0.038	0.077	0.066	0.080	**0.046**	7
Soil (So)	0.083	0.043	0.025	0.016	0.026	0.015	0.019	0.039	0.066	0.060	**0.039**	8
Rainfall (RF)	0.046	0.029	0.020	0.021	0.039	0.023	0.019	0.019	0.033	0.100	**0.035**	9
Curvature (CV)	0.036	0.019	0.017	0.021	0.013	0.012	0.010	0.013	0.007	0.020	**0.017**	10
λ	11											
N	10											
CI	0.11											
RCI: *n* = 10	1.49											
CR	0.07											
CR%	7.46											

λ Maximum eigenvalue; *CI* Consistency index; *CR* Consistency ratio

logic (Eq. 7) was used in the fuzzy overlay of layers using the Raster calculator tool of ArcMap v. 10.4.1 software.

$$\begin{aligned} GPZs = & \left(0.280 * W_{Sl}\right) + \left(0.202 * W_{Ge}\right) + \left(0.148 * W_{Li}\right) \\ & + \left(0.092 * W_{TWI}\right) + \left(0.084 * W_{LD}\right) \\ & + \left(0.058 * W_{LULC}\right) + \left(0.046 * W_{DD}\right) \\ & + \left(0.039 * W_{So}\right) + \left(0.035 * W_{RF}\right) \\ & + \left(0.017 * W_{CV}\right) \end{aligned} \tag{7}$$

The resulting GPZs map was reclassified using the *Natural Breaks* tool into five categories: very low, low, moderate, high, and very high.

Validation

It is a necessary procedure to validate the GPZs map that allows an examination of how well the modeling process performs. For the validation of the GPZs map, 74 wells data were used in the area under the receiver operating characteristics (ROC) curve or precisely AUC method. ROC method is considered a parametric analysis method widely applied in the validation process of GPZs mapping studies (Ahmed et al. 2021; Das 2019; Mohammady et al. 2012; Pourghasemi et al. 2013). Based on the site specifications, the cumulative number of wells available in each potential region and the cumulative areas under various groundwater zones show a correlation, as seen by the AUC plots. The values of the ROC curve, ranging from 0.6 to 1, are

Table 7 Weights of the criteria and scores of the sub-criteria

	Criteria	Sub-criteria	Scoring	Final weights
1	Slope	10 <	5	0.280
		10–20	4	
		20–30	3	
		30–40	2	
		40 >	1	
2	Geomorphology	Flat	1	0.202
		Gravelly sandy plain	5	
		Old flood plain	5	
		Plateau	2	
		Limestone hill	3	
		Dissected mountain	4	
3	Lithology	Limestones	4	0.148
		Marl	3	
		Dolomite	3	
		Sandstone	4	
		Marine sandstone	5	
		Sediment	5	
4	Topographic wetness index (TWI)	Very low	1	0.092
		Low	2	
		Moderate	3	
		High	4	
		Very high	5	
5	Lineament density	Very low	1	0.084
		Low	2	
		Moderate	3	
		High	4	
		Very high	5	
6	LULC	Water bodies	4	0.058
		Vegetation/forest	3	
		Cropland	5	
		Bare land	2	
		Built-up land	1	
7	Drainage density	Very low	1	0.046
		Low	2	
		Moderate	3	
		High	4	
		Very high	5	
8	Soil	Silty loam	3	0.039
		Sandy loam	4	
		Clay	1	
		Very fine sand	5	
		Coarse sand	4	
		Clayey loam	2	
9	Rainfall	> 900	1	0.035
		900–1000	2	
		1000–1100	3	
		1100–1200	4	
		1200 >	5	
10	Curvature	Concave	5	0.017
		Flat	4	
		Convex	2	

categorized as excellent (0.9–1), very good (0.8–0.9), good (0.7–0.8), moderate (0.6–0.7) and poor (0.5–0.6).

Results

Assessment of groundwater potential zones

Slope (Sl)

The slope of a watershed describes the amount of water available for recharging and the harshness of the landscape. Areas featured by steep slopes are linked with a greater runoff volume and reduced infiltration (Melese and Belay 2022a, b). As a result, the slope is one of the most important factors that influencing runoff and infiltration rates. ASF DEM was utilized to generate the slope. The degree of groundwater potential was used to allocate weights to each slope class. An area with a great slope angle has comparatively low GPZs because of the surface flow, in marked contrast with low slope regions which stimulates the infiltration rate (Kanagaraj et al. 2019).

The final slope classified into five categories (Table 7). The < 10° and 10°–20° classes form a considerable area for the river basin. These classes, distributed in the western section, have the lowest slope and topographic height. The rest of the slope categories were specified for the eastern regions (Fig. 3a).

Geomorphology (Ge)

Geomorphology is a key component in determining groundwater potentiality and prospects because it regulates the subsurface flow of groundwater (Rahmati et al. 2015; Das et al. 2022). Prior investigations have reported geomorphology characteristics as an influential factor for delineating GPZs (Ifediegwu 2022a, b; Achu et al. 2020). Here, six types of geomorphological features have been found, i.e., flat, gravelly sandy plain, old flood plain, plateau, limestone hill, and dissected mountain (Fig. 3b). In this regard, the plain geomorphological units are characterized by a higher susceptibility to recharging the groundwater (Barua et al. 2021). Therefore, the gravelly sandy plain and old flood plain have good permeability; therefore, the maximum score has been given to these classes (Table 7).

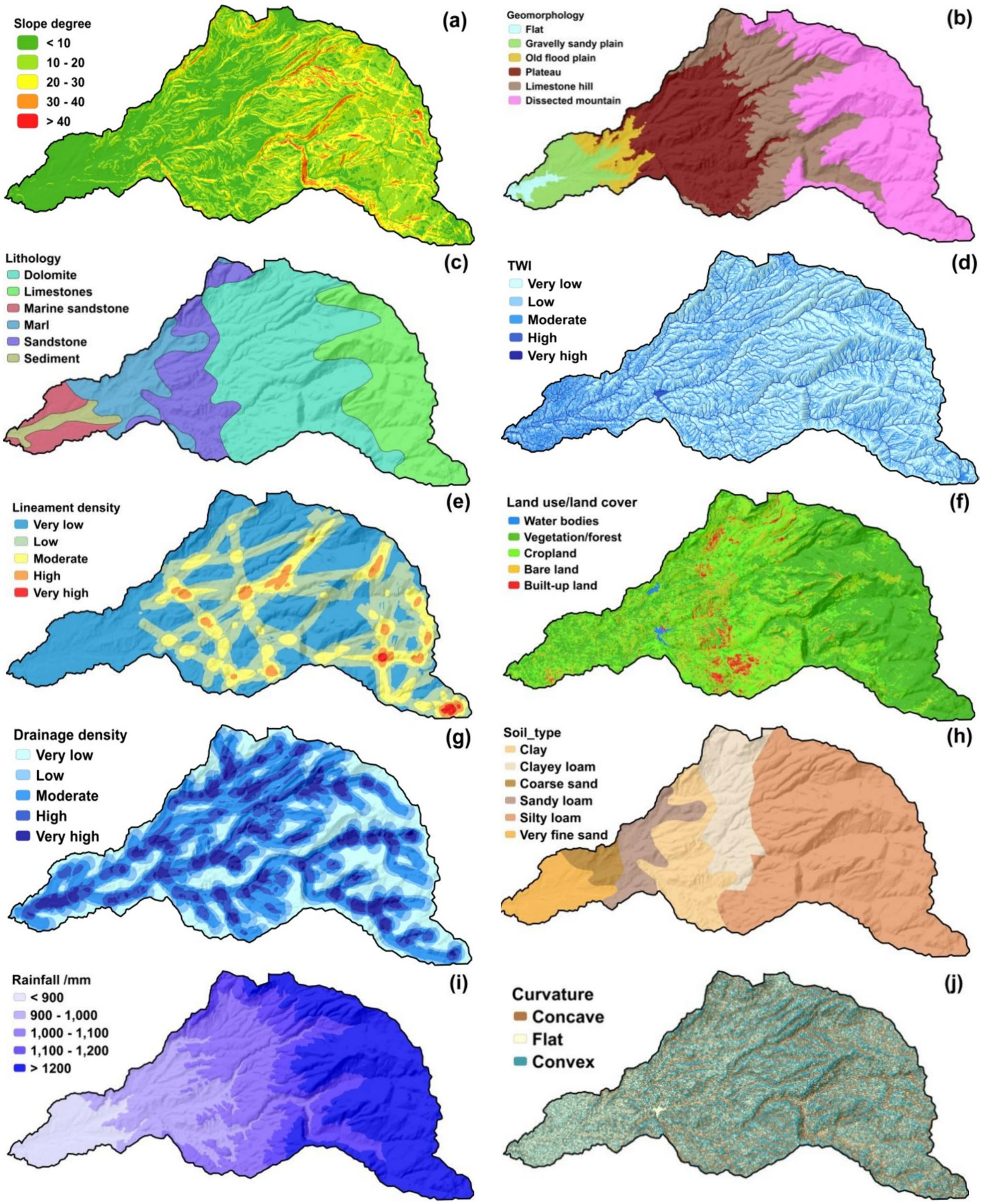

Fig. 3 Layers for generating groundwater potential recharging zones map. **a** slope degree, **b** geomorphology, **c** lithology, **d** TWI, **e** lineament density, **f** LULC, **g** drainage density, **h** soil, **i** rainfall, and **j** curvature

Floodplains were placed basically along the main bed river of the AlAlqerdaha river.

Lithology (Li)

The lithology has a major impact on groundwater recharge as it completely determines the infiltration and flow operations (Ghanim et al. 2023; Tolche 2021). The existence of lithological features affects groundwater potential significantly. Basaltic rock, for example, is solid and hard by nature, with little permeability and porosity. It has been given less importance, whereas alluvium or sandy loamy soils get maximum importance. Minerals, alteration, cracks, and weather conditions contribute to lithology's weighting. This study has extracted seven lithological features: limestone, marl, dolomite, sandstone, marine sandstone, and sediment (Fig. 3c). Marine sandstone and Sediment have been given the highest weightage for maximum groundwater permeability, followed by the rest of the features (Table 7). Fieldwork revealed that the riverine and marine sedimentary environment gives greater water recharge to the aquifer, and this is consistent with many related studies (Barua et al. 2021; Alrawi et al. 2022; Ghadeer 2022).

Topographic wetness index (TWI)

The TWI is an important component of the hydro-geological system developed by Beven and Kirkby (1979). TWI can be utilized to denote the determinant of topographical factors on the magnitude and location of watery sources of surface runoff creation (Melese and Belay 2022a, b). TWI describes potential groundwater infiltration into the groundwater, relying on terrestrial features and their effect on the local topography (Grimm et al. 2018). Many researchers have utilized TWI as a criterion for defining potential groundwater zones (Fig. 3d). It can be calculated using the following equations (Eq. 8):

$$TWI = \ln\left(\frac{As}{\tan(\beta)}\right) \tag{8}$$

where *As* denotes the specified catchment area, and *tan* denotes the slope angle, correspondingly. TWI of the study basin is organized into five categories (i.e., very low, low, moderate, high and very high). The maximum weight was assigned to a very high TWI, which signals a high ability to recharge (Table 7). Moreover, the floodplains along the riverbeds possessed high and very high values of TWI. These areas are highly vulnerable to flooding events, as indicated by many studies (Chaudhry et al. 2021; Uc Castillo et al. 2022).

Lineament density (LD)

The lineaments are the areas of weakness in the geological structures with some linear to curvilinear features, such as fractures, faults and joints with intrinsic permeability characteristics and porosity (Naceur et al. 2022). Lineaments' density significantly impacts groundwater intensity by facilitating the infiltration of water into the groundwater (Al-Ruzouq et al. 2019). The groundwater recharge zone is exactly proportional to lineament density. Lineament analysis is used to better understand the interaction between managed water infiltration and movement and surface water penetration and fracture systems. The groundwater zone in the upper and lower parts of the studied watershed is excellent and promising, according to the lineament density map. In this study, the lineaments were extracted from geological maps, and the spatial density of lineaments was calculated using Eq. 9. The higher the lineament density, the higher weight ascribed to it, and vice versa (Table 7).

$$LD = \frac{\sum_{i=1}^{n} \mathrm{L}_i}{\mathrm{A}} \tag{9}$$

where, $\sum_{i=1}^{n} L_i$ is the total lineament length and A is the coverage area.

Most of the high lineament densities are distributed in Jurassic and Cretaceous geological compositions which have high infiltration rates (Fig. 3e).

Land use/land cover (LU/LC)

Globally, anthropogenic activities have a negative impact on the ecosystem due to deforestation, erosion, groundwater depletion, and loss of soil quality (Younes et al. 2023). Changes in LU/LC are important drivers of groundwater change. The Gaussian Maximum Likelihood Classifier Algorithm (GMLCA) in ArcGIS 10.4.1 software was employed to execute supervised LU/LC classification for the study area (Fig. 3f). The kappa coefficient was used to validate the categorization result. Water bodies, flora, agriculture, bare ground and built-up land are the five main LU/LC classifications discovered, each with a proportionate share of each class. In this study, the weights were given depending on the potential groundwater recharge, relying on the LULC. Cropland and water surface were given the maximum weightage for maximum water permeability and less weightage was given to built-up land. (Table 7).

Drainage density (DD)

The total length of all the streams in the basin is divided by the area to get the DD. GPZs can be found by structural analysis of a drainage network, and a drainage system's quality is mostly determined by its percolation rate index (Yeh et al. 2016). DD is strongly related to groundwater recharge. Greater DD values refer to a high amount of groundwater recharge (Mallick and Rudra 2021; Mallick et al. 2023). The understanding of this factor presents a practical numerical estimation which reflects the attributes of discharge potential, stream channels, soil, vegetation, topography and permeability data (Roy et al. 2020). Finally, ArcMap v. 10.4.1 and ALOS's DEM were used to construct the DD map (Fig. 3g). DD of the study basin is classified into five classes (i.e., very low, low, moderate, high and very high). The maximum weight was assigned to a very high TWI, which signals a high ability to recharge (Table 7).

Soil (So)

The ability of a region's topsoil to infiltrate water has a significant impact on groundwater supply. Grain structure, size, texture, shape and potential porosity can positively influence water percolation (Allafta et al. 2020; Das et al. 2022). Moreover, soil type is governed by pore saturation and dryness conditions that influence increased water entry into the soil (Aykut 2021a, b). The porosity of soil types regulates water passage into the earth. The groundwater potential of coarse-grained soil types (such as lithosols) is good. However, the groundwater potential of fine-grained soil types (ferralsols) is poor (Ifediegwu 2022a, b). As a result, soil characteristics are played a crucial role in controlling the GPZs determination. In the current assessment, the soil types have been categorized into six classes: silty loam, sandy, loam, clay, very fine sand, coarse sand and clayey loam (Fig. 3h). In very fine sand, coarse sand and sandy loam soils, porosity and permeability are higher with more rapid infiltration accelerations, whereas they are significantly lower in clayey loam and clay types (Owuor et al. 2016; Allafta et al. 2020). Therefore, the weight attributed to GPZs is larger for sandy soils (Table 7).

Rainfall (RF)

Rainfall is one of the important climatic element that controls the abundance of groundwater (Mallick and Rudra 2021). It is, therefore, vital to comprehend the spatial dynamics of the rainfall in GPZs investigation. The rainfall data were picked up from the General Directorate of Meteorology–Damascus. The mean yearly rainfall over the western part of Syria is around 1000 to 1200 mm. The maximum concentration is found from July to September. The eastern part receives maximum rainfall (> 1200 mm) and the western part of the Syria area receives > 800 mm of rainfall per year (Fig. 3i). Terrain complexity enacts a vital role in increasing the spatial variability of precipitation values (Uc Castillo et al. 2023). The central-east regions of the river basin were characterized by mountainous and plateau geomorphological units with steep slopes, in contrast to the plain western regions. Thus, groundwater recharge values are greater in the eastern part compared to the other sections. Distribution of precipitation values were classified into five precipitation categories: < 600 mm, 600–800 mm, 800–1000 mm, 1000–1200 mm and > 1200 mm. The higher precipitation areas were assigned a greater weight as shown in Table 7.

Curvature (CV)

The curvature is a kind of curve unit that deviates a linear function or a surface deviates from being flat. In other sense, curvature is a topographic component that represents direction flow and specifying the pace at which the greatest slope direction varies (Melese and Belay 2022a, b). Curvature was derived from DEM data for this investigation. Curvature has been categorized into three sections: convex, flat, and concave, as shown in Fig. 3j and Table 7. Concave and flat curvatures have been given maximum scores in response to groundwater recharge potentiality.

Assessment of GPZs

As one of the most important life-sustaining resources, groundwater has been an ever-declining resource. However, its recharge rate has fallen significantly over the last four to five decades due to anthropogenic activities and skewed development patterns. For the sustainable development of a specific area, it is paramount to become well acquainted with the groundwater potential of that area. This kind of information can be extremely important for planning and carrying out corrective actions that enhance the process of groundwater recharge.

The AHP method has been applied to identify the GPZs based on the weighting of distinct conditioning layers and their sub-classes to determine the weights of these layers. Moreover, decision-making grounded in methodical expert judgment is made with less mathematical complexity, the AHP method is promising tool for evaluating groundwater recharge potential quickly, precisely, and cost-effectively. There are various categories of potential groundwater zones located in the AlAlqerdaha River basin. The GPZ map below shows the extent of each zone in Fig. 4. The AHP method classified the GPZs of the study area as follows: very low, 21.39 km^2 (10.87%); low, 52.45 km^2 (26.65%); moderate, 65.64 km^2 (33.35%); high, 40.45 km^2 (20.55%) and very high, 16.90 km^2 (8.58%) (Table 8).

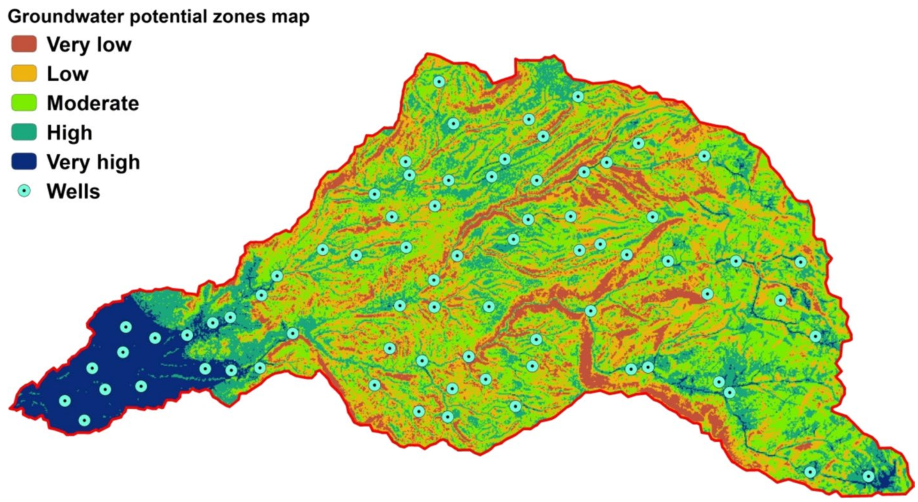

Fig. 4 Groundwater potential zones map generated by the AHP model in the Al-Alqerdaha River basin

Table 8 Different areas of groundwater zone classification

Groundwater zones availability degree	Area (Km^2)	%
Very low	21.39	10.87
Low	52.45	26.65
Moderate	65.64	33.35
High	40.45	20.55
Very high	16.90	8.58

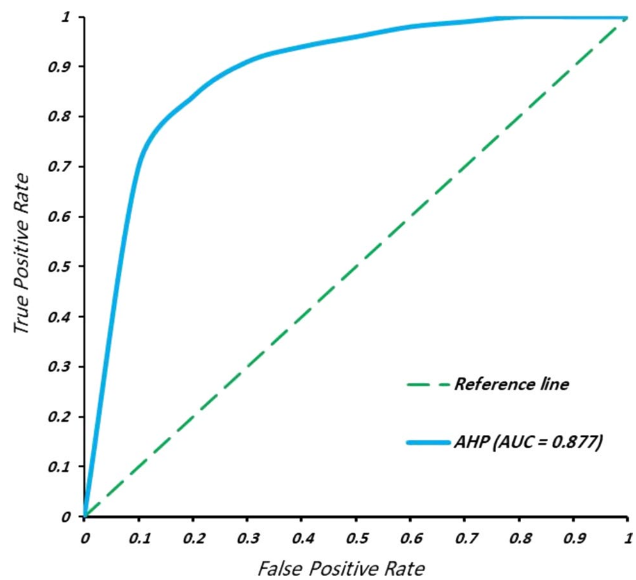

Fig. 5 ROC and AUC curve for the groundwater potential zones map produced by the AHP model

Validation of GPZs map

The accuracy of the groundwater potential mapping utilizing a GIS-based AHP method has been evaluated in numerous studies using the ROC method (Echogdali et al. 2022). The ROC curve and the spatial distribution of 74 wells across the study basin were utilized in this investigation to assess the outcome of GPZs maps. Relevant literature indicates that AUC values ranging between 0.7 and 0.9 indicate satisfactory accuracy for a GPZs map (Maity et al 2022; Rane et al. 2023). Based on Fig. 5, the applied methodological-based integration between AHP and GIS produced a GPZs map with good accuracy in the study area (AUC of 87.7%).

Discussion

The Eastern Mediterranean is among the regions most vulnerable to the consequences of climate change, which will negatively affect the abundance of many natural resources, especially the abundance of water (Aw-Hassan et al. 2014; Abbara et al. 2021). Most of the population of the Eastern Mediterranean region, including Syria, depends primarily on groundwater resources to secure their water requirements for drinking purposes and various socio-economic development processes. In this regard, the groundwater system in Syria is subject to poor management procedures and weak sustainable spatial organization as a result of the consequences of the war (Mohammed et al. 2020a, b). Sustainable management of water resources in Syria is crucial to meeting the requirements of various sectors in the aftermath of the war (Baba et al. 2021). In this investigation, a comprehensive spatial assessment of the GPZs distribution in western Syria was conducted using AHP–GIS integration.

Regarding the spatial distribution of GPZs, the high and very high zones of GPZs are concentrated mainly in the western part of the river basin. This part is considered a riverine and marine depositional environment with highly permeable lithological formations, including sands and sandstones. Moreover, the plain geomorphological characteristics reduce the surface runoff velocity, thus the possibility of higher groundwater recharge. Also, the very high GPZs are determined in the easternmost study basin. The high precipitation values with dissected calcareous lithological formations have greatly enhanced groundwater recharge in those areas. The high and moderate GPZs dominated most of the AlAlqerdaha River basin, especially in the central and eastern parts. These areas are characterized by Marl and Dolomite lithological formations, agricultural and forest vegetation covers, high geological lineaments density and high precipitation rate (1000–1200 mm). Steep slope and low discharge intensity factors combined with low permeability lithological formations achieve low and very low GPZs. These areas, however, are distributed on the central and eastern slopes of the AlAlqerdaha River basin. Overall, the result emphasized the great importance of lithological and geomorphological factors, especially the slope, in controlling the spatial allocation of GPZs in AlAlqerdaha River basin.

The results in this evaluation demonstrated the high efficiency of the AHP model in identifying the zones with high potential for groundwater resources in the study basin. This model achieved high predictive ability with an AUC value of 87.7% in identifying GPZs. This result is consistent with many evaluations conducted in the Eastern Mediterranean (Aykut 2021a, b; Sulaiman and Mustafa 2023). RS and GIS techniques have proven highly efficient in producing a GPZs map in a data-scarce area such as western Syria. Moreover, providing reliable spatial data with proper derivation of its layers represented a major challenge. Therefore, the approach used in this assessment can be applied in other watersheds in Syria, thus enhancing the sustainable management of groundwater resources.

Syria was estimated to have the highest decrease in groundwater storage capacity between January 2003 and December 2014 (Faour and Fayad 2014; Hassan and Krepl 2015; Lezzaik and Milewski 2018) among other Middle East and North African countries. The same study reports that this change sharply correlates with population density. Population density dynamics in Syria are expected to obey certain climate and war-related stresses, as reported between 2006 and 2010 (Kattaa et al. 2010; Mourad and Alshihabi 2016; Ash and Obradovich 2020). Thus, the expected climate and conflict-induced inner migration will directly impact the groundwater storage capacity. At this stage, it could include only LU/LC data as evidence of anthropogenic activities. Due to a lack of available data, we could not integrate the other social criteria into the model. However, future studies must consider the integration of climate-related variables and a broader gradient of socio-political aspects in groundwater prediction models. Diverse scenarios about the future climate and war-related social dynamics will better inform groundwater management authorities to enable a more resilient and sustainable future in countries like Syria and the Eastern Mediterranean. One of the disadvantages of the AHP method used in this evaluation is the definition of class limits and weights assigned to each influencing factor. These weights are determined based on the feelings and experience of experts and the user's ability to distinguish and self-determine the limits of each class. Therefore, using the AHP technique requires extreme caution to achieve the least amount of bias possible (Ki et al. 2023).

Determining GPZs is of utmost importance in western Syria, especially areas with high groundwater potential as a result of high population density. Importantly, this identification can contribute to the speed of socio-economic recovery in the post-war period in the study area by developing the agricultural sector, meeting the population’s water requirements, enhancing tourism and industrial investment opportunities, conserving other natural resources, and establishing water infrastructure projects, especially rain-harvesting reservoirs.

Conclusion

In this study, remote sensing and geographic information system were introduced and evaluated the AHP model as an feasible tool for delineating the GPZs within the AlAlqerdaha basin of the Syrian coastal basin. As a first step toward preparing the thematic permeability layers, we used slope, geomorphology, lithology, TWI, lineament density, LU/LC, drainage density, soil, rainfall, and curvature data. The last step in our methodology was to identify appropriate charge areas, i.e., potential groundwater zones, by overlaying the artificial groundwater recharge with two- and three-dimension drainage map. However, the findings suggest that the AlAlqerdaha River basin area was categorized into five GPZs: very low, 21.39 km^2 (10.87%); low, 52.45 km^2 (26.65%); moderate, 65.64 km^2 (33.35%); high, 40.45 km^2 (20.55%) and very high, 16.90 km^2 (8.58%). High and very high GPZs mainly denoted to the western regions of the River basin. The AHP-based spatial modeling indicated that the GPZ maps showed an excellent acceptable reciprocity with well locations (AUC = 87.7%, n = 74). Additionally, the results of the mapping and AUCs were in good agreement with well data.

This study provided a reliable approach to demarcate GPZs in a unique area in western Syria that suffers from poor groundwater management procedures as a result of the war. The outputs of this assessment provide important values that help local decision-makers create and implement sustainable and resilient groundwater management strategies. Moreover, the approach applied in this evaluation can be implemented on other river basins in Syria.

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Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of interest The authors have no conflicts of interest to declare.

Ethical approval Disclosure of potential conflicts of interest

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Authors and Affiliations

Hazem Ghassan Abdo[1] · Dinesh Kumar Vishwakarma[2] · Karam Alsafadi[3] · Ahmed Ali Bindajam[4] · Javed Mallick[5] · Suraj Kumar Mallick[6] · Karikkathil C. Arun Kumar[7] · Jasem A. Albanai[8] · Alban Kuriqi[9,10] · Artan Hysa[11]

✉ Hazem Ghassan Abdo
hazemabdo@tartous-univ.edu.sy

Dinesh Kumar Vishwakarma
dinesh.vishwakarma4820@gmail.com

Karam Alsafadi
karam.alsafadi@xmu.edu.cn

Ahmed Ali Bindajam
abindajam@kku.edu.sa

Javed Mallick
jmallick@kku.edu.sa

Suraj Kumar Mallick
surajkumarmallick5@gmail.com

Karikkathil C. Arun Kumar
arunkumar.kc@yahoo.com

Jasem A. Albanai
albanay.com@gmail.com

Alban Kuriqi
alban.kuriqi@tecnico.ulisboa.pt

Artan Hysa
ahysa@epoka.edu.al

[1] Geography Department, Faculty of Arts and Humanities, Tartous University, Tartous, Syria

[2] Department of Irrigation and Drainage Engineering, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand 263145, India

[3] Key Laboratory of the Ministry of Education for Coastal and Wetland Ecosystems, Xiamen University, Xiamen, Fujian 361102, China

[4] Department of Architecture, College of Architecture and Planning, King Khalid University, Abha 61411, Saudi Arabia

[5] Department of Civil Engineering, College of Engineering, King Khalid University, Abha, Kingdom of Saudi Arabia

[6] Department of Geography, Shaheed Bhagat Singh College, University of Delhi, New Delhi 110017, India

[7] L&T Technology Services, Hyderabad, India 500081, Telangana

[8] School of Geography and the Environment, University of Oxford, Oxford, UK

[9] CERIS, Instituto Superior T'ecnico, University of Lisbon, 1649-004 Lisbon, Portugal

[10] Civil Engineering Department, University for Business and Technology, 10000 Pristina, Kosovo

[11] Department of Architecture, Epoka University, Tirana, Albania