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Integrated GIS-based multi-criteria analysis for groundwater vulnerability assessment and potential zone mapping in the Ank Djamel basin, northeast Algeria

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ABSTRACT

This study aims to develop an integrated framework for assessing groundwater vulnerability and delineating potential recharge zones within the Ank Djamel basin, located in northeastern Algeria. Utilizing a GIS-based multi-criteria decision analysis combined with remote sensing techniques, this research addresses a critical knowledge gap concerning groundwater vulnerability assessment in semi-arid regions. Four established vulnerability assessment models – DRASTIC, SINTACS, GOD, and SI – were applied alongside the Analytical Hierarchy Process to systematically weigh the influencing factors. The study area, covering approximately 1232 km², exhibits notable spatial heterogeneity in vulnerability levels. Specifically, the SI model classified 34.37% of the basin as highly vulnerable, whereas the DRASTIC model identified 16.68% under the same category, with the GOD model yielding the most conservative estimates. Validation against nitrate concentration measurements corroborated the reliability of the DRASTIC and SI models in capturing agricultural contamination risks. Furthermore, groundwater potential mapping indicated that 40.10% of the area possesses moderate potential, while 11.74% (equivalent to 144.36 km²) demonstrates high and promising potential. Model accuracy was substantiated by a validation rate of 71%, reflected by an area under the curve (AUC) of 0.710. This integrative analytical approach offers a robust decision-support tool for sustainable groundwater resource management, facilitating the identification of protection zones and optimal drilling sites. The study's originality lies in the comprehensive integration and empirical validation of multiple vulnerability models, thereby significantly enhancing their applicability to comparable semi-arid environments. Acknowledging data availability and quality constraints, the framework underscores the importance of incorporating spatial data robustness in future hydrogeological investigations.

Keywords: vulnerability, groundwater potential zone, AHP, GIS, semi-arid, Northeastern Algeria.

INTRODUCTION

Groundwater resources are an essential part of the world's freshwater supplies, supporting human activities such as home usage, industry, and agriculture as well as ecosystems (Idir et al., 2025; Mozas and Ghosn, 2013; Rassou, 2009). The sustainability and quality of groundwater resources are important issues since about half of the world's population relies on them as their main source of drinking water (Battistoni-Lemière, 2022). But these resources are especially susceptible to contamination from man-made and natural sources, endangering their ability to meet present and future demands (Belkoum et al., 2024).

The vulnerability of groundwater in semi-arid locations like Algeria is made worse by the lack of precipitation and the growing reliance on these resources for industrial, agricultural, and household purposes (Abdelaziz and Hakim, 2010; Guest et al., 2006). Groundwater is essential to agriculture, especially in the north, for irrigation. This intense exploitation raises the risk of contamination and salinization, frequently coupled with overuse of pesticides and fertilizers (Bouchemal, 2017; Bourjila, 2023).

These difficulties are aptly demonstrated by the Ank Djamel watershed, which is situated in the Batna and Oum El Bouaghi regions. Aquifer degradation due to salinization, industrial contamination, and overuse for agricultural irrigation are some of the main issues facing this basin (Dinar, 2023). A comprehensive evaluation of groundwater vulnerability in this area is crucial due to these demands.

Despite the availability of various groundwater vulnerability models, their application in the Algerian context faces limitations due to insufficient local data, variability in hydrogeological conditions across semi-arid regions, and the lack of integration with socio-economic factors. Many existing models do not fully capture the complex interactions between natural and anthropogenic influences on groundwater quality and availability in this area. This study hypothesizes that integrating multiple vulnerability indices with AHP-based potential mapping provides a more accurate and decision-relevant model for semi-arid basins like the Ank Djamel sub-basin, improving sustainable groundwater management.

An essential technique for locating at-risk locations, safeguarding public health, and directing sustainable aquifer management plans is groundwater vulnerability assessment (Mehdi and Moustapha, 2024; Kurwadkar, 2017; Abdelmadjid and Omar, 2017; Michael et al., 2013). By taking into account geological, hydrological, and human stresses on resources, it facilitates well-informed decision-making. Concurrently, assessing groundwater potential is an essential strategy for managing water resources sustainably, especially in developing nations where the population is increasing and inadequate management capabilities impact resource availability and quality (Hssaisoune et al., 2020; Hua et al., 2011).

The analytical hierarchy process (AHP), created by Thomas Saaty, offers a structured approach for complex decision-making by organizing problems into hierarchies and facilitating criterion evaluation through pairwise comparisons (Saaty, 1970; Kihm et al., 2024). While traditional groundwater exploration methods are dependable, they are expensive and data-intensive (Wiederhold et al., 2021). Integration of GIS technologies and remote sensing offers a more efficient alternative, enabling detailed resource exploration and decision-support (Hagos et al., 2021; Manderso et al., 2023).

The objective of this research is to provide a comprehensive framework that integrates mapping of groundwater potential and vulnerability assessment in the Ank Djamel sub-basin. The specific goals are to: (1) assess intrinsic aquifer vulnerability using various assessment techniques; (2) map groundwater potential zones using multi-criteria analysis; (3) identify and prioritize vulnerable zones based on anthropogenic pressures and pollution threats; and (4) offer suggestions for sustainable groundwater management strategies.

STUDY AREA

The Ank Djamel sub-basin is 1232 km² in size and includes the provinces of Batna and Oum El Bouaghi in Northeastern Algeria. The basin (Figure 1) has a semi-arid environment with high rates of evapotranspiration and little precipitation. Rising between 800 and 1,200 meters above sea level, the terrain ranges from mountainous peripheries to flat center regions surrounding salt lakes (sebkhats) (Bouali,h et al., 2024).

The geological framework includes diverse formations ranging from Triassic to Quaternary periods, with predominant limestone, sandstone, and alluvial deposits (Figure 2). The central depression contains several sebkhats (Ank Djamel, Guellif, El Maghsel, and Djandli) that influence local hydrogeology. Agriculture represents the primary economic activity, with intensive irrigation practices placing significant pressure on groundwater resources.

The hydrogeological system consists of multi-layered aquifers with varying degrees of confinement. The main aquifer is the region's principal supply of groundwater and is tapped by 351 active wells. From less than 6 meters at Sabkhat

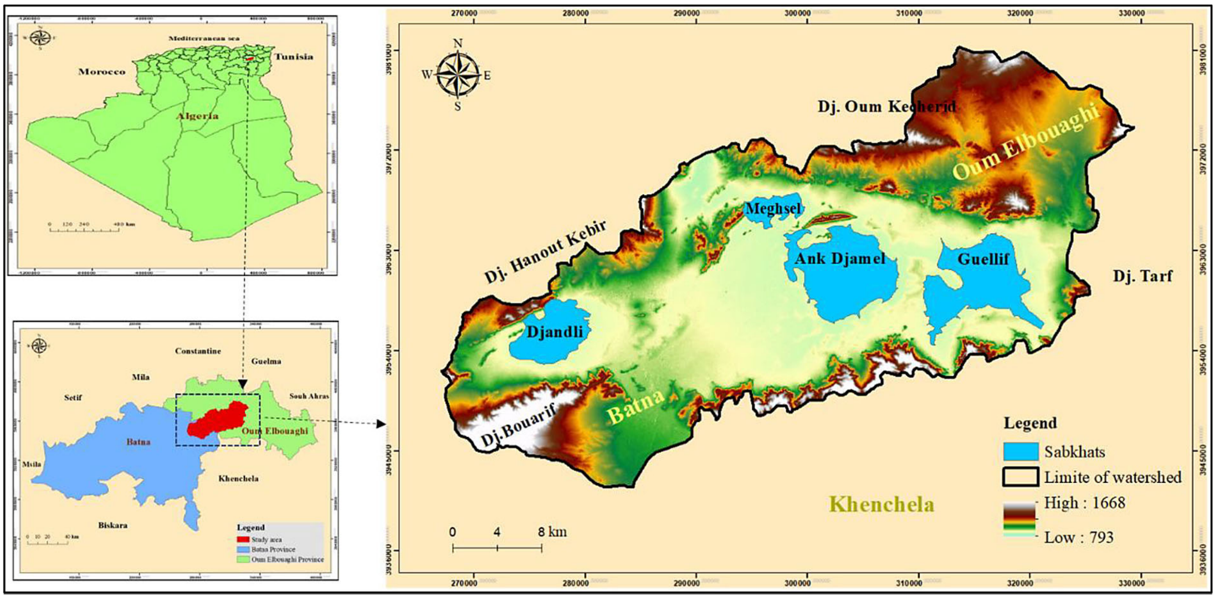

Figure 1. Location map of study area: the Ank Djamel watershed in northeastern Algeria

to more than 31 meters in mountainous regions, groundwater depths in the basin vary greatly.

METHODOLOGY

Data collection and processing

A thorough database that combined hydro-climatic, borehole, cartographic, and alphanumeric data was created. Hydrogeological data from 351 operating wells, digital elevation models (DEM), geological maps, soil maps, Sentinel-2A satellite images for land use classification, and meteorological data from 1992–2022 were the main sources of data.

All of the data were transformed into a uniform raster format with a resolution of 30 × 30 m in order to guarantee uniformity and the highest level of accuracy in spatial analysis. The study was conducted using ArcGIS 10.8 for data processing, interpolation, and analysis.

Groundwater vulnerability assessment

Four internationally recognized vulnerability assessment methods were implemented:

DRASTIC method

Utilizes seven parameters (depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity) with weights ranging from 1 to 5 and ratings from 1 to 10 (Fannakh et al., 2025; Rahim, B et al., 2019). The DRASTIC index is calculated as:

$$DRASTIC = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad (1)$$

SINTACS method

An adaptation of DRASTIC for Mediterranean basin conditions, considering the same parameters but with different weighting scenarios specific to regional hydrogeological and climatic characteristics (Soyaslan, 2025).

GOD method

A simplified approach using three parameters: Groundwater occurrence (confined/unconfined), Overall lithology of the vadose zone, and Depth to groundwater (Richa et al., 2025; Mahrez et al., 2018). The GOD index is calculated as:

$$\mathrm{GOD} = \mathrm{G} \times \mathrm{O} \times \mathrm{D} \quad (2)$$

SI method (susceptibility index)

Focuses on agricultural pollution, particularly nitrates, incorporating five parameters: depth to groundwater, net recharge, aquifer media, topography, and land use, classified according to CORINE Land Cover classification (Fannakh et al., 2025).

The Table 1 presents the vulnerability assessment criteria for four different methods:

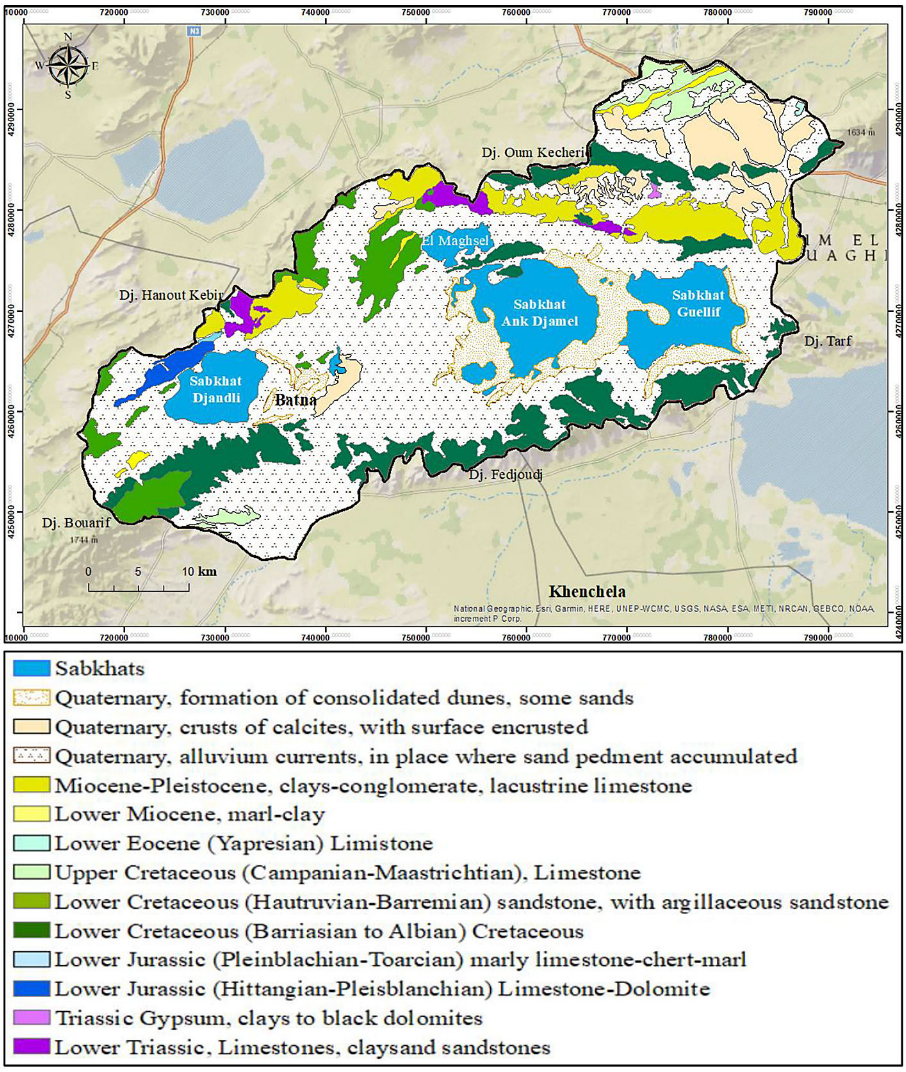

Figure 2. Geological map of Ank Djamel basin (Adapted from geological map of Algeria 1976)

DRASTIC, SI, GOD, and SINTACS. Each method categorizes vulnerability into five levels: very high, high, moderate, low, and very low based on specific numerical ranges.

Groundwater potential mapping

The AHP methodology was employed to integrate ten hydrogeological parameters for groundwater potential mapping:

1. Rainfall – annual precipitation data (1992–2022) processed using inverse distance weighting (IDW) interpolation
2. Geology – lithological formations classified based on hydrogeological significance
3. Slope – derived from DEM, classified into four categories (0–2%, 2–3%, 3–5%, >8%)
4. Drainage density – calculated using ArcGIS network analysis tools
5. Land use/Land cover – extracted from Sentinel-2A imagery using supervised classification
6. Lineament density – identified from DEM using automated extraction techniques
7. Soil type – four main categories (saline, calcareous, calcic, alluvial)
8. Net recharge – calculated using water balance equations and hydrological soil groups
9. Alteration type: four categories based on surface mineral alteration patterns
10. Depth to water – includes data collected from the well site.

Pairwise comparison matrices (Table 2) were constructed based on expert knowledge and literature review, with consistency ratios maintained below 0.1 (Chen et al., 2025; Saaty 1979). The final groundwater potential index (GWPI) was calculated as:

Table 1. Vulnerability assessment criteria for the DRASTIC, SI, GOD, and SINTACS methods (Salem et al., 2025)

Vulnerability	DRASTIC	SI	GOD	SINTACS
Very high	> 200	> 85	0.7–1	> 210
High	161–200	65–85	0.5–0.7	186–210
Moderate	121–160	45–64	0.3–0.5	105–186
Low	80–120	< 45	0.1–0.3	< 105
Very low	< 80	-	-	-

$$GWPI = \Sigma(Wj \times Xi) \quad (3)$$

where: Wj is the normalized weight of the jth thematic layer and Xi is the normalized weight of the ith feature.

In the first stage, a Pairwise Comparison Matrix (PCM) representing the relative relevance of each parameter was created using Saaty's 1–9 scale (Table 3). In order to ensure agreement with recognized research findings in the field, the weights assigned were obtained from prior studies (Saaty, 2008). This method guarantees that the weight assignment procedure is based on research findings and takes into account the most recent knowledge of groundwater potential factors (Suryawanshi et al., 2025; Idir et al., 2025).

The Pairwise Comparison Matrix reveals the relative importance of each thematic layer affecting groundwater vulnerability. Depth to water (25.22%) and type of alteration (17.66%) have the highest weights, indicating they most strongly influence vulnerability assessment, followed by lineament density and soil media. Parameters such as rainfall and net recharge hold smaller relative importance.

Table 2 was created using the analytic hierarchy process (AHP) methodology through the following systematic approach:

1. Assignment of numerical values – the numerical values in Table 2 were assigned based on the relative importance of each criterion for groundwater potential assessment in the study area. These values reflect:
- The hydrogeological characteristics specific to the Annaba region
- The relative influence of each criterion on groundwater occurrence and recharge
- Expert judgment based on field observations and understanding of local conditions
- Previous research on groundwater potential mapping in similar geological and climatic settings
2. Pairwise comparison matrix generation – the pairwise comparison matrix was generated using the GWPZ (Groundwater Potential Zone) Excel-based tool. The process involved:
- Initially assigning importance values to each of the 10 criteria (rainfall, geology, slope, drainage density, LULC, lineament density, soil media, net recharge, type of alteration, and depth to water) based on their significance in the study area
- The GWPZ tool automatically constructed the complete pairwise comparison matrix (10 × 10) from these input values
- The matrix follows Saaty's fundamental scale (1–9), where values represent the relative importance of row criteria compared to column criteria (Figure 3).
3. Matrix properties:
- Diagonal elements equal 1 (each criterion compared to itself)
- Lower triangular values are reciprocals of upper triangular values, maintaining matrix consistency

The tool automatically calculated the eigenvector (priority weights) and consistency ratio (CR = 0.15) Saaty (1980).

The judgments within each thematic layer underwent validation through the application of the consistency ratio (CR) (Equation 4). This metric serves as a crucial tool for evaluating the coherence and logical alignment of decisions made by the stakeholders. By quantifying the degree of consistency in the decision-making process, the CR offers valuable insights into the overall dependability and robustness of the assessments (Suliman, 2022).

$$CR = CI/RI \quad (4)$$

where: RI (The random consistency index) is derived from extensive simulation studies and fluctuates based on the matrix's order. In this study, the RI value is 1.49 since ten variables were employed (Table 4).

CI (consistency index) is calculated, using a specific mathematical formula, which takes into

Table 2. Pairwise comparison between thematic layers

Matrix		Rainfall	Geology	Slope	Drainage density	LULC	Lineament density	Soil media	Net recharge	type of alteration	Depth to water	Normalized principal Eigenvector
		1	2	3	4	5	6	7	8	9	10	
Rainfall	1	1	1/2	1/3	1/2	1/3	1/4	1/4	2	1/5	1/6	2.98%
Geology	2	2	1	1/3	2	1/3	1/3	1/4	3	1/4	1/5	4.49%
Slope	3	3	3	1	3	2	1/2	1/3	4	1/2	1/3	9.02%
Drainage density	4	2	1/2	1/3	1	1/3	1/4	1/4	3	1/4	1/5	3.81%
LULC	5	3	3	1/2	3	1	1/2	1/3	4	1/3	1/3	7.59%
Lineament density	6	4	3	2	4	2	1	2	5	1/2	1/3	13.51%
Soil media	7	4	4	3	4	3	1/2	1	5	1/2	1/3	13.58%
Net recharge	8	1/2	1/3	1/4	1/3	1/4	1/5	1/5	1	1/6	1/7	2.13%
type of alteration	9	5	4	2	4	3	2	2	6	1	1/2	17.66%
Depth to water	10	6	5	3	5	3	3	3	7	2	1	25.22%

Table 3. shows the quantity and verbal phrasing of a pair of criteria's relative relevance (Ngah et al., 2024)

Intensity of importance	Definition	Explanation
(1)	Equal importance	Two activities contribute equally to the objective
(3)	Moderate importance	Experience and judgment slightly favor one activity over another
(5)	Strong importance	Experience and judgment strongly favor one activity over another
(7)	Very strong importance	One activity is favored very strongly over another, its dominance is demonstrated in practice
(9)	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
(2,4,6,8) Can be used to express intermediate values		

account the eigenvalues of the comparison matrix. The formula for computing the CI is as follows (Equation 5):

$$CI = \frac{\lambda max - n}{n-1} \quad (5)$$

where: λmax represents the principal eigenvalue of the comparison matrix, n denotes the number of criteria being compared, a Consistency Index value of 0.15 was obtained in this study.

The Saaty scale provides a structured framework for assigning weights, ensuring the judgments reflect varying degrees of influence from equal importance (1) to extreme importance (9). This scale helped standardize expert evaluations underpinning the matrix in Table 2.

The calculated Consistency Ratio of 0.041 confirms excellent consistency in our pairwise comparisons, validating that the weight assignments are reliable and logically coherent.

RESULTS AND DISCUSSION

Groundwater vulnerability assessment

Depth to water

The basin's eastern and western zones are distinguished by notable water depth, up to 110 meters, as seen on the water depth chart (Figure. 4a). Toward the center of the basin, especially in the southern portion (south of Sabkhat Guellif and Ank Djamel), the water depth progressively drops.

Net recharge (R)

The water balance and hydrological soil type were used to determine the net recharge in the research region (Figure. 4b). The eastern regions of the research area have the greatest values, with an average of 41.83 mm. The computed net recharge is 25.53 mm in the western portions of the basin, while the recharge values drop to 22.05 mm in the middle.

		Criteria		more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	Rainfall	Geology	B	2
1	3		Slope	B	3
1	4		Drainage density	B	2
1	5		LULC	B	3
1	6		Lineament density	B	4
1	7		Soil media	B	4
1	8		Net recharge	A	2
2	3	Geology	Slope	B	3
2	4		Drainage density	A	2
2	5		LULC	B	3
2	6		Lineament density	B	3
2	7		Soil media	B	4
2	8		Net recharge	A	3
3	4	Slope	Drainage density	A	3
3	5		LULC	A	2
3	6		Lineament density	B	2
3	7		Soil media	B	3
3	8		Net recharge	A	4
4	5	Drainage density	LULC	B	3
4	6		Lineament density	B	4
4	7		Soil media	B	4
4	8		Net recharge	A	3
5	6	LULC	Lineament density	B	2
5	7		Soil media	B	3
5	8		Net recharge	A	4
6	7	Lineament density	Soil media	A	2
6	8		Net recharge	A	5
7	8	Soil media	Net recharge	A	5
1	9	Rainfall	type of alteration	B	5
1	10		Depth to water	B	6
2	9	Geology	type of alteration	B	4
2	10		Depth to water	B	5
3	9	Slope	type of alteration	B	2
3	10		Depth to water	B	3
4	9	Drainage density	type of alteration	B	4
4	10		Depth to water	B	5
5	9	LULC	type of alteration	B	3
5	10		Depth to water	B	3
6	9	Lineament density	type of alteration	B	2
6	10		Depth to water	B	3
7	9	Soil media	type of alteration	B	2
7	10		Depth to water	B	3
8	9	Net recharge	type of alteration	B	6
8	10		Depth to water	B	7
9	10	type of alteration	Depth to water	B	2

Figure 3. Missing title

Aquifer media

Clay, sandstone, limestone, and dolomites make up the aquifer lithology in the western portion of the research area (Figure. 4c). While clay and conglomerate are present in the eastern portion and some central-western regions of the basin, gravel and sand are found in very small amounts in the northeast and center of the basin.

Soil media (S)

Using the Algerian soil map (Tebessa) at a scale of 1:500,000, a soil permeability map of the research region was created (Figure. 4d). There are four different types of soil: calcareous soils, which are found in the central south of the basin and in the western part; limestone soils, which cover the northern part and extend towards the east and west; alluvial soils, which are found in the center of the basin between Sabkhats Ank Djamel and Djandli; and saline soils, which are characterized by the presence of clayey and saline sediments in Sabkhats, which are mainly found near the Sabkhats, such as Ank Djamel, Guellif, El Maghsel, and Djandli.

Topography(T)

A digital elevation model, or DEM, provided the topographical information for the research area. The potential for pollutant penetration is controlled by the variance in the slope of the ground. Here, it is assumed that the area becomes more sensitive and that infiltration increases with decreasing slope. According to the underlying assumption, the research region is more vulnerable to groundwater contamination since most of it (Figure. 4e) has slopes that range from 0% to 6%. On the other hand, the research region's minority of locations with slopes more than 12% are thought to be less susceptible to pollution infiltration.

Impact of vadose zone (I)

The stratigraphic logs of wells were used to gather the vadose zone data, which were subsequently categorized based on their capacity to permit and convey water. The highest grade was given to the western portion of the study area (Figure. 4f), which is primarily composed of sand and gravel that is rich in silt and clay. The vadose zone in the central and eastern regions is composed of limestone, gravel clay, sandy clays, and, in smaller amounts, clay and marl. The corresponding ratings for these areas were medium and lowest.

Hydraulic conductivity of the aquifer (C)

The majority of the aquifer system's hydraulic conductivity is moderate, according to the examination of the data (Figure. 4g). The hydraulic conductivity of the research region increases

Table 4. Random consistency index (RI) values for n variables (Vagiona et al., 2012)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.89	1.12	1.25	1.32	1.40	1.45	1.49

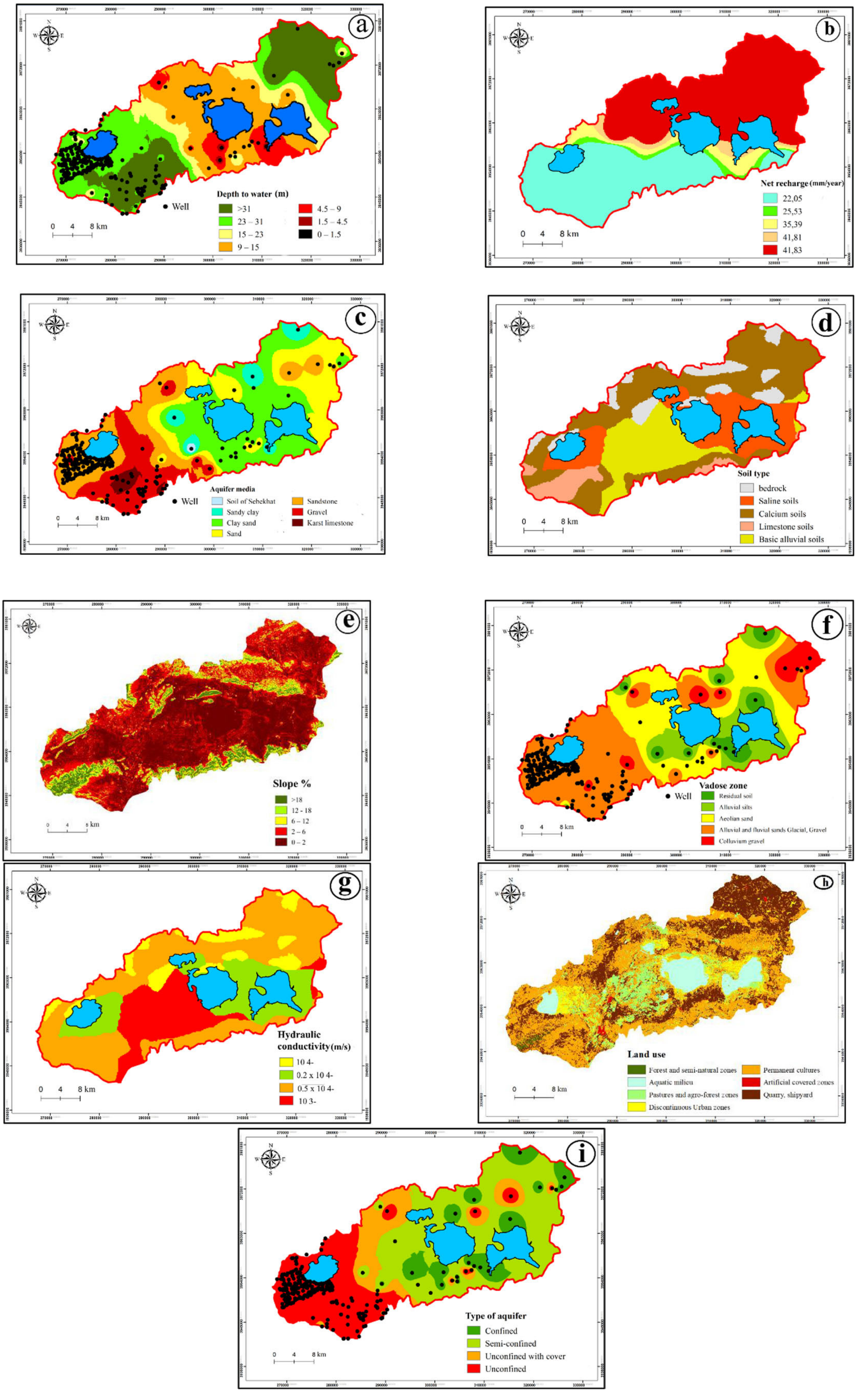

Figure 4. Input parameters used in groundwater vulnerability mapping: (a) groundwater depth, (b) net recharge, (c) aquifer lithology, (d) soil types, (e) topography, (f) impact of vadose zone, (g) hydraulic conductivity, (h) land use and (i) type of aquifer

toward the north of the study area, with values ranging from 0.2 × 10^{-4} m/s in the south to 0.58 × 10^{-4} m/s in the northern portion of the basin. The aquifer's fractured limestone formations provide an explanation for this fluctuation.

Lund use (LU)

The research area's land use map (Figure 4h) was created using Sentinel 2 satellite images and an LCLU (land cover land use) classification (Alciaturi et al., 2025). The Corine land cover classification shows that 9.73% of the study area is utilized for pasture, agroforest, and agricultural purposes; 0.46 is preserved as forest and semi-natural lands; 29.06 is preserved as a quarry and shipyard; and the remaining 8.12% is used for open water and other purposes.

Type of aquifer (G)

The aquifer in the study area (Figure 4i) becomes fully restricted toward the southwest after changing from unconfined to semi-confined in the northeast.

Validation using nitrate concentration data

The nitrate concentrations in this investigation vary from 5 to 135 mg/l (Figure 5). Groundwater nitrate concentrations in the northeast and northwest of the research area range from 50 to 139 mg/l, indicating significant contamination associated with intensive agricultural practices. The values in the remaining research region are below 50 mg/l.

DRASTIC – the vulnerability map (Figure. 6a) reveals four distinct classes: very low (18.47%), low (26.38%), moderate (38.46%), and high (16.68%). High vulnerability zones are concentrated in the northern and central parts of the basin, characterized by shallow groundwater depths and high hydraulic conductivity.

SI – three vulnerability classes were identified: low (34.10%), moderate (31.53%), and high (34.37%). The nearly equal distribution reflects balanced sensitivity to evaluated parameters, with high vulnerability zones primarily in agricultural areas (Figure. 6b).

GOD – shows the most conservative assessment with three classes: very low (38%), low (30%), and moderate (32%). No extremely vulnerable zones (Figure. 6c) were identified, indicating the method's conservative nature for general assessments.

SINTACS – identifies three classes (Figure. 6d) with moderate vulnerability dominating (63%), while low (20%) and high (17%) vulnerability zones are less represented.

Groundwater potential mapping

When the CR is 0.10 or less, the consistency of the assessments is deemed satisfactory. The judgments must be reevaluated if the CR value is 0.10 or more. The computed CR value in this study was 0.041, which is within the permitted range and validates the consistency and validity of the conclusions. (Ncibi et al., 2020).

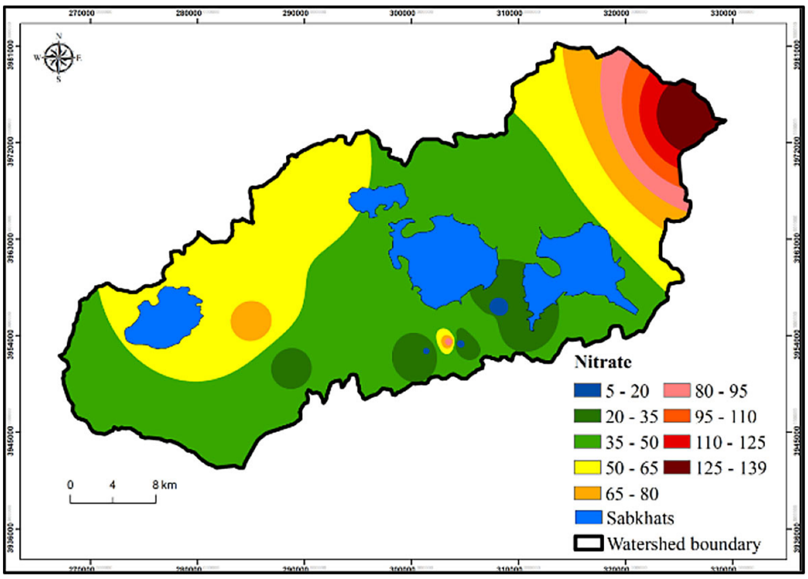

Figure 5. The nitrate concentration map

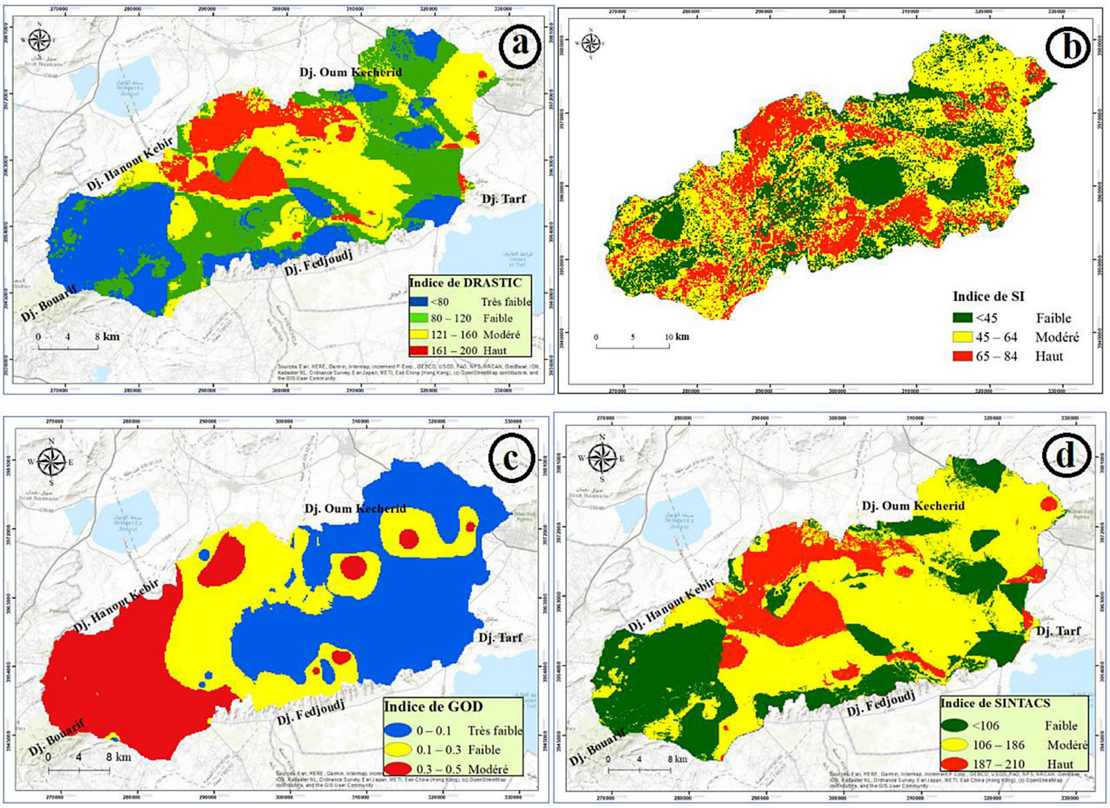

Figure 6. Vulnerability maps: DRASTIC, SI, GOD et SINTACS

The AHP was used to determine the weights. Each feature class was then given a rating value on a scale from very low to very high, ranging from 1 to 5. The geometric mean criteria for normalization were used to these ratings. The normalized ranks for each class and the normalized weights for each layer are shown in Table 5.

Groundwater-contributing factors were rated on scales of intensity and class, with normalized weights reflecting their roles in the Ank Djamel basin. Depth to water and alteration types dominate, corroborating the matrix results, while other factors such as land use and drainage density carry moderate influence.

Description of thematic layers of AHP method

- Rainfall

Rainfall is the main source of groundwater recharge, infiltrating soil and rock fractures to replenish underground water reserves. It ranks as the 9th important factor with a normalized weight of 0.03. Data (1992–2021) show rainfall exceeds 500 mm in the north and northwest of the Ank Djamel basin, while the south and southeast receive less than 500 mm (Figure 7A).

- Geology (G)

The basin's geology (Figure 7B) is diverse: recent deposits like sabkhas and alluvium cover 51.75%, mainly in low-lying areas, offering good water accumulation zones. Carbonate rocks cover 33% in eastern, southern, and western parts. Other formations include dunes/agricultural lands (9%) and Triassic/Miocene rocks (6.2%). Quaternary alluvium and fractured rocks provide good permeability and groundwater potential.

- Slope (S)

Slope controls groundwater recharge by affecting surface runoff. Most of the basin (83.24%) has very gentle slopes (1–3°), favorable for infiltration. Moderate slopes (3°–5%) and steep slopes (5°–8%) occur mainly in surrounding mountains, influencing local recharge conditions (Figure 7C).

- Drainage density

High drainage density indicates greater runoff and less groundwater recharge, while low density favors infiltration. In the basin (Figure 7D), around 48% of the area has moderate drainage density (1–2 km/km²), 19% high (2–5 km/km²), and 33% low (<1 km/km²). This parameter is key for assessing groundwater availability and has a normalized weight of 0.04.

Table 5. Weight of thematic characteristics according to the level of groundwater contribution to the Ank Djamel basin

Criterion	Classes	Note	%
Rainfall (mm)	Low (<500)	1	3%
	Moderate (>500)	2	
Geology	Ancient salt flats	2	4%
	Dune formation/ Scree zone/ Arable lands	3	
	Marly Aptian/ Tortonian/ Berriasian to val/ Lias/ Villafranchien	4	
	Triassic/ Hauterivien/ Burdigalien/ Mio-pliocene/ Miocène/ Miopliocene	5	
	Upper Aptien to Miliodic/ Albien/ Cenomanien s-m/Aptien Cretaceous/ Marine Miocene	6	
	Barremian limes-dolo/ Aptien limestone/ Glaze polyge/ Barremian/ Aptien dolomite	7	
	Sabkha/ Quaternary Alluvium	8	
LULC	Quarry, shipyard	1	8%
	Artificial covered zones, green zones, continuous urban zones	2	
	Industrial discharge, landfill, mines	3	
	Discontinuous Urban zones	4	
	Permanent cultures (vines, orchards, olive trees.)	6	
	Pastures and agro-forest zones	7	
	Forest and semi-natural zones	8	
	Aquatic milieu (swamps, saline, etc.)	9	

Criterion	Classes	Note	%
Net recharge (mm)	Low (<25)	1	2%
	Moderate (25–50)	2	
Soil media	Bedrock	2	13%
	Saline soils	4	
	Limestone soil	6	
	Basic alluvial soils	7	
type of alteration	OH-Bearing Minerals	5	18%
	Ferrugination	4	
	Ferromagnesian	3	
	Barren area	1	
Depth to water (m)	< 6	9	25%
	6–10	8	
	10–15	5	
	15–25	3	
Slope (%)	Very low (1–2)	8	9%
	Low (2–3)	5	
	Moderate (3–5)	3	
	High (>8)	2	
Drainage density (km/km²)	Low (1)	3	4%
	Moderate (1–2)	2	
	High (2–5)	1	
Lineament density (km/km²)	Low (1)	1	14%
	Moderate (1–3)	3	
	High (3–5)	4	

- Land Use (LU)

Land use affects erosion, evapotranspiration, and runoff. The basin (Figure 7E) is dominated by grasslands (45%) and croplands (29%). Built-up areas have lower infiltration and thus lower weight, whereas water bodies, vegetation, and forests have higher weight due to their positive effect on groundwater recharge.

- Lineament density (LD)

Faults, fractures, and joints increase rock permeability. Lineament density ranges from under 1 to 5 km/km². Areas with high density (3–5 km/km²), covering 17% of the basin mainly in the north and northeast, are excellent for groundwater occurrence and are weighted accordingly (Figure 7F).

- Soil type (ST)

Four soil types affect infiltration and water retention (Figure 7G): saline soils near sabkhas, calcareous soils in the center-south and west, limestone soils in the north, and alluvial soils in the central basin. Loosely compacted soils enhance infiltration; clay-rich or degraded soils increase runoff and flood risk.

- Net recharge (NR)

Net recharge represents the volume of water infiltrating to groundwater annually. It varies spatially (Figure 7H): highest in the east (~41.8 mm), lower in the center (~22 mm), and moderate in the west (~25.5 mm). Despite measurement challenges, it is critical for groundwater assessment.

- Alteration type (AT)

Surface alteration patterns indicate groundwater presence and flow (Figure 7I) – hydrothermal (subsurface water circulation), ferruginous (shallow water influence), ferromagnesian (historical water flow), and barren (limited infiltration). These provide insights into groundwater dynamics when combined with other data.

- Depth to water (DW)

Water table depth is the most important parameter with a weight of 0.25. Depths exceed 25

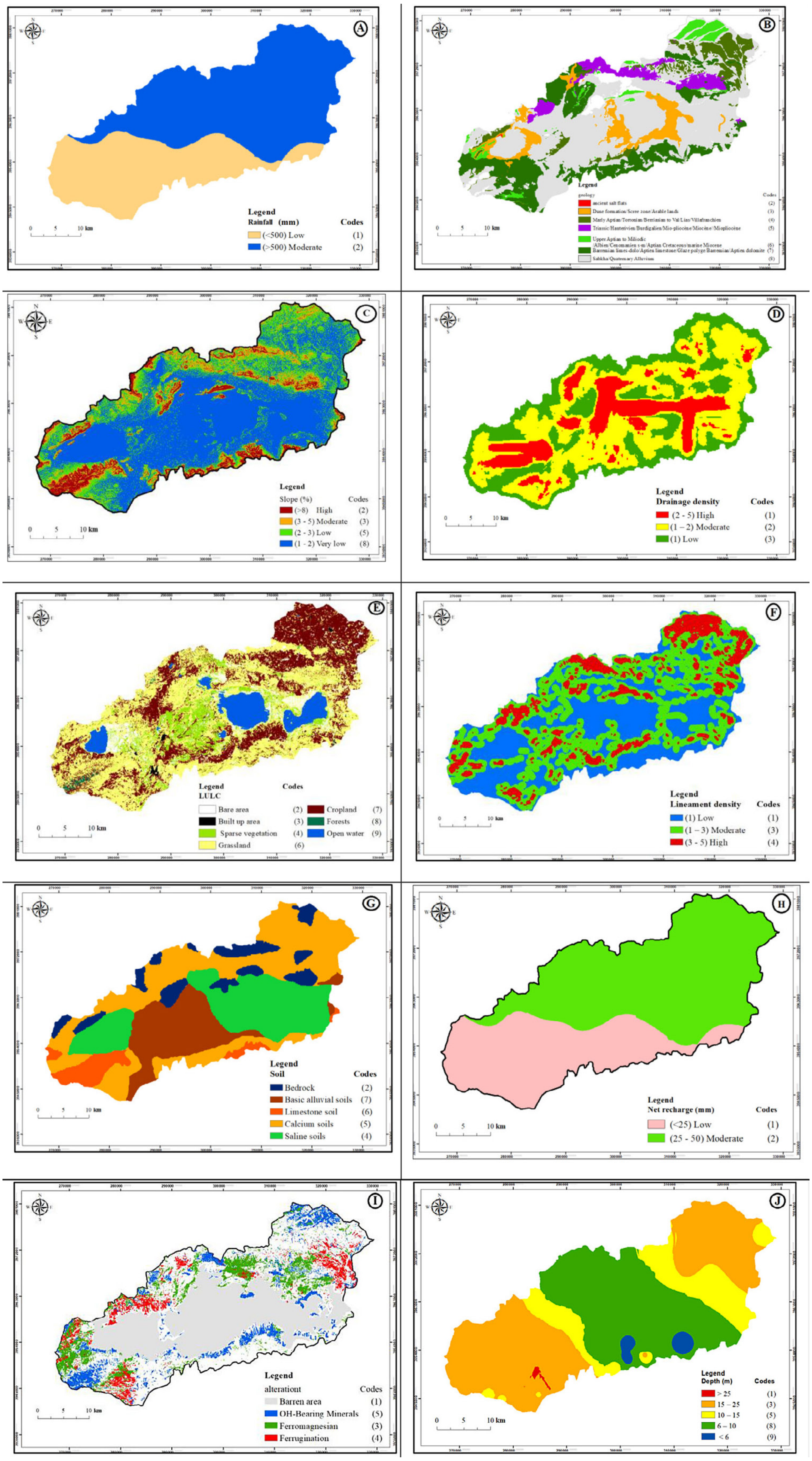

Figure 7. Input parameters used in groundwater potential zone: (A) rainfall map; (b) geology map; (c) slope map; (d) drainage density map; (e) lund use map; (f) lineament density; (g) soil map; (h) net recharge map; (i) alteration map; (j) depth to water

m in the east and west zones, but decrease to less than 6 m in the middle and southern parts of the basin, indicating better groundwater accessibility in those central areas (Figure 7J).

Delineation of groundwater potential zones

Ten key parameters were weighted according to their influence on groundwater potential and combined using a weighted overlay analysis in ArcGIS, based on Malczewski's (1999) equation. Each thematic layer and its characteristics were assigned normalized weights to calculate the Groundwater Potential Index (GWPI).

The Ank Djamel basin's groundwater potential (Figure. 8) was classified into four categories: 'good,' 'moderate,' 'low,' and 'very low'—using the natural breaks method. GWPI values range from 1.93 to 6.39, with thresholds defined as: very low (1.93–3.48), low (3.48–4.22), moderate (4.22–4.91), and good (4.91–6.39).

The resulting map shows that about 11.74% of the area (144.36 km²) has high groundwater potential, 40.10% (494.03 km²) moderate potential, 34.65% (426.88 km²) low potential, and 13.51% (166.44 km²) very low potential.

Correlation between potential and flow rates

There is a significant correlation between field measurements and the groundwater potential map (Figure 9). High flow rates, which range from 60.5 to 68.0 liters per second, are closely correlated with the places that were recognized as having high potential. The efficacy of the multi-criteria approach, specifically the AHP, employed in this study is confirmed by this high association.

Validation of water potential results with flow using the ROC/AUC method

The AHP technique was used to create water potential maps for the Ank Djamel watershed for this study. The flow measurements (l/s) from 40 wells in the research region were used to guarantee the reliability of the modeled results. A direct link between the estimated water potential zones and actual flow data was made possible by this method. Extending this research, the ROC/AUC (Receiver Operating Characteristic - Area Under the Curve) approach was used to assess the predictive model's performance.

The ROC curve demonstrates satisfactory model performance with an AUC of 0.710 (Figure 10), indicating 71% predictive accuracy in identifying groundwater potential zones. The curve shows rapid initial progression (true positive rate reaching 0.45 for low false positive rates) and clearly outperforms random classification, confirming model reliability.

This statistical validation demonstrates that the AHP methodology is well-suited for the specific hydrogeological conditions of the study basin. With 71% accuracy and considering the 29% uncertainty margin, the model provides a solid foundation for optimizing borehole placement

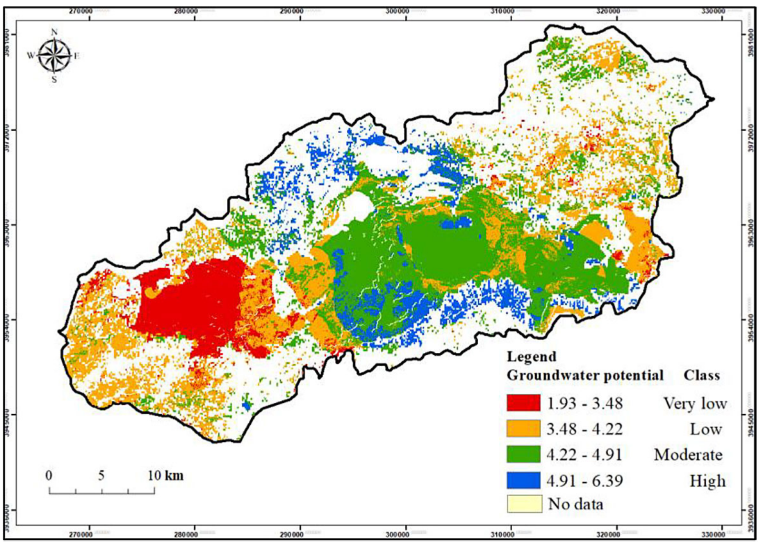

Figure 8. Groundwater potential zone for Ank Djamel basin

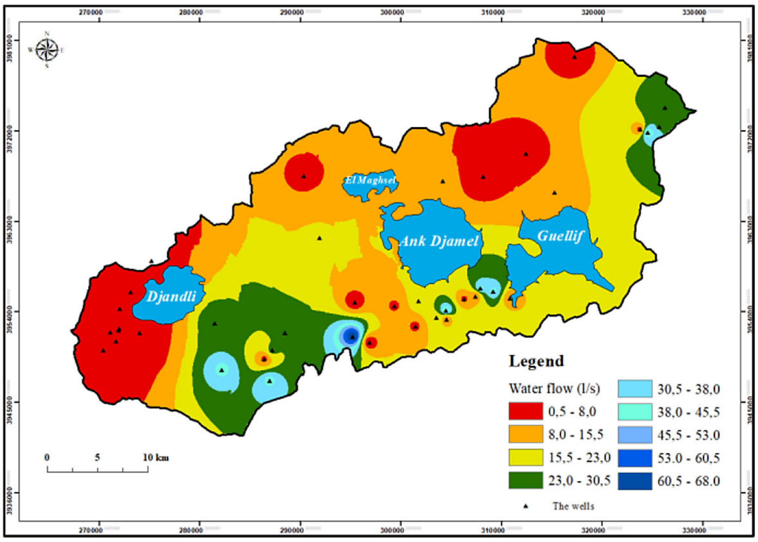

Figure 9. Water flow of Ank Djamel basin

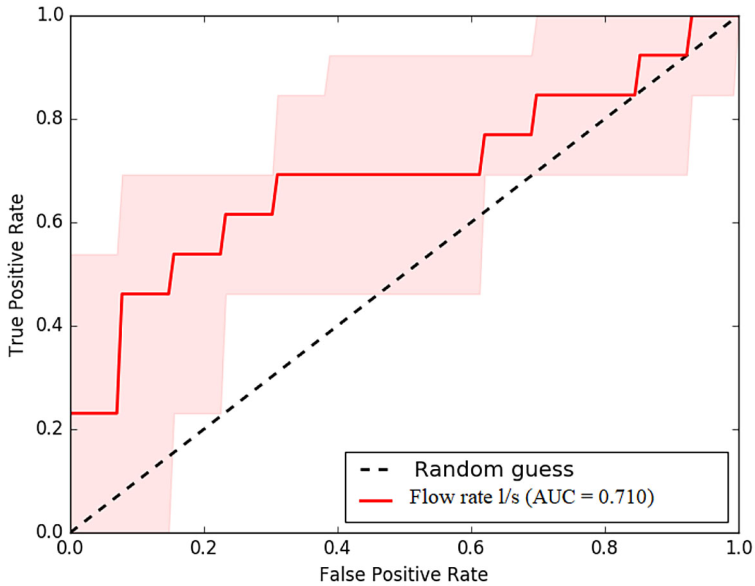

Figure 10. Validation of water potential and flow rate results using the ROC/AUC method

and supporting sustainable groundwater resource management decisions.

Mapping of water resource protection zones based on vulnerability and hydrogeological potential analysis of the Ank Djamel basin

A comprehensive analysis combining groundwater vulnerability and potential maps forms the foundation of an effective strategy to protect water resources in the Ank Djamel watershed. This integrated approach enables precise identification of priority areas, thereby optimizing conservation efforts and promoting sustainable groundwater management in the region.

The integration of various assessment methods (DRASTIC, SI, GOD, and SINTACS) with the groundwater potential map (Figure 11) reveals a heterogeneous distribution of vulnerable zones. Notably, the western part of the basin shows high vulnerability, as indicated by SI (65–84) and DRASTIC (160–200) indices. These areas correspond to moderate to low groundwater potential (1.93–4.22), highlighting a strong link between vulnerability and water potential (Table 6). This complex pattern underscores the need for a targeted protection strategy

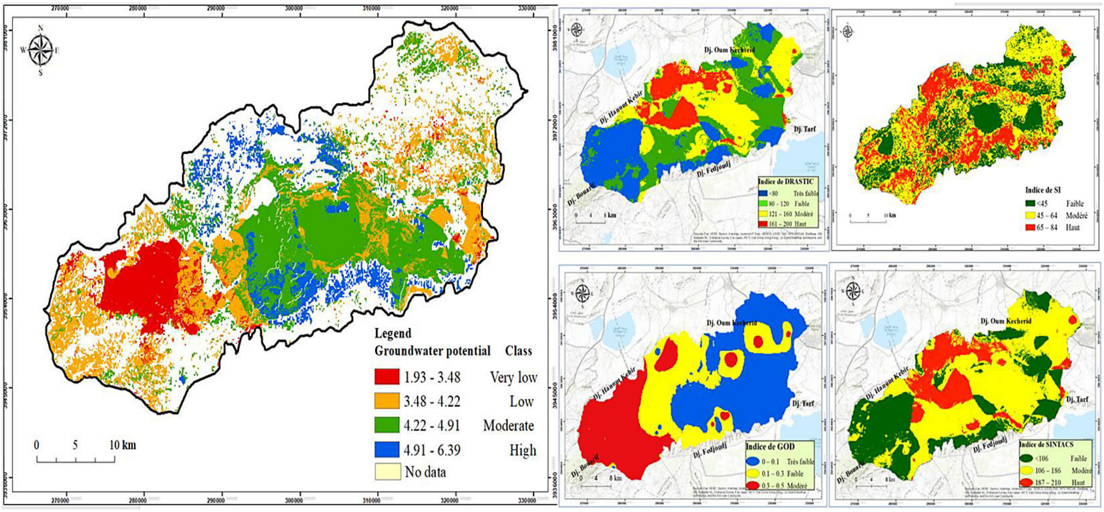

Figure 11. Combination of groundwater vulnerability and potentiality maps

that prioritizes zones based on both sensitivity and potential. Priority protection zones are those with both high groundwater potential and high vulnerability, identifying strategic areas where groundwater preservation is crucial due to their hydrological importance and increased risk of contamination or overexploitation.

Protection strategy

Groundwater protection must be tailored to the specific characteristics of each zone. In areas with high vulnerability, especially in the central and western parts of the basin (identified by all four assessment methods), strict protection zones should be established. These zones require land-use restrictions and controls on human activities to prevent contamination or degradation of water resources.

The central basin, with high groundwater potential (4.91–6.39) and high vulnerability (DRASTIC index 161-200 and SINTACS index 187–210), needs balanced and adaptive management. This strategic area should be protected while allowing sustainable and controlled use. Continuous monitoring through piezometers and regular water quality and quantity checks is essential to support sustainable groundwater management in the regional hydrological context.

Based on the vulnerability and groundwater potential analyses, a protection zone map was created for the Ank Djamel watershed (Figure 12). This map is a valuable tool for implementing effective regulations to safeguard groundwater resources while ensuring their sustainable use. By clearly identifying sensitive and priority areas, the map supports planning and monitoring of essential management measures for resource preservation.

Spatial distribution of protection zones

Immediate protection zones (shown as red points) are mainly concentrated in the central and western parts of the basin, coinciding with areas of high vulnerability (DRASTIC indices 160–200, SI 65–84) and moderate to high groundwater potential (4.22–6.39). Remote protection zones (represented by orange circles) form a peripheral belt around the basin, especially in the northeast near Dj. Oum Kechrid, east towards Dj. Tarf, and southwest near Dj. Bouarif. These areas correspond to moderate vulnerability, reflecting an adaptive strategy addressing hydrological risks according to their intensity and location.

Practical aspects of protection

This configuration ensures effective protection of water resources by integrating local territorial constraints. Strategically placed immediate protection zones establish a network of monitoring points for precise surveillance of the most sensitive areas. Meanwhile, remote protection zones act as essential buffer areas, providing overall and lasting aquifer protection against human pressures and environmental hazards.

The findings of this study align well with numerous investigations conducted in other semi-arid

Table 6. Comparison of values obtained using different methods for assessing hydrogeological potential

Methods	Values
AHP	(4.91–6.39)
DRASTIC	(161–200)
SI	(65–84)
GOD	(0.3–0.5)
SINTACS	(187–210)

basins across North Africa and the Middle East. For instance, studies in southwestern Tunisia and Algeria have similarly highlighted the critical roles of groundwater depth and geological characteristics in determining aquifer vulnerability, alongside challenges from overexploitation under limited recharge conditions (Besser et al., 2017; Seraiche et al., 2025). In these regions, the scarce and irregular rainfall -often less than 100 mm annually- coupled with intensive agricultural water use, exacerbates groundwater depletion and contamination risks. Comparable hydrogeological systems, such as those in the Tozeur-Kebili basin of Tunisia and the Chott Hodna basin in Algeria, demonstrate that management of groundwater resources demands integrated consideration of recharge rates, soil and lithology, and land use patterns, consistent with our findings. Similarly, studies in the Middle East, including the Jordan Rift Valley, reveal that human activities and climatic stressors intensify groundwater vulnerability, emphasizing the need for robust vulnerability assessments to safeguard these vital resources. By situating our results alongside this regional literature, the study reinforces the broader applicability of the Analytic Hierarchy Process (AHP) and thematic layer weighting in groundwater vulnerability mapping for semi-arid environments.

EXPANDING ON POLICY IMPLICATIONS FOR GROUNDWATER PROTECTION ZONES

The identification of groundwater protection zones (GPZs) offers a scientifically grounded framework to inform and enhance water resource management policies, particularly in semi-arid regions vulnerable to overexploitation and contamination. Local authorities and water management agencies can leverage these designated zones to implement targeted and effective policies that safeguard groundwater resources.

Key policy applications include:

- Land use regulation – authorities can impose restrictions on industrial, agricultural, and residential activities within high-risk zones to minimize pollution sources and reduce anthropogenic pressures on vulnerable aquifers. This ensures that activities such as construction, waste disposal, and use of agrochemicals are carefully monitored or limited within critical recharge areas.

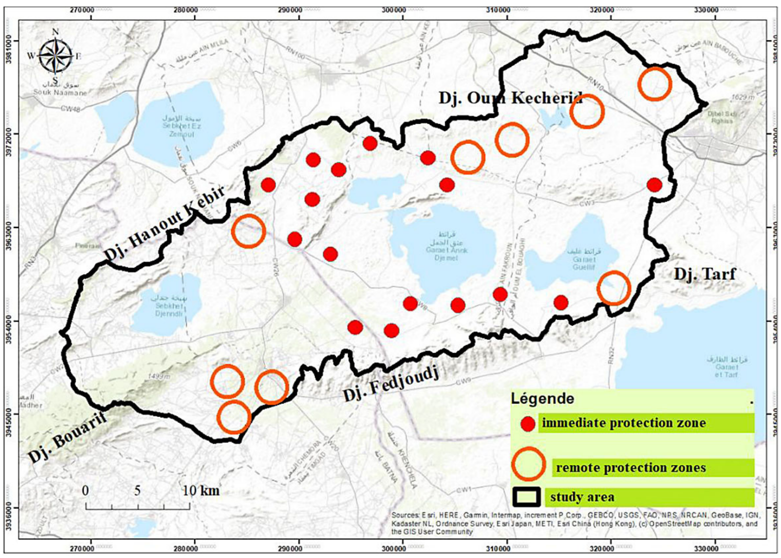

Figure 12. Protection perimeters for the Ank Djamel basin

- Water extraction controls – establishing licensing and monitoring systems for groundwater extraction that align with the capacity and recharge rates of the aquifers, thereby preventing over-extraction and ensuring sustainable use. Strategic limitations can help maintain aquifer balance and water quality over the long term.
- Public awareness and stakeholder engagement – developing educational programs and participatory approaches to involve farmers, industries, and local communities in groundwater stewardship. This promotes adoption of sustainable practices such as efficient irrigation techniques and pollution prevention measures, reducing contamination risks.
- Integrated planning – incorporating GPZ maps into urban and rural land-use planning facilitates informed decision-making that harmonizes development goals with groundwater protection. This integration helps prevent land uses that could detrimentally impact water quality or availability in sensitive areas.
- Recharge enhancement projects – guiding investments towards artificial recharge initiatives, rainwater harvesting, and wastewater reuse projects within protective zones can restore aquifer levels and improve resilience to climatic variability.
- This multi-faceted policy approach ensures that groundwater protection zones serve not only as scientific delineations but as actionable tools that enhance regulatory frameworks and promote sustainable groundwater management. By embedding these zones into governance structures, local authorities and water agencies can safeguard this critical resource, balancing human needs with environmental sustainability in semi-arid contexts.

CONCLUSIONS

This study offers a new integrated paradigm that effectively integrates potential zone delineation and groundwater vulnerability evaluation in semi-arid hydrogeological settings. The AHP-based potential mapping framework achieves statistically robust predictive performance with 71% validation accuracy, while the multi-criteria analytical approach shows the superior efficacy of DRASTIC and susceptibility index (SI) methodologies for agricultural contamination risk evaluation.

Important hydrogeological insights are revealed by the thorough spatial analysis: According to the DRASTIC categorization system, 16.68% of the research area's terrain is classified as very vulnerable to contamination, indicating significant geographic variation in susceptibility distributions. Additionally, 11.74% of the studied area is covered by the methodical delineation of ideal groundwater development zones, which serve as priority locations for sustainable aquifer exploitation. The framework's application for evidence-based water resource management decision-making processes is established by the rigorous validation protocols, which show remarkable method reliability.

The study concludes with the creation of an integrated management paradigm that addresses the twin problems of resource conservation and usage optimization by balancing the demands of aquifer protection with strategic development goals.

The suggested methodology has significant adaption potential across similar semi-arid hydrogeological situations worldwide and is a useful decision-support tool for hydrogeological practitioners. In order to improve long-term sustainability evaluations under changing environmental conditions, future research paths should give priority to the development of temporally dynamic modeling frameworks and the inclusion of climate variability scenarios.

Innovative geospatial technology combined with well-established hydrogeological principles offers significant benefits over traditional assessment methods, providing technically sound and financially feasible solutions for managing and evaluating groundwater resources in settings with limited data. This methodological development offers a repeatable framework for tackling comparable issues in water-stressed areas across the globe, making a substantial contribution to sustainable water resource management techniques in delicate semi-arid ecosystems.

Suggested sustainable groundwater management strategies:

The integrated GIS-based vulnerability assessment framework developed for the Ank Djamel basin provides a spatially explicit basis for targeted groundwater management interventions. To sustainably manage groundwater resources, it is recommended to establish protective buffer zones around highly vulnerable areas identified by the SI and DRASTIC models to mitigate contamination risks, particularly from agricultural nitrate inputs.

Controlled groundwater abstraction should focus on zones with moderate to high recharge potential to balance resource utilization with aquifer replenishment capacity. Continuous groundwater quality and quantity monitoring via GIS-enabled platforms will facilitate adaptive management under changing environmental and anthropogenic pressures.

Data validation with nitrate concentrations underscores the necessity for integrating hydrochemical monitoring with vulnerability mapping to inform risk-based management policies. Additionally, promoting community awareness and regulatory frameworks for water use restrictions in critical recharge zones will enhance long-term aquifer sustainability.

The use of multi-criteria decision analysis ensures that social, economic, and environmental factors are weighted comprehensively in formulating management strategies, making the framework applicable to other semi-arid regions with similar hydrogeological settings.

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