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REPORT

Identification of potential artificial groundwater recharge sites using GIS and the analytical hierarchy process: case study of Tamellalt plain, Morocco

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Abstract
Groundwater resources are crucial in arid and semiarid regions with limited rainfall and surface-water scarcity. However, these areas face challenges such as high evaporation and groundwater contamination, leading to dangerously low groundwater levels. This research identifies suitable locations for artificial groundwater recharge to address these challenges, improve long-term resource performance, and promote water conservation and storage. Artificial recharge sites were identified based on various criteria, in conjunction with geographic information system (GIS) methods, including slope, soil type, geology, geomorphology, land cover, groundwater depth, hydraulic conductivity, electrical conductivity, and drainage density. Each criterion was evaluated using the analytical hierarchy process (AHP), and experts from different disciplines contributed through pairwise comparisons. The study focuses on the Tamellalt region (Morocco) as a representative arid area. The AHP findings reveal that aquifer transmissivity is the most significant factor, accounting for 16.08% of the total influence, while the recharge component represents only 8.22%. Combining thematic maps generated a potential final map, indicating that 54% of the land is suitable for artificial groundwater recharge. These areas are further categorized as good, moderate, and poor, covering respective land areas of 183,600, 125,800, and 30,600 ha. These locations exhibit high infiltration potential and good water quality, making them favorable for artificial recharge, particularly in regions with significant pluvial water accumulation. Overall, this research provides insights into addressing groundwater depletion in arid regions. Identifying suitable sites for artificial recharge offers a potential solution to enhance long-term water resource management, promote conservation, and mitigate water scarcity challenges.

Keywords Geographic information systems · Artificial recharge · Potential recharge zone · Analytical hierarchical process · Morocco

Introduction

One of the most essential elements of the natural water cycle is groundwater deposited in the pores of soil and rock (Dar et al. 2020; Fitts 2002). Unlike other resources, groundwater receives an annual renewal of precipitation by aquifer recharge, making it one of the most sustainable and valuable products on the planet (Lakshmi and Reddy 2018). However, the increasing demand for water for agricultural irrigation has exhausted this natural resource in many locations, causing concern in arid and semiarid areas especially. This research aims to address these concerns by identifying suitable zones for artificial groundwater recharge, in order to enhance the long-term performance of aquifers, and promote water conservation and storage.

The study was undertaken in the Tamellalt region of Morocco, an ideal illustration of an arid region. The climate is arid with a Saharan influence, with low irregular rainfall. Runoff occurs only due to heavy rains, and flood waters can be trapped and used for artificial infiltration. The Tamellalt region's use of groundwater resources is widespread and unregulated. The region faces high water stress due to scarcity of supply, and continuous extraction has led to aquifer stress and the degradation of extraction efficiency.

To ensure adequate recharge and to ascertain the current status of groundwater potential in this region, it is crucial to designate areas of groundwater potential where artificial

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recharge can be employed to increase recharge. According to several reports about the area, the main factors that will influence the delimitation process are geomorphology, drainage density, slope, geology, land use and land cover, soil type, precipitation, and topographic elevation (Murmu et al. 2019; Anbarasu et al. n.d.; Gnanachandrasamy et al. 2018; Chaudhry et al. 2019; Das and Pal 2019; Arulbalaji et al. 2019; Saranya and Saravanan 2020; Dar et al. 2020). These factors characterize the presence and abundance of groundwater, and the geological composition and hydrological properties of the aquifers. Various methods have been used to assign an appropriate weight and rank to these parameters, and then to produce a possible recharge field. In several published studies, these weights and ranks have been assigned to the parameters based on the parameter desirability, the analysis of multicriteria decision-making, and multifactor-influence analysis (Saranya and Saravanan 2020).

Many academics have utilized a variety of techniques to identify potential groundwater recharge regions across the globe. Since each study region includes various contributing factors, it is best to compute weights using a combination of technical and expert methods rather than a rough estimate of percentage of recharge area. Potential groundwater basins can be determined by a statistical approach, expert judgment, and a deterministic method (Gupta et al. 2018). Among the recently developed statistical methodologies, the analytical hierarchy process (AHP) has proven to be an excellent decision-making tool for problems with numerous criteria (Saaty 2008; Aggarwal et al. 2019; Sirinivasa Rao and Jugran 2003; Aggarwaal et al. 2013; Aneesh and Deka 2015; Gupta et al. 2018; Sirinivasa Rao and Jugran 2003; Hossein et al. n.d.). Artificial aquifer recharge schemes developed using AHP have been successful and accurate because this approach can take account of the subjective judgment of the evaluator, since one of the prerequisite factors is the weight of the parameters (Arulbalaji et al. 2019; Gdoura et al. 2015; Khan et al. 2020). AHP is a widely established technique that has been successfully implemented in numerous countries and regions, including the United States, Japan, Europe, the Middle East, Africa, and India (Aggarwaal et al. 2013; Sener and Davraz 2013; Shekhar and Pandey 2015; Jasrotia et al. 2016; Pinto et al. 2017; Muniraj et al. 2019; Arulbalaji et al. 2019). In addition, geographic information systems (GIS) have been utilized in numerous water conservation projects such as those associated with natural groundwater recharge. GIS has been utilized in numerous artificial groundwater recharge investigations. AHP-GIS methods have also found sites with adequate water quality, storage, and infiltration characteristics, which are all required for successful artificial groundwater recharge. Several characteristics such as ground-surface slope, soil type, saturated-zone geology, geomorphology, groundwater depth, land cover, aquifer transmissivity, electrical conductivity of the resident groundwater, drainage density, and unsaturated-zone geology, may be taken into account and have been used to determine prospective groundwater artificial recharge locations.

This research employs an integrated GIS and AHP strategy to the study region in Morocco, in order to (1) construct thematic layers of data for future determination of groundwater recharge potential, (2) identify and delineate future groundwater recharge areas, and (3) validate the resulting groundwater recharge zone. The primary purpose of determining probable groundwater recharge areas within the research area was to generate a reference map for groundwater exploration and development, to ensure the most efficient management of groundwater resources.

Materials and methods

Studied area

The study area is located in Tamellalt Plain, in the southeast of Morocco, within the Figuig Basin (Fig. 1). The Tamellalt aquifer covers ~1,869 km^2. It is entirely contained within the rural administration area of Bni Guil. This aquifer underlies the Tamellalt Plain, south of Bouarfa, which covers ~3,400 km^2, is oriented east-west, and is bounded on the north and south by east–west-oriented mountain chains, with its highest point at 1,940 m above sea level (asl) being the mountain Jbel Lakhdar. There are no active wadis in the area, which means that the groundwater originates from infiltration of the surface flow following intense floods, which occur relatively infrequently, two to three times a year.

The methodological framework of the study

The process to obtain meaningful results involved several steps described in Fig. 2. First, data from several agencies generated thematic maps highlighting key factors such as slope, soil, geology, recharge, groundwater depth, land use, aquifer transmissivity, electrical conductivity, drainage density, and unsaturated zone geology. These maps were prepared to provide an overview of the study area and to identify the factors contributing to artificial groundwater recharge. Once the data were collected, they were processed, and each factor was classified into five categories based on its contribution to the groundwater recharge process. The recharge potential categories range from “very good” to “very poor”. This classification allowed the factors to be objectively evaluated regarding their relevance to the study. A pairwise comparison matrix was then applied to determine the relative weight of each factor. This step was critical to ensure that each factor was appropriately weighted according to its importance in the study area. Using a pairwise comparison matrix made the assessment more objective and comprehensive. Finally, GIS was used to integrate the reclassified

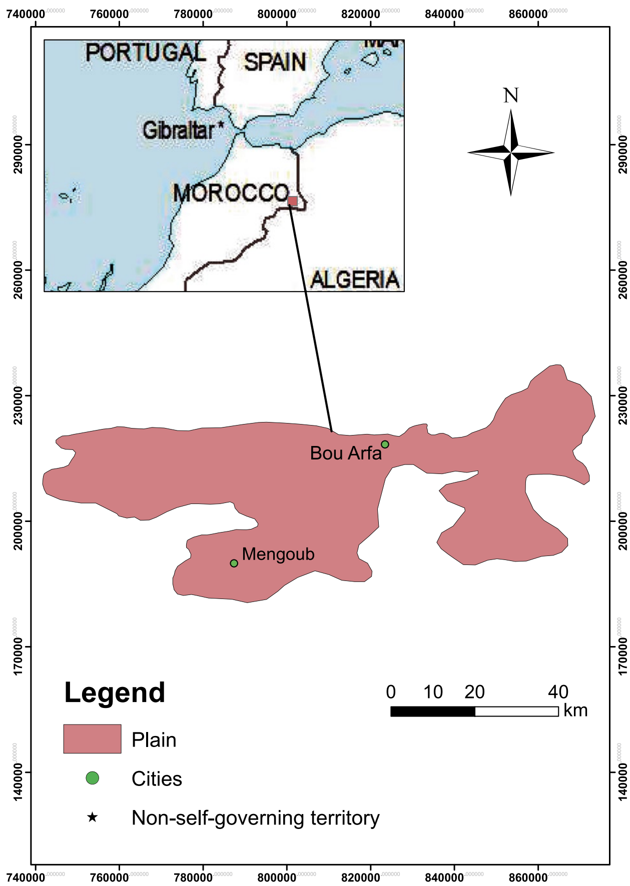


Fig. 1 Location map of the study area: Tamellalt Plain in southeast Morocco

thematic maps with their corresponding weightings. The GIS overlay provided a comprehensive view of the study area by combining all the critical factors into one map, which helped identify the best locations for artificial groundwater recharge.

Data collection and processing

This study analyzed 10 thematic layers that could be used to identify potential regions of artificial groundwater recharge: slope, soil media, saturated zone lithology, geomorphology, land cover, hydraulic conductivity (*K*), electrical conductivity, groundwater depth, drainage density, and unsaturated zone geology. The Oujda-Angad Prefecture, the Moulouya Basin Hydraulic Agency, and the Provincial Department of Agriculture supplied the data that were analyzed and utilized for the study. The information on hydraulic conductivity was gained by pumping tests. Layered thematic data for weighted overlay analysis were processed using ArcGIS 10.4.

The Moulouya Basin Hydraulic Agency provided the form file to delimit Tamellalt and its watershed. Slope and drainage density maps were generated using ArcGIS tools and digital terrain model (DTM) data. The slope classes were categorized as follows: 3, 3–5, 5–8, 8–18, and >18%. The drainage density values ranged from 0 to 0.006371 m/m^2 and were classified into five groups: 1–208, 208.1–427, 427.1–660, 660.1–931, and 931.1–1396 km/km^2.

The provincial agriculture office provided the soil map, which depicts soil texture classes in Tamellalt, such as fractured limestone, loam, sandy loam, topsoil, and sand. In the interim, the Moulouya Basin Hydraulic Agency has produced the 2019 land cover map. The same agency provided statistics for irrigated urban areas, open field crops, and uncultivated land cover types. Land cover maps had already been compiled and included in form files. Geology and geomorphology maps were created using data from wells and existing maps from the Moulouya Basin Hydraulic Agency. The geological chart depicts sand, sandstone, and limestone. In the meantime, the geomorphological map of the alluvial plains, electrical conductivity, aquifer transmissivity, and groundwater maps were created using the agency's records and pumping tests to collect the necessary data. Using ArcGIS, all data from the research area's wells were transformed into points indicating the well locations.

All points were interpolated using the weighted reverse distance approach to generate a continuous surface. From 1976 to 2015, 117 well water data with electrical conductivity ranging from 332.11 to 894.84 µS/cm were categorized into 400, 401–800, and over 800 µS/cm categories. Aquifer hydraulic conductivity values ranged from 0.11 × 10^{-3} to 13 × 10^{-3} m/s and were categorized into five groups: 0.11–2.69 × 10^{-3} m/s, 2.7–5.27 × 10^{-3} m/s, 5.28–7.84 × 10^{-3} m/s, 7.85–10.4 × 10^{-3} m/s, and >10.5 × 10^{-3} m/s. The groundwater depth spans from 0.5 to 97.9 m and is split into five classes: 0–10, 11–15, 16–20, 21–30, and >31 m. Using GIS, each parameter has been reclassified based on the relative impact of these parameters on groundwater storage, movement, and quality (Table 1).

Potential artificial groundwater recharge factors

To gain a better understanding of the factors that affect groundwater and its recharge, several hydrogeological parameters were evaluated (McCurry and Oyne 2022): slope, soil media, geology of the unsaturated zone, geomorphology, land cover, groundwater depth, hydraulic conductivity of the aquifer, electrical conductivity, drainage density, and geology of the saturated zone. The variables were selected based on several crucial factors, including their penetration and percolation capacities and their association with water quality and storage. The relationship between groundwater and these parameters is then utilized to estimate which regions of the Tamellalt Plain have the most potential for artificial groundwater recharge.

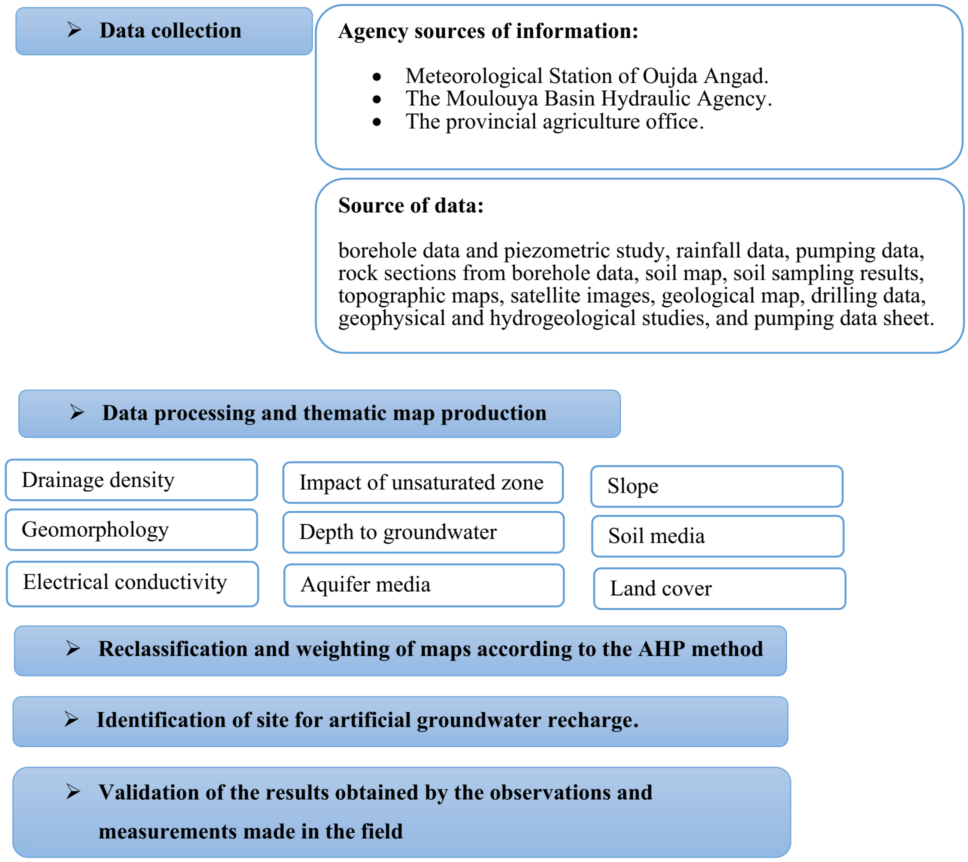


Fig. 2 The procedural steps used in the study

Slope (S)

The slope directly impacts the quantity of runoff and infiltration (Gogate and Rawal 2015). Low-inclination areas hold water longer, allowing it to leak more than areas with a high incline, which do not hold water or allow water to leak into the aquifer. Thus, the surface topography is an indicator of water transmission with runoff or its maintenance on the surface for a period of time until it is leaked into the groundwater. A high class has been given to plain areas because runoff rates are low, so that surface water will flow into the groundwater (Fig. 3).

Lithology of the saturated zone

Lithology refers to rock characteristics, the different components and the descriptions from fragile to opaque; an aquifer is a rock formation containing water. For each lithological layer, the larger the granule size, the larger the cracks in this layer, and the greater the potential for recharge. The impact of the unsaturated zone on the aquifer function is similar to that of soil cover: its effect depends on the layer's influence (Fig. 4). The unsaturated zone is subjected to complex processes that combine aquifer and topographical characteristics. According to Krishnamurthy and Srinivas (1995), a region's geological structure substantially affects the transportation and storage of groundwater because it may, or may not, provide a pathway for groundwater movement. Thus, the local geological structure provides an overview of a region's permeability and water circulation potential (Sethupathi et al. 2010; Earle 2015). The Tamellalt plain is dominated by limestone, followed by sand and sandstone, although sandstone covers only a minor part of the region (Fig. 4).

Unsaturated zone

Between the ground surface and the permanent water table lies a zone of varying saturation called the vadose or unsaturated zone. It is a crucial water cycle component and can hold at least 8.5 times as much water as rivers (Oki and Kanae 2006). The amount of water and dissolved substances (which affect agricultural production) and the drainage of the water to depth (which permits the recharging of groundwater at the water table) are the two primary factors involved in water and pollutant transport from the surface through this zone. Although this zone has a significant influence, Bataillard et al. (2008) argue that its complexity and heterogeneity prevent groundwater studies from considering it. Understanding the properties of the unsaturated zone (thickness, texture, permeability, etc.) allows one to monitor and quantify the volume of water infiltrated and the transfer time of the various contaminants. The unsaturated zone in the study area is characterized by the presence of clayey-marl limestone, marly limestone, limestone and silty sand (Fig. 5).

Hydraulic conductivity (*K*)

The hydraulic conductivity of a layer is its capacity to transport water. It depends on the layer components' media properties and the degree of saturation. A layer of high hydraulic transmission is more suitable for artificial recharging due to increased rate of water movement through the layer to the groundwater (Fig. 6).

Depth to groundwater (*D*)

According to (Chitsazan and Akhtari 2009), the depth to groundwater is the distance between the ground surface and the water table. Hammouri et al. (2013) and Blancada (2014) used groundwater depth to indicate groundwater storage. Those studies hypothesized that substantial groundwater extraction has led to higher water levels; therefore, it serves as an indirect indicator of a falling groundwater level. The map of groundwater depth in the study area is depicted in Fig. 7.

Soil

When studying groundwater circulation, soil drainage and texture are two essentials properties that must be considered. Soil texture impacts the amount of water that enters the soil, whereas soil drainage controls water movement inside the soil. Thus, these two soil characteristics provide an overview of the soil's infiltration and percolation capacities: the capacity of the soil to allow infiltrated water to reach groundwater. The infiltration rate is significantly influenced by the permeability of the soils in place (Fig. 8).

Drainage density

Horton (1945) and Agriinfo.in (2003) defined drainage density as the ratio of a watershed's total length of streams to its contributing area. Drainage density and land surface infiltration capability are related (Sedhuraman et al. 2014 and Waikar and Nilawar 2014). According to this study, low drainage density zones have high infiltration, porosity, and permeability. In contrast, locations with a high drainage density have a low infiltration capacity (Fig. 9).

Electrical conductivity

Electrical conductivity is an indirect water quality measurement. Total dissolved solids (TDS) and salinity indicate the water's electrical charge and quality (Fondriest Environmental 2014). High electrical fluctuations also result in poorer water quality. Thus, this parameter is essential to monitor in artificial groundwater recharge projects, since it influences groundwater extraction from the perspective of an aquifer's future use (Fig. 10).

Geomorphology

Geomorphological units include landforms such as plains, terraces, volcanoes, hills, valleys, and mountains. Consequently, this parameter influences groundwater in two distinct ways: via slope and primary material (Ghosh 2021). This depicts the effect of runoff and infiltration on the recharge potential of groundwater in a region. Sedhuraman et al. (2014) also used this analysis method to evaluate the landforms' slope and soil and rock composition. Due to varying infiltration capacities, the groundwater recharge potential of various geomorphological units will vary (Krishnamurthy and Srinivas 1995). The study area's geomorphological characteristics are depicted in Fig. 11.

Land cover

Existing land cover categories include forests, wetlands, impermeable surfaces, agriculture, and others (National Ocean Service 2009). Knowledge of land cover is essential for artificial groundwater recharge projects because it influences the presence and infiltration of groundwater in the region. Additionally, as depicted in Fig. 12, land cover affects evapotranspiration and the water cycle, influencing groundwater (Waikar and Nilawar 2014).

Analytical hierarchy process

The analytical hierarchy process (AHP) is a decision-making tool developed by (Saaty, 1988), which is widely used in various fields, including environmental management. Identifying potential groundwater recharge sites is a complex problem that requires an effective approach. The AHP approach is a widely accepted technique that has proven effective in solving such problems. Many researchers have applied the AHP method to improve the weighting and evaluation of each component of the methodology (Arulbalaji et al. 2019; Ghosh 2021; Gu and Xu 2011; Ourarhi et al. 2023). The importance of each parameter contributing to the recharge process is assessed using the Saaty scale (1–9), and importance values are assigned accordingly (Table 2).

Table 1 Reclassification of the study variables

Parameter	Recharge potential category	Class
Slope (%)	Very good	0–3
	Good	3–5
	Moderate	5–8
	Poor	8–18
	Very poor	>18
Soil media	Very good	Sand
	Good	Topsoil
	Moderate	Fractured limestone
	Poor	Sandy loam
	Very poor	Loam
Land cover	Very good	Uncultivated land
	Poor	Irrigated field crops
	Very poor	Built-up area
Hydraulic conductivity ($\times 10^{-3}$ m/s)	Very good	>10.5
	Good	7.85–10.4
	Moderate	5.28–7.84
	Poor	2.7–5.27
	Very poor	0.11–2.69
Electrical conductivity (µS/cm)	Very good	0–400
	Good	401–1,300
	Moderate	1,301–2,700
	Poor	2,701–3,000
	Very poor	>3,001
Depth to groundwater (m)	Very good	>31
	Good	21–30
	Moderate	16–20
	Poor	11–15
	Very poor	0–10
Drainage density (km/km^2)	Very good	1–208
	Good	208.1–427
	Moderate	427.1–660
	Poor	660.1–931
	Very poor	931.1–1,396
Aquifer media	Very good	Pebbles, gravel, sandstone, limestone, or coarse sands that are highly permeable
	Good	Sand, clay gravel, and slightly to moderately permeable clay sands
	Moderate	Karstic limestone, rocks with the permeability of fractures or cracks; Permeable basalts; Limestone massif
	Poor	Weathered metamorphic rocks
	Very poor	Limon clay, marl, and clay
Geomorphology	Very good	Plain; flood plain; coastline
	Good	Valley
	Poor	Hills and wavy reliefs
Impact of the unsaturated zone	Very good	Karst limestone; basalt
	Good	Sand and gravel
	Moderate	Sandstone, limestone, sand, and gravel; metamorphic/igneous
	Poor	Shale, silt, and clay
	Very poor	Confining layer

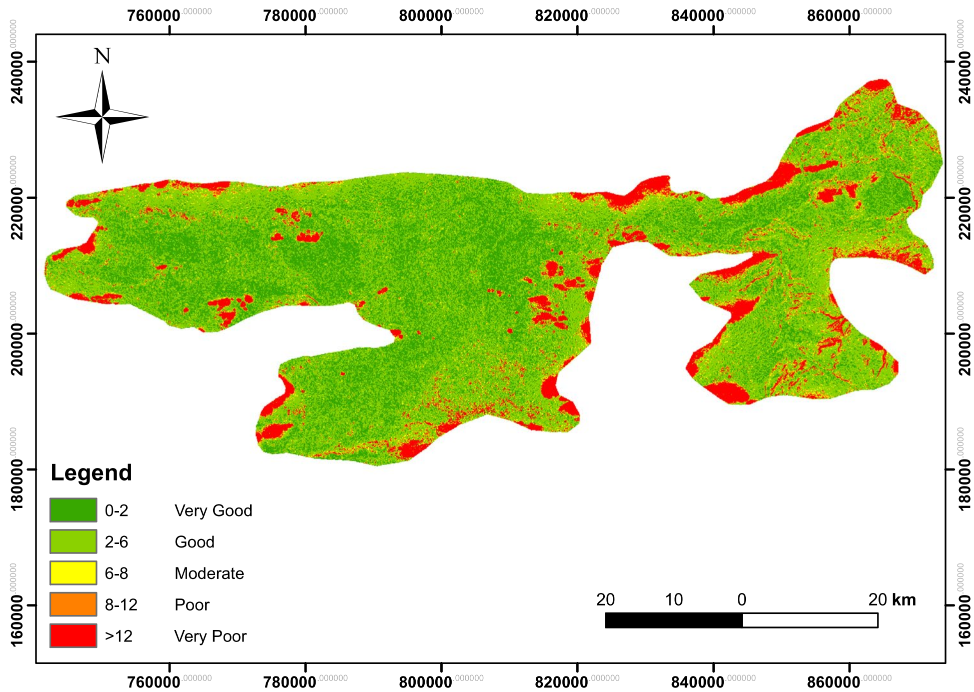


Fig. 3 Study area map: ground-surface slope and potential for artificial groundwater recharge (very good, good, moderate, poor, very poor)

The AHP method consists of several steps (Ourarhi et al. 2023; Yu et al. 2022):

- The initial step involves computing the M_i product for every row element in the judgment matrix; i = number of the factors; u = judgment matrix; m = number of the parameters: $M_i = \prod_{j=1}^{m} u_{ij,}(i, j = 1, 2, \ldots, m)$.
- In the next step, the W_i is computed, which is determined by: $\mathbf{W_i} = M_i^{1/m}$.
- To get the weight value of the component specified in the second step, the vector = $[\mathbf{W}_1, \mathbf{W}_2, \ldots, \mathbf{W}_m]^{\mathrm{T}}$ must be normalized in the third step: $\mathbf{W_i} = {}^{\mathbf{W_i}}\Big/{}_{\sum_{j=1}^{m} \mathbf{W_j}}$
- Subsequently, the maximum eigenvalue of the judgment matrix max is determined: $\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{m} \frac{(P \times \mathbf{W})_i}{\mathbf{W}_i}$ where P is the pairwise comparison and $\mathbf{W}$ is the normalized weight vector.

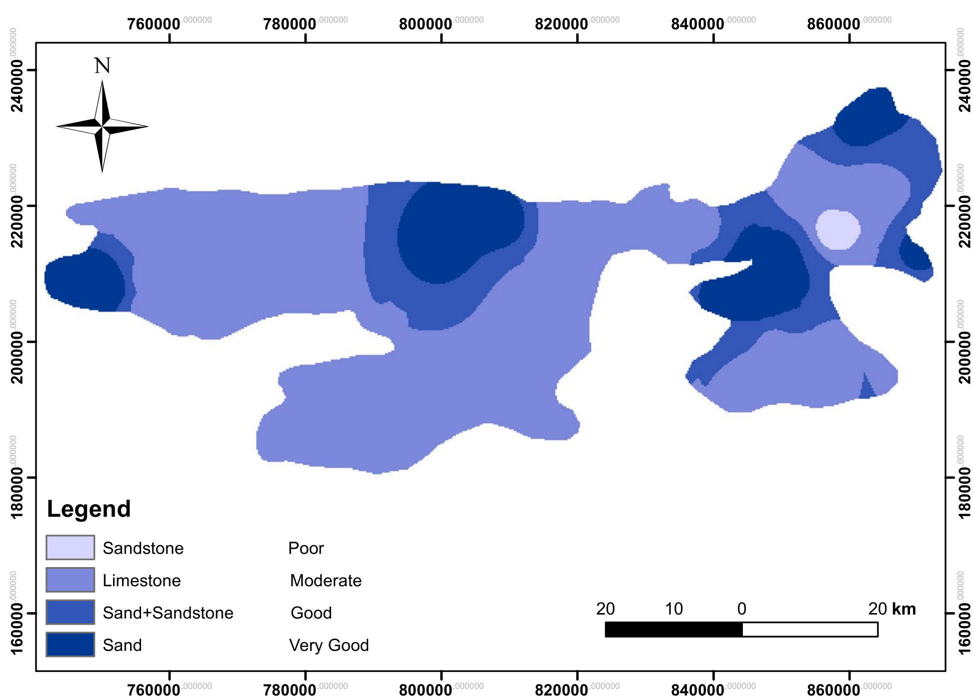


Fig. 4 Study area map: aquifer geology

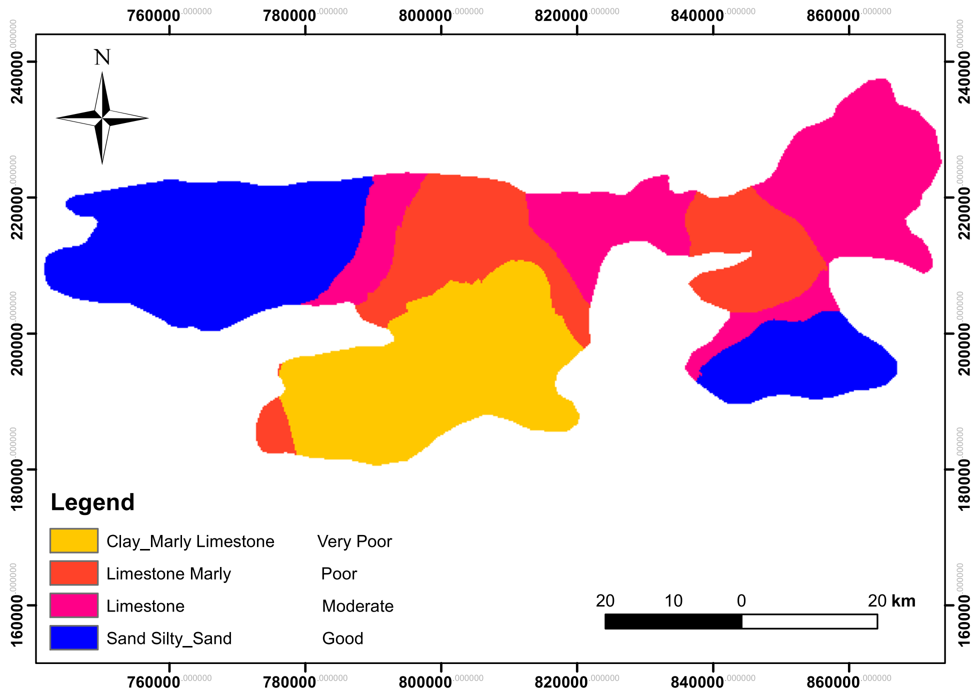


Fig. 5 Study area map: unsaturated zone lithology

The major eigenvalue of the generated matrix is used to determine the weight for each parameter. The following formula is used as a verification procedure to guarantee the correctness of the result: $CR = \frac{CI}{RI}$ where CR denotes the coherence ratio, CI denotes the coherence index, while RI represents the random coherence index based on the matrix order shown in Table 3.

The coherence index (CI) is determined by the following equation.

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

where λ_{max} represents the principal eigenvalue, and n refers to the size of the comparison matrix.

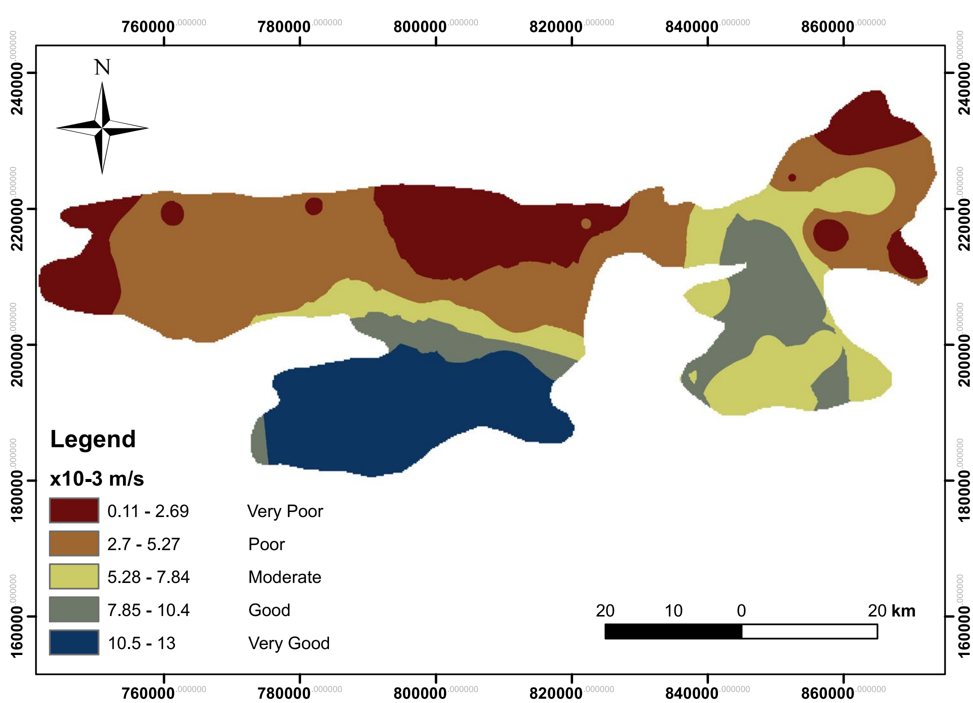
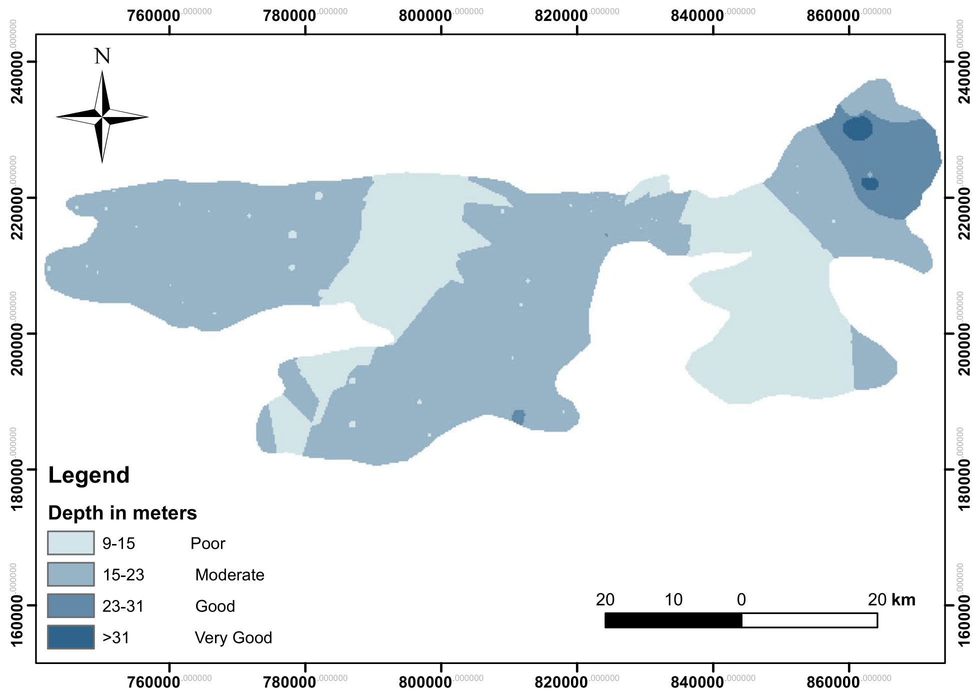


Fig. 6 Study area map: hydraulic conductivity of the aquifer

Fig. 7 Study area map: depth to groundwater level

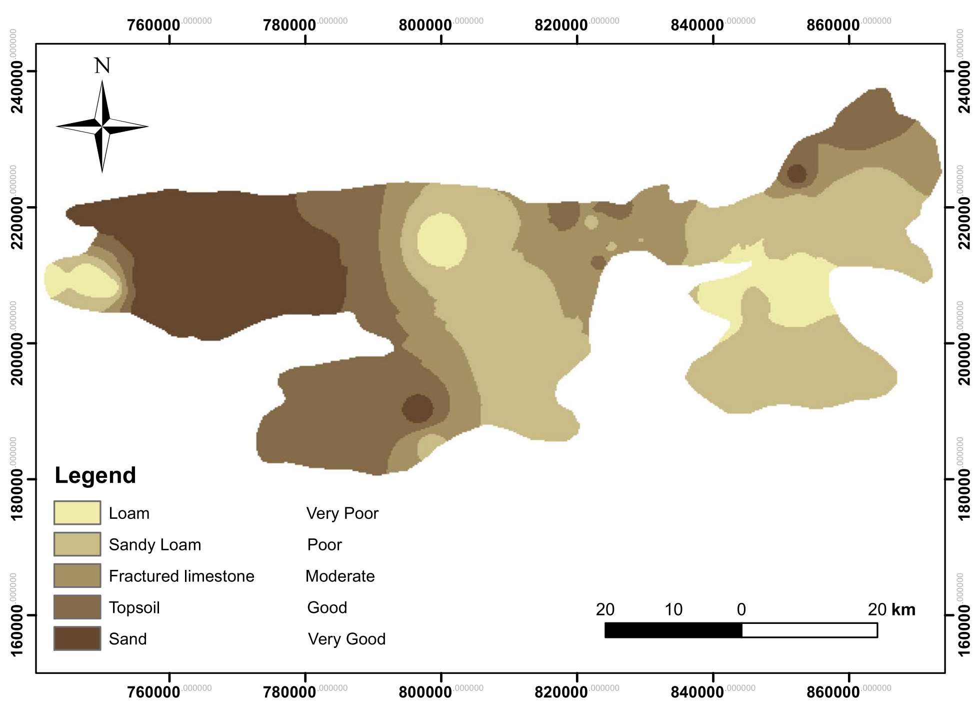


To achieve a realistic and acceptable consistency of the weight analysis matrix, the value of CR should be less than 0.1. If the CR value is more than 0.10, there is an inconsistency in the judgment, and the reasons must be investigated and remedied. If, on the other hand, the consistency value is 0, it indicates that the choice has a perfect degree of consistency in the pair (Arulbalaji et al. 2019; Ghosh 2021).

Validation of the technique

Different methods can be used to validate the results when identifying potential groundwater recharge sites. The methods are based on the AUC (area under the curve) and ROC (receiver-operating characteristic) techniques (Das et al. 2021; Navane and Sahoo 2021) by comparing the maps of the artificial groundwater recharge sites with the

Fig. 8 Study area map: soil type



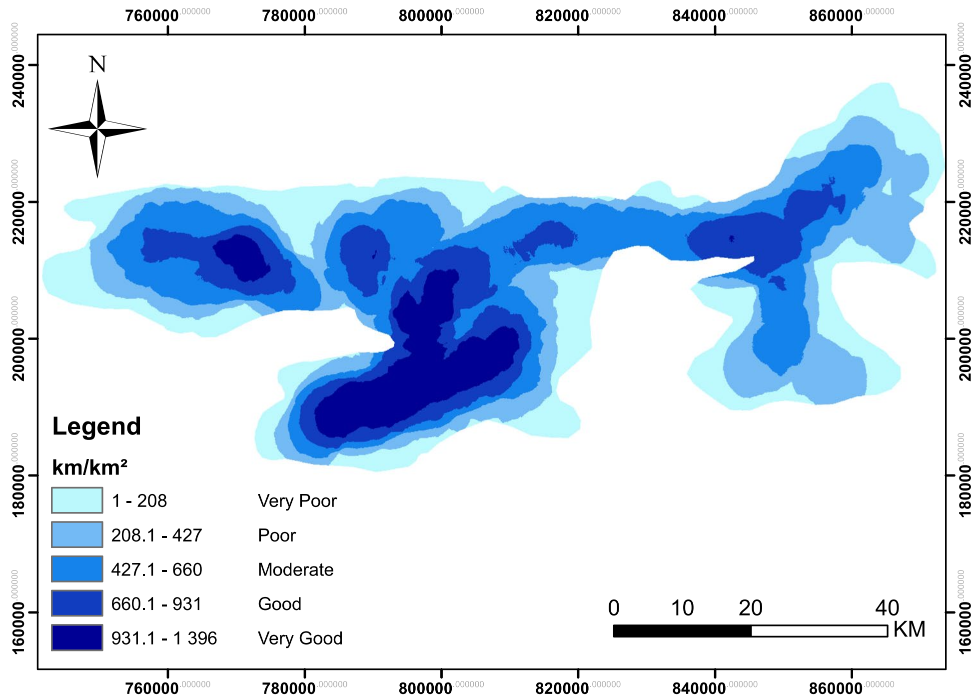


Fig. 9 Study area map: drainage density

groundwater levels in the wells. Validation can also take place through study of the groundwater quality by comparing the concentrations of pollutants in areas with very good potential for artificial recharge and those with low potential.

Consequently, the results were validated by monitoring the groundwater levels of the two wells studied. In addition, for more accuracy, there was a comparison between the spatial distribution of salinity in the study area and the generated maps of potential artificial recharge sites.

Results and discussion

Reclassification of variables and preliminary potential mapping

Table 1 summarizes the selected parameters and categories associated with recharge potential mapping. Each parameter has been reclassified based on the relative impact of these parameters on groundwater storage, movement and quality.

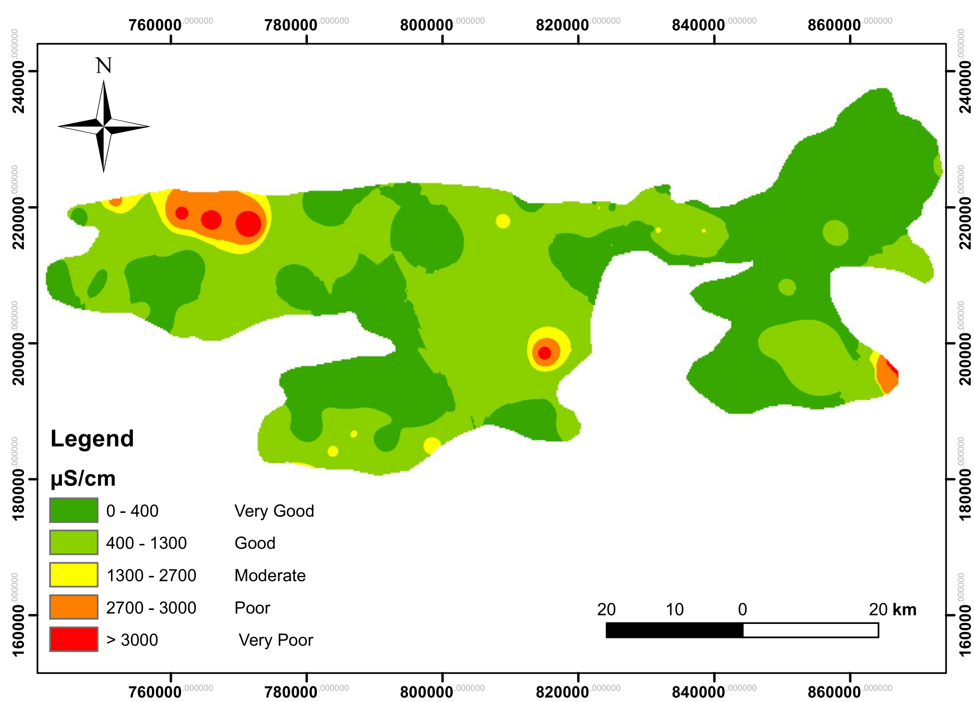
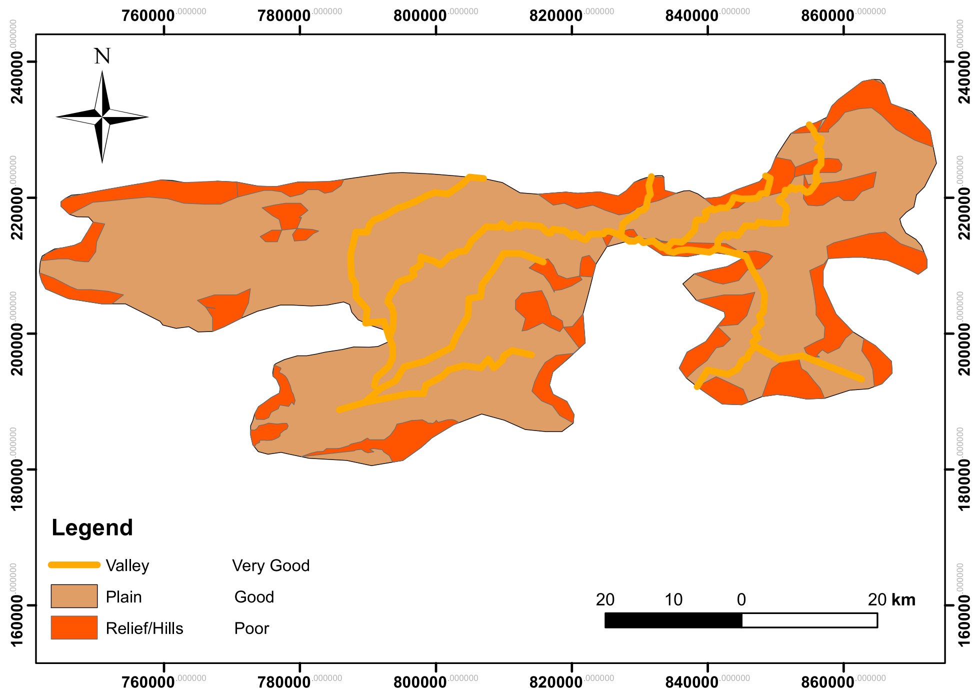


Fig. 10 Study area map: electrical conductivity of the resident groundwater

Fig. 11 Study area map: geomorphology



The slope of 0–3% has been assigned a very good category of potential recharge. In the study area, as the plain is steeply inclined, more than 8% of slopes are considered inadequate for recharge. The terraces on flat ground and floodplains scored relatively highly in terms of geomorphology, while areas with a steep slope were considered inappropriate (poor potential to recharge; Figs. 3 and 4).

As discussed previously, soil texture impacts the amount of water infiltration into the rock and, thus, the capacity for recharge (Singhal et al. 2017). The infiltration capacity of coarse-textured soils such as sand is very good, and the percolation potential of well-drained soils is also very good. Table 1 displays the distribution of different natural soil types in the Tamellalt Plain. The drainage throughout the limestone was considered moderate; however, sandy loam and loam are classified as having poor and very poor recharge potential, respectively, while the

Fig. 12 Study area map: land cover

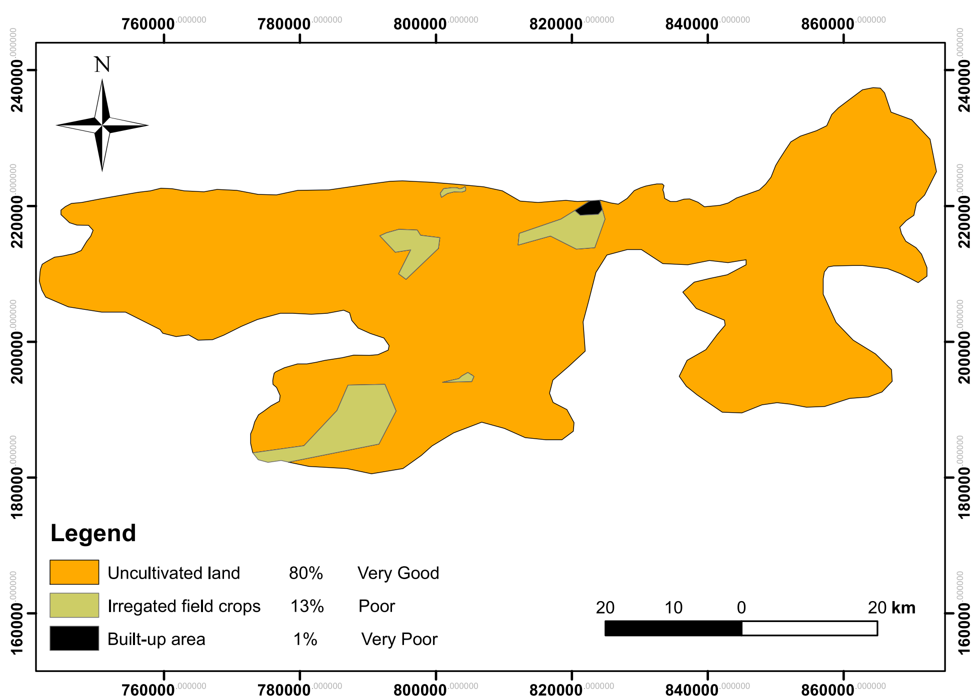


Table 2 The scale of relative significance for pairwise comparison (Saaty 1980)

Definition	Intensity of importance
Equal importance	1
Somewhat more important	3
Much more important	5
Very much more important	7
Most important	9
Intermediate values	2, 4, 6, 8

arable topsoil layer and sand are considered good and very good with respect to drainage (Figs. 5 and 6).

Land cover has been reclassified based on infiltration capability. Uncultivated land is ranked to be the most suitable site for recharge. Meanwhile, built-up areas have been classified as having very poor potential for recharge because they have impermeable surfaces that limit water infiltration. Irrigated field crops have been classified as having poor potential (Fig. 12).

Higher values of hydraulic conductivity indicate greater groundwater movement. The local Water Utilities Administration classification method for aquifer hydraulic conductivity established the aquifer hydraulic conductivity classes used here. Above a hydraulic conductivity of 5.28×10^{-3} m/s there is significant groundwater movement in the aquifer, whereas a hydraulic conductivity of less than 5.28×10^{-3} m/s is considered too poor for recharge (Fig. 6).

Electrical conductivity has a negative relationship with water quality. High electrical conductivity indicates high salinity and TDS content; hence, the sites with low electrical conductivity were much preferred. The grading on electrical conductivity was based on the water quality matrix of the Mary River Catchment Coordinating Committee (Mary River Catchment Coordinating Committee 2013). An electrical conductivity of 0–800 µS/cm is considered acceptable for basically all water uses; therefore, 0–400 µS/cm was graded very good, while 400–800 µS/cm was graded good (Fig. 10).

The drainage density represents the watershed's layout in terms of drainage (Horton 1945). Due to its inverse relationship with watershed permeability, information on drainage density is vital (Ahmed and Sajjad 2018; Ourarhi et al. 2022). Permeable land areas are thought to appear as low-density drainage areas. Because porous soil allows infiltration, runoff along the ground surface is reduced. The values of infiltration induced by drainage density were divided into five equal intervals, ranging between 1 and 1,396 km/km^2. The lowest drainage density class (1–208 km/km^2) received the highest rating (Fig. 9).

Regarding geological formations (Fig. 11), most of the aquifer environment is limestone, while the remaining part is sand and sandstone. These types of rock are characterized as having significant permeability, given the size of their granules, and therefore good and very good recharge potential.

The distance between the ground surface and the groundwater level is not the same for the whole plain. However, most of the plain area is characterized by a shallow to medium depth range (9–23 m); hence, groundwater storage capacity was relatively small. Four classifications for the depth to groundwater values range between 9 and 31 m (9–15, 15–23, 23–30, and > 31 m; Fig. 12).

AHP methodology for weighting and improving evaluation

The weight and assessment of each theme layer in this research were calculated using AHP. This research took into account 10 thematic layers, and the consistency index (CI) and consistency ratio (CR) findings are as follows: CI = 0.041422 and CR = 0.0278 to <0.1. The purpose of these characteristic layers is to aid in the delineating of potential locations for artificial groundwater recharge in the area. These characteristics are added together and given different weights based on their significance. A low-weighted parameter emphasizes a modest influence on groundwater potential for artificial recharge (GWPAR), whereas a high-weighted parameter represents a layer with a larger impact (Ourarhi et al. 2022). Following the Saaty scale (1–9) of relative relevance values, weights were given to each parameter. Additionally, weights were allocated based on an analysis of earlier research and field experience. The pairwise comparison matrix and normalized weights for each parameter, using the AHP model and consistency test, are shown in (Tables 3 and 4).

To create the potential map, each thematic map was reclassified and given values from 1 to 5, with 5 being the highest (Table 5). After applying the weighted sum tool to the maps, a final map, with a GWPAR value between 2.53 and 4.10, was generated. Based on the indices used to evaluate potential regions for artificial groundwater recharge, the distribution relative to the total area is as follows (Fig. 13): 9% poor potential, 37% moderate potential, and 54% good potential. According to Figs. 13 and 14, most of the plain is

Table 3 Random coherence index (RI) value in relation to the matrix order (n) (Saaty, 1990)

	Matrix order (n)									
	1	2	3	4	5	6	7	8	9	10
RI	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 4 Pairwise comparison matrix and weight of each setting

	Slope	Soil	Unsaturated zone geology	Geomorphology	Depth to groundwater	Land cover	Electrical conductivity	Hydraulic conductivity	Drainage density	Aquifer geology	Weight (w_n)
Slope	1	1	1	7/5	5/8	3/4	1	3/5	1	3/5	8.37%
Soil	1	1	4/5	3/4	2	4/3	4/5	4/9	3/4	5/8	8.88%
Unsaturated zone geology	1	5/4	1	9/7	1	3/4	6/7	7/9	1	5/7	9.09%
Geomorphology	5/7	4/3	7/9	1	4/5	5/8	1	5/9	9/7	7/9	8.22%
Depth to groundwater	8/5	9/5	1	5/4	1	3/2	1	1/2	9/4	1	11.70%
Land cover	4/3	3/4	4/3	8/5	2/3	1	1	1/2	1	4/3	9.83%
Electrical conductivity	1	5/4	7/6	1	1	1	1	1/2	1	7/6	9.40%
Hydraulic conductivity	5/3	9/4	9/7	9/5	2	2	2	1	2	9/7	16.08%
Drainage density	1	4/3	1	7/9	4/9	1	1	1/2	1	1	8.42%
Aquifer geology	1	8/5	7/5	9/7	1	3/4	6/7	7/9	1	1	10.02%

Table 5 Groundwater potential for artificial recharge (GWPAR) classification (Sandoval and Tiburan 2019)

Index class	Degree of GWPAR
1.00–1.80	Very poor
1.81–2.60	Poor
2.61–3.40	Moderate
3.41–4.20	Good
4.20–5.00	Very good

suitable for recharge (183,600 ha or 54%); however, 37% of the surface area is somewhat suitable for recharge (15,800 ha). Comparatively, just 9% of the total area (30,600 ha) is deemed inadequate for artificial recharge purposes.

Model validation

To confirm the results, Figs. 15 and 16 show a positive correlation between the rainfall and piezometric series for 2012, recorded at two water points in different areas. There is a significant rise in the piezometric level going hand in hand with an increase in average rainfall. The rise in the water table in Fig. 15 is explained by the location of 463/41 being in a sector that is part of the area identified as favorable for artificial recharge. Figure 15 shows an increase in the rainfall over the year; however, the water level at 463/41 is characterized by relative stability.

Conclusion

Groundwater is crucial for the effective management of water resources in arid and semiarid regions such as the Tamellalt Plain in southeastern Morocco. In such areas, there is low rainfall and a scarcity of surface waters for agricultural and residential use. Moreover, these areas are often subject to evaporation and groundwater

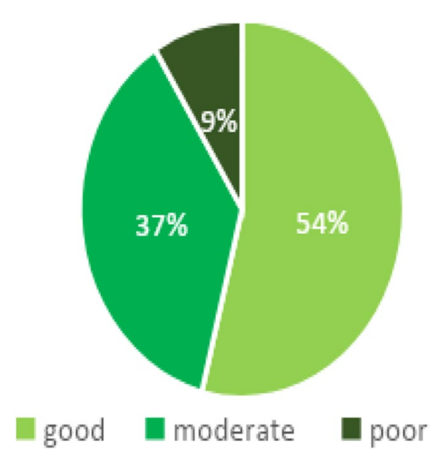


Fig. 13 Proportions of the study area with potentials for artificial groundwater recharge

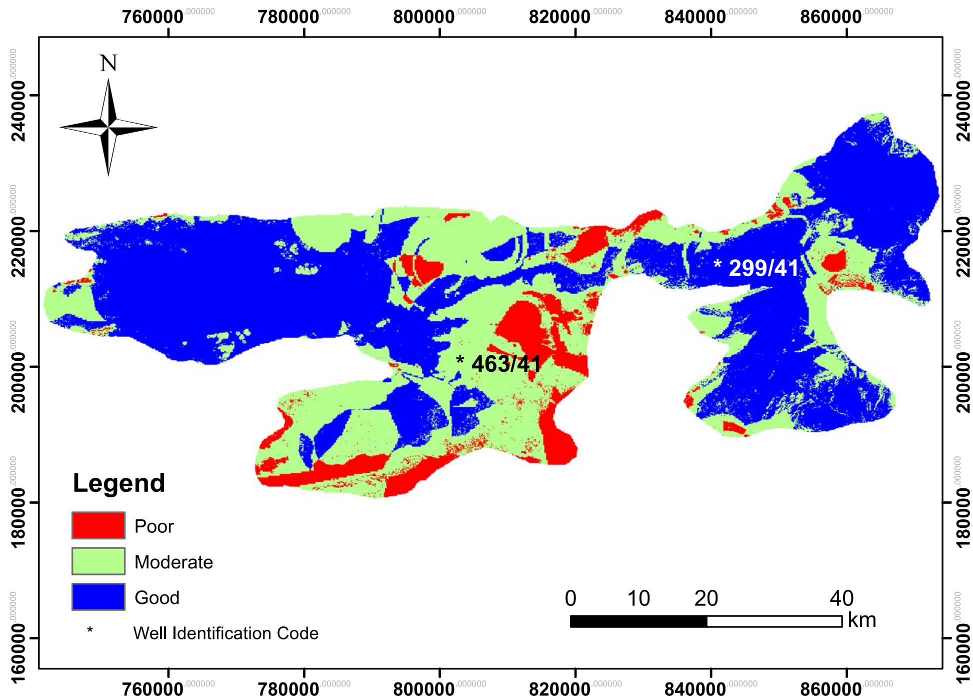


Fig. 14 Distribution of potential areas for artificial groundwater recharge, and the locations of the monitored wells

contamination, and as a result, dangerously low groundwater levels are occurring. This paper aims to identify potential places for artificial groundwater recharge, thereby improving the long-term performance of aquifers in terms of water supply, and to assist in the promotion of water conservation and longer-term water storage. Suitable artificial recharge locations were found based on several parameters. The ground-surface slope, the soil, the geology of the saturated and unsaturated zones, the geomorphology, the land cover, the electrical conductivity, hydraulic conductivity, and depth to groundwater are all influencers of infiltration and percolation characteristics. Each parameter was classified and evaluated with its potential for artificial recharge using an analytical hierarchy process (AHP). The following aptitude scales were employed in the reclassification: very poor, poor, moderate, good, and very good. The model was applied to the Tamellalt region. The AHP findings contributed to creating a final map that integrated all the thematic maps via superposition. It was found that 54% of the study area is suitable for artificial replenishment of subsurface waters. The regions of good, moderate, and poor potential cover 183,600, 125,800, and 30,600 ha, respectively.

Future work can improve potential water management strategies to increase artificial recharge at the area level, particularly in the case of alluvial aquifers in arid regions, which are recharged only during occasional floods and often only yield improvement in a portion of the potential reservoir. It is feasible to boost water-supply output by gradually increasing artificial recharge via the construction of check dams, an approach that would lengthen the contact period

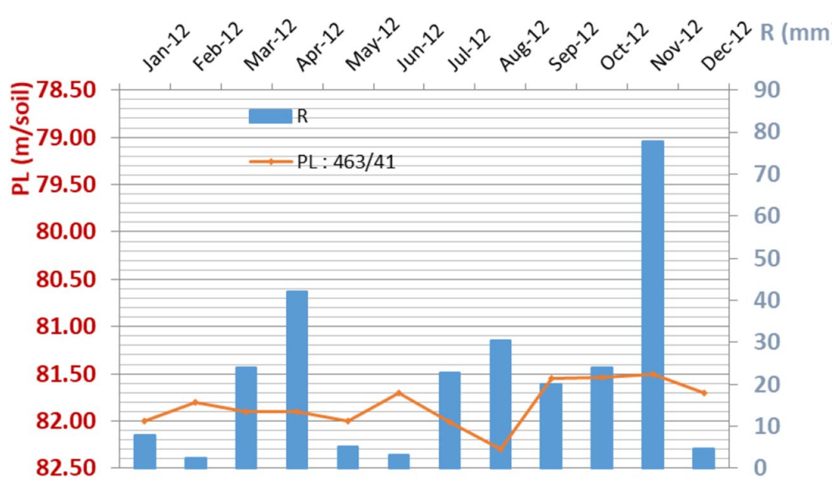


Fig. 15 Piezometric level (PL) measured in piezometer N°IRE 463/41 against rainfall (R). (m/soil) refers to the depth (m) relative to soil surface level

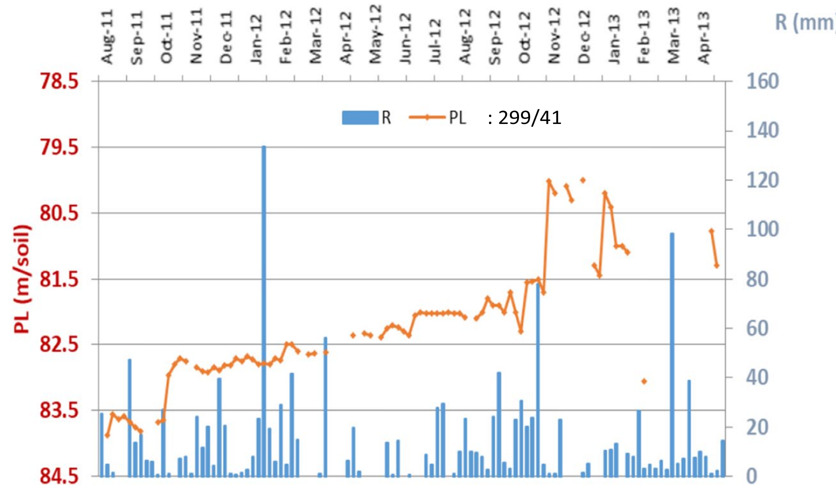


Fig. 16 Piezometric level (PL) measured in piezometer N°IRE 299/41 against rainfall (R)

between the alluvium and the flood waters, resulting in more infiltration than under natural circumstances.

Declarations

Conflict of interests The authors declare no conflict of interest.

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