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ORIGINAL PAPER

Fuzzy analytical hierarchy process for groundwater potential mapping in a Mediterranean catchment: the case of the Medjerda catchment in northeast Algeria

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Abstract

In this study, groundwater potential was mapped for a Mediterranean catchment using remote sensing techniques, geographical information systems (GIS), and the fuzzy analytical hierarchy (FAHP) process. Seven environmental factors were considered to influence groundwater potential, including soil type, lithology, precipitation, land use/cover, slope, lineament density, and drainage density. A FAHP method was implemented to calculate the weight of each factor and each class in the groundwater potential. The FAHP confusion matrix was established by eliciting opinions of local experts on factors that drive groundwater potential in this area. A weighted overlay was made in Arc-GIS™ for producing the final groundwater potential map. Three groundwater potential classes were considered (low, moderate, strong). Areas of very high potential represent 107.09 km^2 (8%) of the total surface of the basin and are located in alluvial and calcareous formations of a high density of lineament and in areas with a low slope which promotes rapid infiltration. About 1022.124 km^2 (71%) of the surface of the sub-catchment is characterized by a moderate to strong potential, while the remainder 305.945 km^2 (21%) is characterized by a low potential. The results of the classification are validated by establishing the receiver operating characteristic (ROC) curve using 61 data from the wells located in the study area. The area under curve (AUC) yields 75.5% demonstrating the effectiveness of the method in identifying groundwater potential areas.

Keywords Medjerda · Groundwater · Remote sensing · GIS · FAHP · ROC

Introduction

Groundwater remains a limited and vulnerable natural resource that is indispensable for critical production and ecosystem functions and services, including drinking water provision and provision of water for agriculture and industrial development (Valipour 2015; Serele et al. 2020). For designing sustainable and water-secure development programs in a given region, the groundwater potential needs to be known. This is particularly needed for the Mediterranean region which is considered a hot spot for climate change and where pressures on water resources are ever-increasing due to population growth, and the intensification of climate change impacts. Yet the assessment of the groundwater potential remains problematic since groundwater potential is determined by a panoply of factors that vary in space or time or both. Determining factors include, for a given region, the lithology and geology, the drainage system, the soil type, the lineament features, the geomorphology, the topography and the slope, the local climate and in particular the precipitation regime, the land use/land cover (LULC), and the hydrological conditions, amongst others. The interconnection between these factors controls the delineation of groundwater potential zones in the area, but there is no scientific agreement on how this interconnection should be modeled (Jha et al. 2010; Chowdhury et al. 2010; Jaiswal et al. 2003; Pradhan 2009; Avtar et al. 2010; Nagarajan and Singh 2009; Singh et al. 2011; Acharya et al. 2019). With the availability of current remote sensing (RS) products at higher spatial and temporal resolutions, geographical information

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system (GIS), and multi-criteria decision analysis tools, a new set of tools and instruments emerge that can be used to identify groundwater potential in a robust and cost-effective way (Al-Adamat et al. 2003; Saha et al. 2010; Saraf and Choudhury 1998; Jaiswal et al. 2003; Jha et al. 2007; Ganapuram et al. 2009; Semere Solomon and Quiel 2006). Multi-criteria decision-making (MCDM) is defined as a selective method for evaluating and prioritizing many complex decisions and computing the relative importance of factors. MCDM techniques for groundwater potential mapping were already introduced in previous pioneering studies (Kumar et al. 2017; Ghorbani Nejad et al. 2017; Jaiswal et al. 2003; Solomon 2003; Jha et al. 2007; Ganapuram et al. 2009; Magesh et al. 2012; Kumari and Dhanaraj. 2021; Radulović et al. 2022). The used techniques include the frequency ratio technique (FR), the certainty factor technique (CF), the weights-of-evidence technique (WOE), the Dempster-Shafer technique (DS), the use of fuzzy logic index models, the use of multi-influencing factors (MIF), the analytical hierarchy process method (AHP), and the fuzzy analytical hierarchy process method (Fuzzy-AHP). The efficiency of these techniques depends on the scientific data that are available. In addition to being less time-consuming and economical, MCDM approaches are inexpensive compared to other classical approaches such as borehole testing, stratigraphic studies, and hydraulic characteristics analysis, which despite its efficiency and reliability are extremely costly and also time-consuming (Todd 1980; Moss and Moss 1990; Fetter 1994; Jha et al. 2010). In particular, the fuzzy-AHP approach can be used for groundwater potential mapping (Srivastava and Bhattacharya 2006; Gupta and Srivastava 2010; Machiwal et al. 2011; Agarwal et al. 2013; Kaliraj et al. 2014; Manap et al. 2014; Rahmati et al. 2015; Shekhar and Pandey 2015; Agarwal and Garg 2016; Singh et al. 2018) but this technique has not been implemented and validated to assess GWP in Algerian water systems. The Medjerda river basin (MRB) is a transboundary watershed in the northeast of Algeria and northwest of Tunisia. The active basin area is 23,700 km^2. Agriculture dominates the land use of the basin and accounts for 40 to 70% of the gross domestic product of MRB countries (FAO 2018). The basin has experienced recent strong demographic pressure and considerable agricultural and industrial development. This requires an increased demand for groundwater (Directorate of Water Resources, Ministry of Agriculture and Rural Development, MADR), in particular, to sustain irrigation water needs. According to Kadir et al. (2020), about 60% of groundwater in the upstream part of the MRB is affected by irrigation activity. In order to effectively manage the current scenario of water scarcity, the groundwater potential should be better assessed in the MRB. The main objective of this study is therefore to propose, to implement, and to validate a fuzzy-AHP-based procedure to map the groundwater potential of the upstream Algerian part of the MRB. The use will be made of the most recent geodata sets that are currently available, and expert elicitation to implement the method. The method will be validated using data about the position of groundwater wells and measured groundwater productivities using receiver operating characteristic (ROC) curve analysis.

This work provides a general framework to help managers understand the interactions and linkages between groundwater potential and the factors that influence it, and thus develop strategies for impact assessment and sustainable management of groundwater resources to ensure that the quantity and quality characteristics of these valuable resources are maintained. It focuses primarily on water quantity issues. This document contains a more detailed section on the characterization and mapping of groundwater conditioning factors, the development of the final groundwater potential map, and at the end general guidance on the development of strategies for better management of groundwater resources and associated factors.

Study area

The Medjerda catchment is located between Algeria and Tunisia (Fig. 1). It is known as one of the most important basins of the Maghreb by its geographical position. It covers an area of 23,700 km^2, including 7600 km^2 in Algeria. It is drained mainly by the Medjerda stream which originates in the town of Khemissa (region of Souk Ahras) and runs a total length of 460 km, including 120 km in Algeria and 340 km in Tunisia. The study area of the Medjerda sub-catchment is situated in the northeast of Algeria, between latitudes 7°37′E and 8°25′, and longitudes 36°05′ and 36°27′N. It covers a geographical area of 1411km^2. It is surrounded by the basin of the Constantines coast east to the north, the sub-basin Mellegue (Tebessa) to the south, to the east by the Algerian-Tunisian border, and to the west by the basin of Seybouse (Guelma). It constitutes an intermediate zone between two distinct geomorphological domains, namely mountainous areas and forests in the north with a high relative altitude of 700–1400 m and grassland areas and high plains in the south (MADR). Within the upper part of this basin, the Ain Dalia dam was constructed, which supplies drinking water to some cities of the wilaya of Souk Ahras and the bordering wilayas (ANBT 2014). The region is characterized by a semi-arid climate with an average annual rainfall of 600 mm (ONM 2018).

Materials and methods

General methodology

We followed the overall methodology of Yousef Razandi et al. (2015), for mapping groundwater potential that includes 3 steps (Fig. 2).

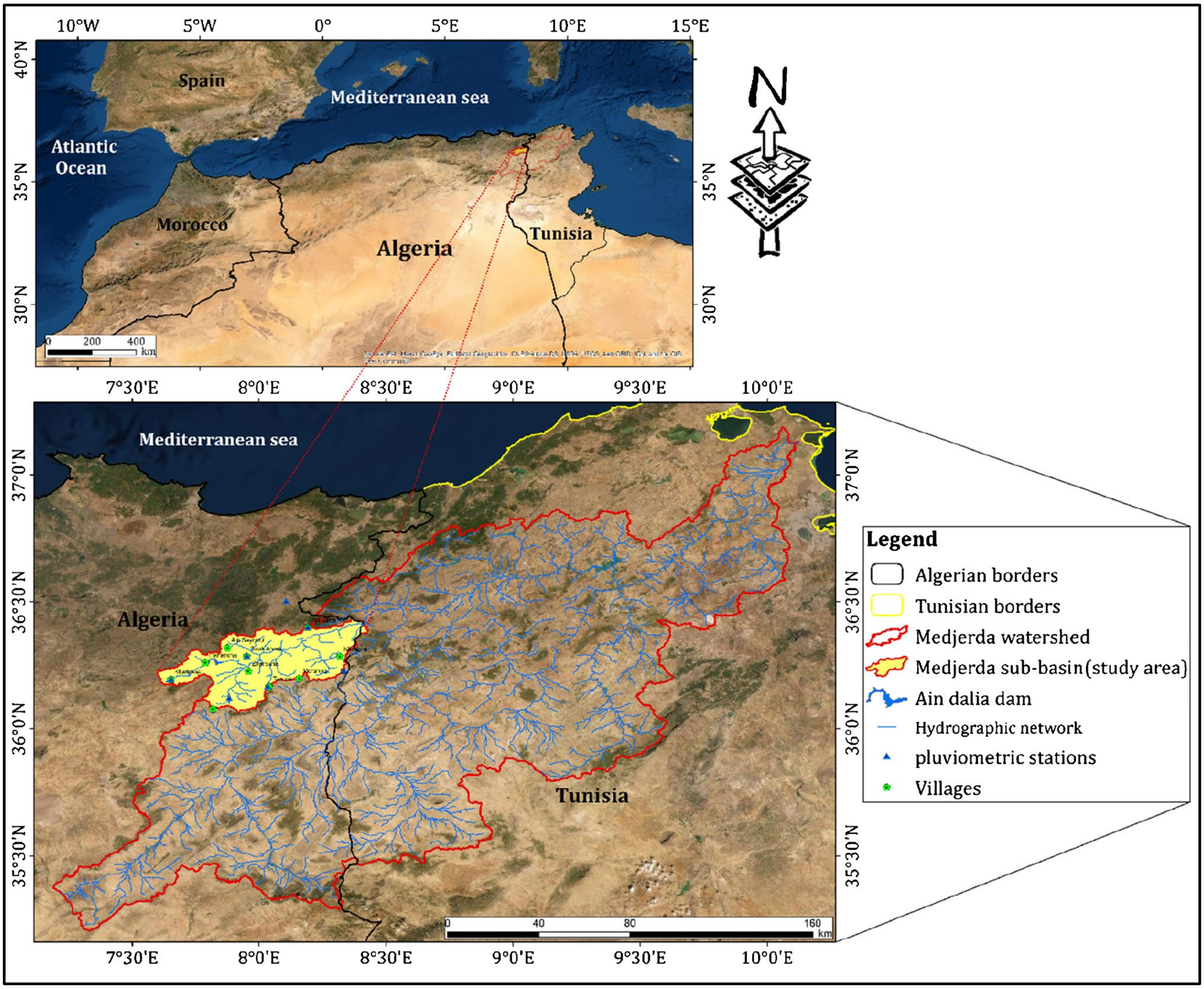

Fig. 1 Location of the study area

(a) The preparation of the database (raster-format thematic layers) for the various factors that influence the potential of groundwater.

For this step, a GIS environmental database was constructed from publicly available and local data sources. Data were collected and processed for seven thematic factors determining groundwater potential, i.e., (1) soil type, (2) geology and lithology, (3) rainfall, (4) slope, (5) lineament density, (6) land use/cover, and (7) drainage density. Table 1 describes the sources of all the selected factors.

(b) The analysis of the relationship between factors that influence groundwater storage.

For this step, an MCDM based on fuzzy-AHP was set up to determine the weights of the different factors driving groundwater potential. The weights were subsequently implemented in a GIS model to map groundwater potential.

(c) The validation of mapping results using the performance of wells located in the study area.

In this last step, productivity data from local wells were used to validate the groundwater potential maps. Confusion matrices were established, and the ROC curve was used to validate the groundwater potential map.

Preparing the geodata set

Table 1 shows that the source and method for the processing of the data vary from one factor to another. The soil map of the study area was collected from the Ministry of Agriculture and Rural Development of Algeria (MADR). The soil

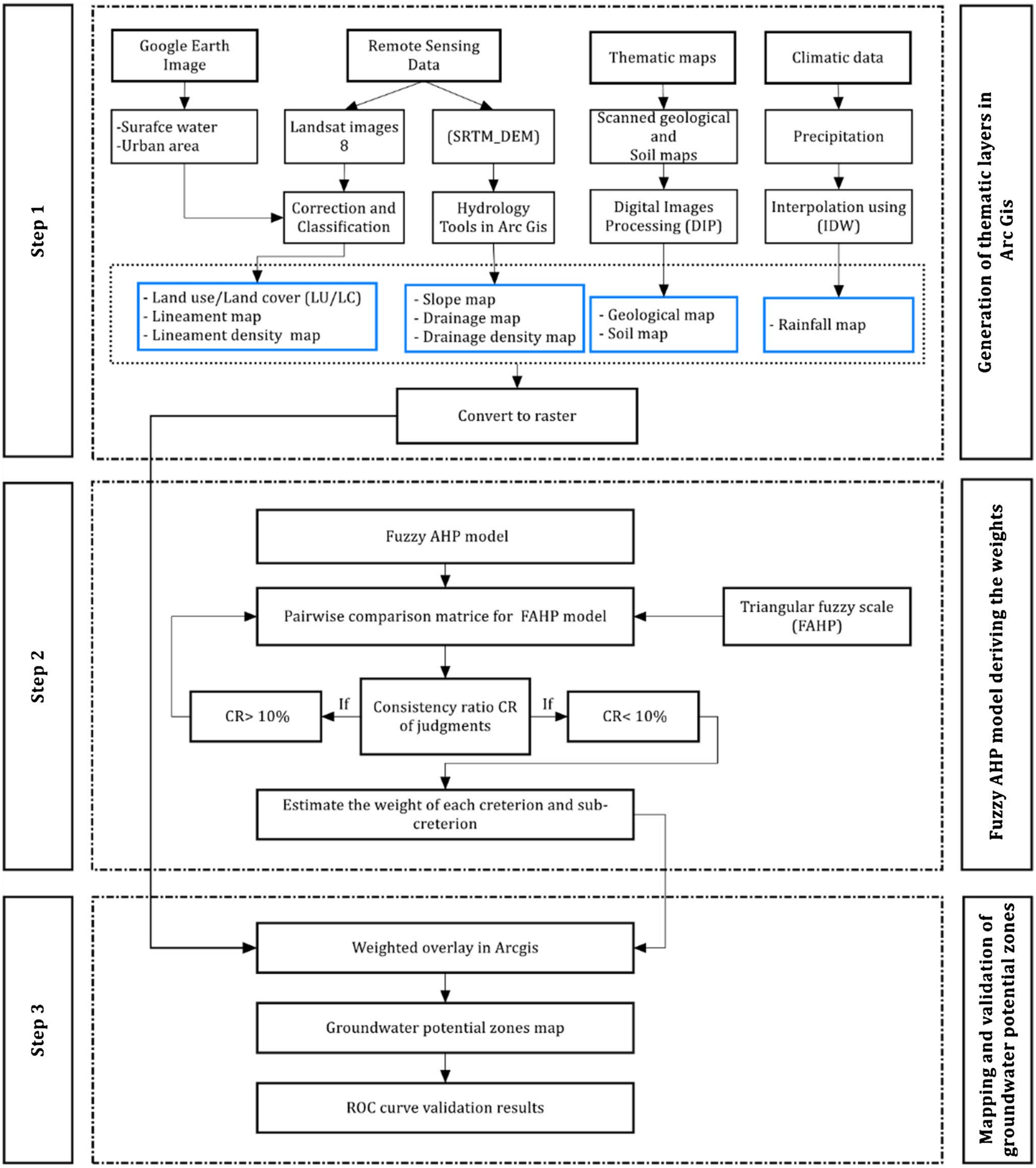

Fig. 2 Flow chart of the global methodology used in this study

map was scanned, rectified, digitized, rasterized, and reclassified. Seven soil types were considered. The lithological map was extracted from the geological map available at the National Water Resources Agency (ANRH) in Algeria at a scale of 1/250,000. The maps were obtained in pdf format, transformed into images, digitized, and rasterized using ArcGis 10.4.

Monthly precipitation data were collected from seven rainfall stations located in the study area, managed by the meteorological service of the Souk Ahras. The monthly

Table 1 Data sources for implementing the GWP model

Factors	Sources
Soil	The soil map of Algeria, collected from the Ministry of Agriculture and Rural Development (MADR)
Geology	Geological maps of Algeria with a scale of 1/250,000, collected from the National Water Resources Agency (ANRH 2008)
Rainfall	Monthly mean precipitation data, collected from the meteorological station of the region of Souk Ahras (1990–2019)
Slope	Topographic data, collected from NASA's Shuttle Radar Topography Mission (SRTM) at a resolution of 30 m
Lineament density	Landsat 8- OLI satellite images (resolution 30 m), downloaded from the United States Geological Survey website (USGS 2019) Geological maps of Algeria with a scale of 1/250,000, collected from the National Water Resources Agency (ANRH 2008)
Land use/cover	Landsat 8-OLI satellite images (resolution 30 m), downloaded from the United States Geological Survey website (USGS 2019) High-resolution Google Earth images (2019)
Drainage density	Extracted from the SRTM images

data were aggregated to mean annual precipitation data (1990–2019). The inverse distance interpolation method available in ArcGIS 10.4 was used to create a precipitation map. The SRTM images were downloaded from the USGS earth explorer data portal. The image was used for extracting the slope at each point of the study area, and to extract the hydrographic network. The drainage density map was subsequently obtained from the treatment of the hydrographic network map. The land use/cover map was constructed from the Landsat 8 satellite images downloaded from the United States Geological Survey website (USGS). After contrast enhancement, radiometric and atmospheric corrections a supervised classification with training samples was made allowing to obtain different land use/cover classes. The Landsat 8 image processing has been carried out in the ENVI 5.3 software. Based on these same images, the lineaments map was obtained. According to Yassaghi (2006) and Mogaji et al. (2011), lineaments extracted from satellite images contain also non-geological surface features such as roads, electric cables, forest boundaries, and agricultural areas. To eliminate these features, we compared lineaments with features observed on Google Earth high-resolution images. The final lineaments map was obtained by merging the lines extracted from the satellite images Landsat 8 with the lineaments of the geological map. The lineaments density map was obtained by directly processing the lineaments map by the ArcGIS software using the line density option. All spatial data were converted into a 30 m resolution raster format and georeferenced within WGS 1984 UTM zone 32 coordinate system.

Designing and implementing the fuzzy-AHP model

The concept of fuzzy set theory was introduced by Zadeh in 1965. It was introduced to deal with partial truth values and uncertainty ranging from absolutely true to absolutely false. It introduces fuzzy numbers in order to express linguistic variables correctly (Zadeh, 1975). It also allows dealing with imprecision and ambiguities aiming at traceability and rigorism for describing vague features of the real world (Emrouznejad and William, 2017). Fuzzy set theory is widely used in MCDM models and is applied in many fields such as overall management, decision-making, artificial intelligence, information systems, expert systems, logic and control theory applications, and statistics (Chen 2001; Chen and Tzeng 2004; Chiou et al., 2005); Ding and Liang 2005; Figueira et al. 2005; Geldermann et al. 2000; Ho et al. 2010; Triantaphyllou 2001; Ölçer and Odabaşi 2005; Wang and Lin 2003; Wang et al. 2012; Xu and Chen 2007; Emrouznejad et al. 2014; Emrouznejad and William 2017). The analytical hierarchical process (AHP) method was introduced by Saaty in the 1970s (Saaty 2008). It is a technique based on mathematics, psychology, and sociology for organizing and structuring factors in complex systems, supporting decision-making. It is often used for hierarchizing factors in complex environmental system models (T. L. Saaty, 2008). Yet, the method exhibits also some weaknesses due to the uncertainty associated with the judgments of decision-makers and the numbers representing their degree of importance (Yang & Chen, 2004). Consistent with the fuzzy set theory and the Saaty AHP method, Van Laarhoven and Pedrycz (1983) proposed the fuzzy-AHP method to overcome the drawbacks and shortcomings of the traditional Saaty AHP method. The fuzzy-AHP method uses triangular fuzzy numbers to effectively manage imprecision and reduce uncertainty and inconsistency corresponding to the subjective judgments of experts when evaluating selected criteria (Calabrese et al. 2016; Emrouznejad and William, 2017). It is also adapted to abolish multi-criteria decision-making problems (Lee et al. 2013) and to manage qualitative assessments (Dağdeviren et al., 2008). In the present study, we used the geometric mean method (Buckley, 1985), which allowed us to derive fuzzy weights for each fuzzy pair comparison matrix, using fuzzy ratios instead of precise Saaty ratios (Buckley, 1984; Konidari

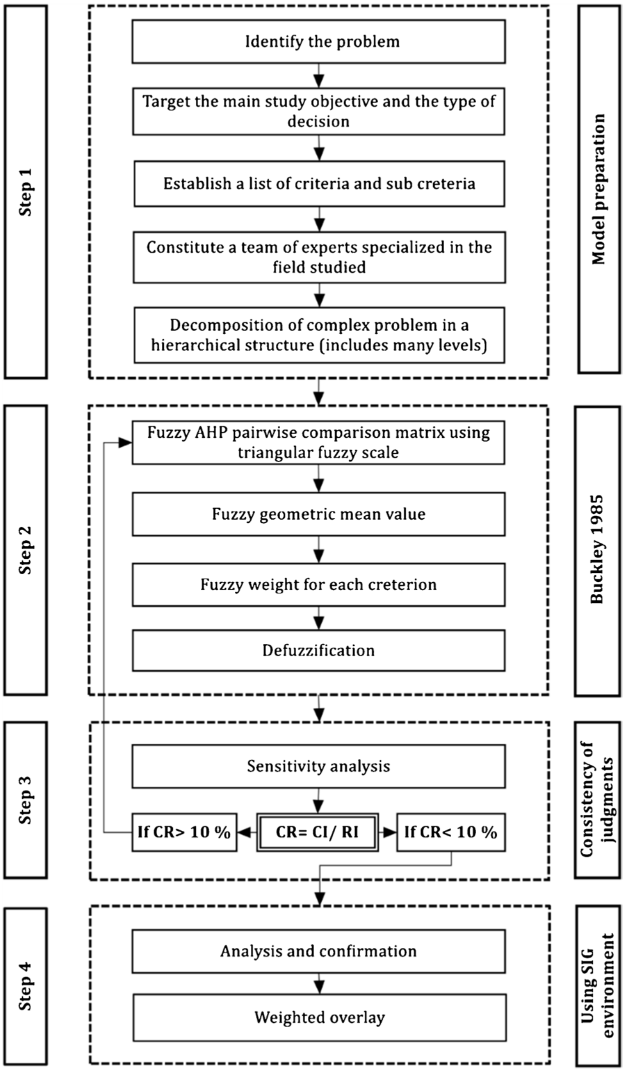

Fig. 3 Flow chart of fuzzy-AHP approach

& Mavrakis, 2007). This method offers certain advantages such as the ease of calculating and guarantees a unique solution (Emrouznejad and William, 2017). In order to verify the effectiveness of the geometric mean method and the triangular fuzzy numbers. We integrated the last step of the AHP method (calculation of the coherence index) to prove the existence of a high degree of precision and coherence while performing pairwise comparisons between the different factors affecting the groundwater potential.

The fuzzy-AHP can be summarized in five steps (Fig. 3).

Setting up the fuzzy pairwise comparison matrix

In our model, the groundwater potential is dominated by 7 environmental factors. The importance of each factor is identified by fuzzy-AHP. In the fuzzy-AHP method, each factor is compared to all other factors using fuzzy triangular numbers (FTN) and corresponding linguistic variables to represent the degree of importance of the judgments. The keys that are used in this comparison are given in Table 2. In this study, the comparisons were made by a team of 8 experts, with the required qualities in groundwater science or management. The team includes engineers and researchers from the National Agency of Water Resources (ANRH) and the Directorate of Agricultural Services of Souk Ahras (DSA) and university professors specialized in hydrogeology, geology, hydrology, and agronomy. Comparison matrices were formed between the selected factors as well as between their classes to determine the extent of their influence on groundwater potential. Obtaining less uncertainty and very precise results requires consistency between the different expert judgments. To assure this consistency, each expert received a detailed report which includes a description of the problem and the factors that contribute to the problem. Ultimately, the decision-making and completion of the matrices required the collective work of experts so that everyone could explain and defend their choices to reduce the degree of uncertainty and to obtain very precise and consistent results.

Table 2 Linguistic variables for pairwise comparison of each criterion

Linguistic variables	Triangular fuzzy numbers	Triangular fuzzy reciprocal numbers	Explantation
Equal importance	(1,1,1)	(1,1,1)	Equal influence of two criteria on the objective
Moderate importance	(2,3,4)	(1/4,1/3,1/2)	Judgment favors slightly the influence of one factor over another
Strong importance	(4,5,6)	(1/6,1/5,1/4)	Judgment strongly favors the influence of one factor over another
Very strong importance	(6,7,8)	(1/8,1/7,1/6)	Judgment very strongly favors the influence of one factor over another
Extreme importance	(9,9,9)	(1/9,1/9,1/9)	An extremely important factor compared to another
Intermediate values	(3,4,5) (5,6,7) (7,8,9)	(1/5,1/4,1/3) (1/7,1/6,1/5) (1/9,1/8,1/7)	Exact comparison between two factors

The fuzzy pair comparison matrix $\widetilde{D} = \left[\widetilde{a}_{ij}\right]$ is constructed as:

$$\widetilde{D} = \begin{bmatrix} (1,1,1) & \widetilde{a}_{12} & \dots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & (1,1,1) & \dots & \widetilde{a}_{2n} \\ \vdots\ \vdots & & \ddots & \vdots \\ \widetilde{a}_{n1}\widetilde{a}_{n2} & & \cdots & (1,1,1) \end{bmatrix} \tag{1}$$

where $\widetilde{a}_{ij} \otimes \widetilde{a}_{ij} \approx 1$ and $\widetilde{a}_{ij} \cong \frac{w_i}{w_j}$,i, j = 1, 2…, n.

Usually, only integers (1,1,1), (2,3,4), (4,5,6), (6,7,8), and (9,9,9) are used to express the degree of comparison. According to Van Laarhoven and Pedrycz (1983), the intermediate values (1,2,3), (5,6,7), and (7,8,9) can be selected in the case where there are more detailed comparisons.

Calculating the fuzzy mean for each criterion

The fuzzy geometric mean value $\widetilde{r}_i$, for each criterion i is computed as:

$$\widetilde{r}_i = \left(\widetilde{a}_{i1} \otimes \widetilde{a}_{i2} \otimes \dots \widetilde{a}_{in}\right)^{1/n} \tag{2}$$

Calculating the fuzzy weight for each criterion

The fuzzy weight $\widetilde{w}_i$ for each criterion i is calculated as:

$$\widetilde{w}_i = \widetilde{r}_i \otimes \left(\widetilde{r}_1 + \widetilde{r}_2 + \cdots + \widetilde{r}_2\right)^{-1} \tag{3}$$

where $\widetilde{r}_k = (l_k, m_k, u_k)$ and $(\widetilde{r}_k)^{-1} = (1/u_k, 1/m_k, 1/l_k)$.

Defuzzification of the fuzzy weights

The fuzzy weights $\widetilde{w}_i = (l_i, m_i, u_i)$ are defuzzified by the center of area method as follows (Buckley 1985; Tzeng and Huang 2011):

$$\widetilde{w}_i = \frac{l_i + m_i + u_i}{3} \tag{4}$$

Consistency of judgments

Determining the priority of each of these seven groundwater conditioning factors using subjective judgments can produce uncertainty due to inconsistency between judgments. So it is necessary to check the degree of consistency by calculating the CR ratio (Saaty 2004). This ratio is calculated as follows:

$$CR = \frac{IC}{RI} \tag{5}$$

where IC represents the coherence index calculated by:

$$\mathrm{IC} = \frac{\lambda\mathrm{max} - n}{n - 1} \tag{6}$$

where λ max is the maximum eigenvalue of the comparison matrix, and n the number of criteria compared. RI is referred to as the random ratio index. Its value is given according to the number of criteria n (Table 3).

According to Saaty (1980), the CR must be less than 10%. If the value of CR < 10%, inconsistency is negligible and subjective judgment is acceptable. If, however, the value of CR > 10%, the judgments of the comparison matrix must be carefully checked and a new comparison needs to be established.

GIS combination with MCDM methods

Criteria weighting and classification

The weighting of the seven selected factors on the groundwater potential depends on the results of comparison matrices (Gumma and Pavelic. 2013; Thapa et al. 2017; Serele et al. 2020) The classification of each factor is based on the calculation of the weight of subclasses, since the influence and importance of subclasses differ from one class to another. The weight of each class was also calculated using comparison matrices between them. The rank of each class is given based on the weight obtained from the degree of their influence on groundwater potential (Shaban et al. 2006), using a scale of importance from 1 to 9 such that the value 9 represents maximum importance for groundwater recharge, while the value 1 represents the lowest importance. All comparisons between the factors and these classes were made on the basis of the results of the experts.

Preparation and classification of thematic maps

Once the weight assignment process was completed, all thematic layers must have the same projected coordinate system(UTM WGS 1984 Z32), after which all thematic layers were rasterized (respecting the same pixel size for all thematic layers 30 m), and reclassified according to the calculated fuzzy weights. In order to calculate the groundwater

Table 3 Random inconsistency index (RI) for different values of n (Saaty 1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

potential index (GWPI), all the necessary data prepared were introduced into the same system using the weighting overlay method. The whole process was carried out using Arc GIS software.

Groundwater potential index (GWPI)

The weighted linear combination (WLC) technique (Malczewski 2000) was used to calculate the groundwater potential index, using the different thematic layers, the standard weight of each factor, and the rank of each class as follows:

$$GWPI = \sum_{t=1}^{m} (Wt \times X_f) \tag{7}$$

Where Wt represents the weight of each groundwater conditioning factor; Xf : represents the rank of each class for each factor; m represents the total number of factors. The final equation of groundwater potential for our case is given by the following formula:

$$\begin{aligned} GWPI =& Pd_w Pd_r + G_w G_r + Rf_w Rf_r + S_w S_r \\ &+ Dl_w Dl_r + Lu/c_w L(u/c)_r + Dd_w Dd_r \end{aligned} \tag{8}$$

where Pd: soil types; G: geology; Rf: rainfall; S: slope; Dl: density lineaments; $L(u/c)$: land use/land cover; Dd: drainage density; w: the weight of each factor; and r: the rank of each class.

Validation of results

Validation of results is one of the very important processes in most scientific fields because it adds scientific importance and greater confidence to the results (Chung and Fabbri 2004; Rahmati et al. 2015). In our case, we use the receiver operating characteristic (ROC) curve model to assess the validity of the GWP model. According to Liu et al. (2005), the ROC is defined as a performance curve that represents the relationship between sensitivity (true-positive rate) and specificity (false-positive rate) for all classification threshold values of the model. In our case, the ROC model allowed us to predict the accuracy of the classification of potential groundwater zones by the FAHP model.

The ROC model uses the following two equations.

The true-positive rate (TPR) represents the average of true-positive results, that is, the fuzzy-AHP model capable of identifying an area of high potential as an area of high potential.

$$TPR = \frac{TP}{TP + FN} \tag{9}$$

where TP represents the sum of true-positive results; and FN the sum of false-negative results. The false-positive rate (FPR) represents the average of the false-positive results. This means that the FAHP model is capable of identifying a zone of low potential as really this zone is of low potential.

$$FPR = \frac{FP}{FP + TN} \tag{10}$$

where TN: true-negative results; and FP: false-positive results.

Finally, the area under the ROC curve (AUC) provides an overall measure of performance on all possible classification thresholds. It measures discrimination, that is, the ability of the model to correctly classify areas of high and low potential. The more the area under the curve increases, the larger probability that the positive results of the classification are correct. If the surface reaches 1, this means that all classification results are correct.

Results and discussion

Analysis of selected factors

Slope

The slope is one of the most important factors in identifying potential groundwater areas (Ettazarini 2007; Al Saud 2010; Razandi et al. 2015). It influences the speed, direction, and infiltration of surface water into groundwater reservoirs. Spatial variation in the degree of slope results in a difference in the amount of surface water that infiltrates into the ground and helps recharge and replenishes groundwater reservoirs. The steep slope areas are characterized by high surface runoff and low infiltration (Prasad et al. 2008; Magesh et al. 2012; Şener et al. 2018) while there is a significant infiltration in the plains and the horizontal areas. Based on a geopedological study conducted by the National Water Resources Agency (ANRH) in the study area, the slope map was classified into five classes from very low to very strong, namely: 6–12% (low), 12–18% (moderate), 18–25% (high) and > 25% (very high). The map is shown in Fig. 4.

The land areas with very low slopes of 0–6% cover 12.08% of the total area of the watershed. This class offers potentially a high infiltration rate and provides a real potential for agriculture development (ANRH 2009). It, therefore, exhibits a probable important groundwater potential. These areas are situated in the Taoura and Mdaorouch plains of the study area. The very high upper slopes (> 25%) represent almost 31.33% of the total surface and correspond to the mountain complexes, surrounding the median zone. These zones are often covered by forest massifs. The weights and

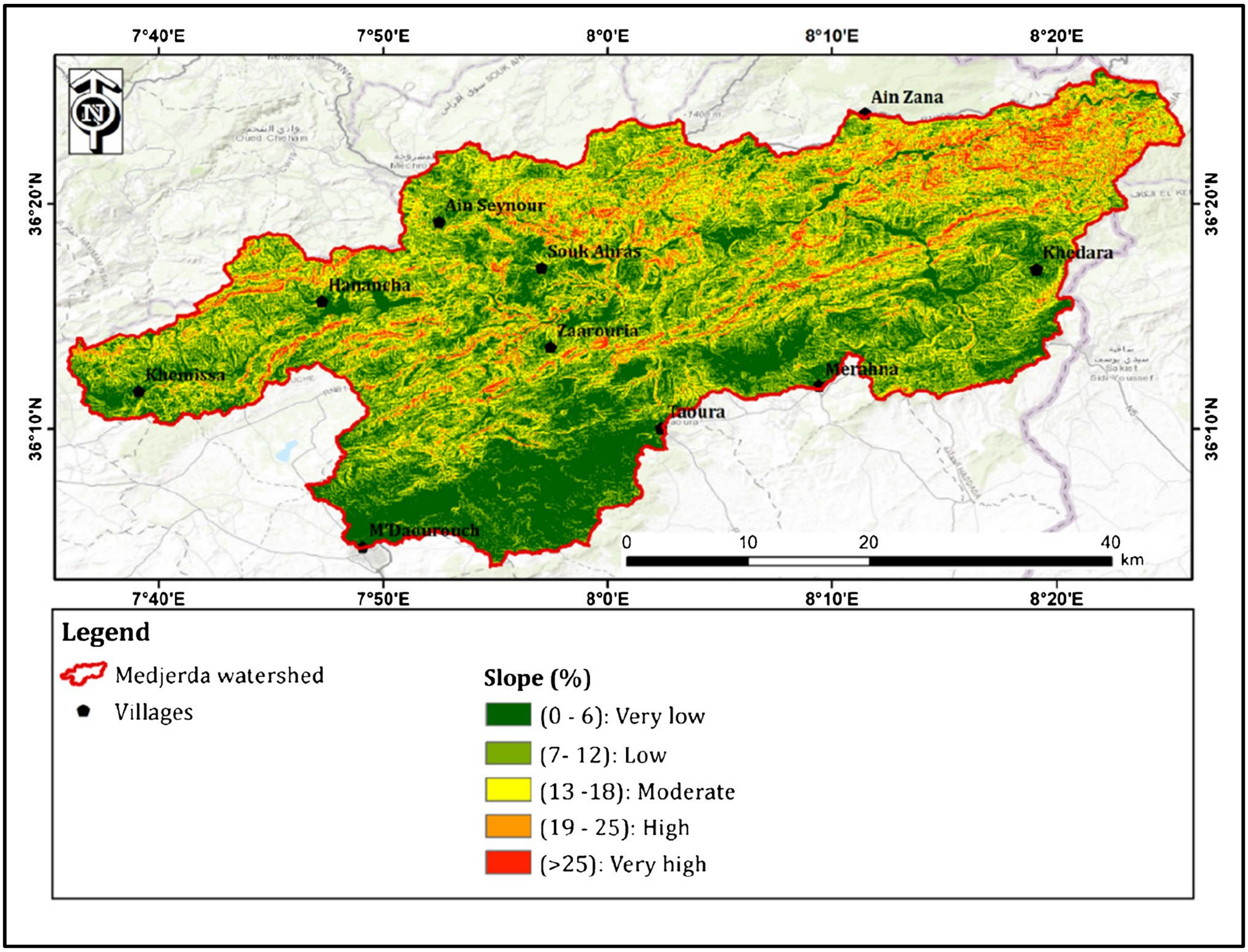

Fig. 4 Slope map of the study area

rank of the slope factor were established on the basis of their perceived influence on groundwater infiltration and recharge. The very high slope class ($> 25\%$) was assigned a very low weight (0.03) and therefore a very low rank (1). This indicates that this class is unfavorable to infiltration, and that it favors surface runoff. The highest rank value (9) was given for low slope classes that allow important groundwater infiltration and low runoff.

Drainage density

The drainage density is a second important geomorphological characteristic for mapping potential groundwater zones. It represents the ratio of the total length of the streams L of a watershed to the total area (A) of the same basin: $Dd = (\sum L)/A$, expressed in km/km^2. It is related to the nature of the soil, its infiltration capacity, and, inversely, its runoff capacity (Rambert, 1973). Permeable and unsaturated soils promote infiltration and underground flow and will exhibit small runoff and hence low drainage densities. The more impermeable soil with lower infiltration capacities will exhibit considerable runoff and hence high drainage densities (Jhariya et al., 2016). A region with a high drainage density indicates a zone with a low groundwater potential and a region with a low drainage density indicates important infiltration and therefore an area with high groundwater potential (P. Kumar et al., 2016).

The drainage density map (Fig. 5) was classified in five categories: > 2.60 (very high), 2.00–2.60 (high), 1.45–2.00 (moderate), 0.84–1.45 (low), and 0–0.84 (very low). Almost 50% of the total area is of very good drainage density.

Lithology

The lithology is a third important factor for delineating potential groundwater zones (Nouayti et al., 2017). It determines the porosity and permeability of the soil and possible groundwater systems (Adiat et al. 2012; Rahmati

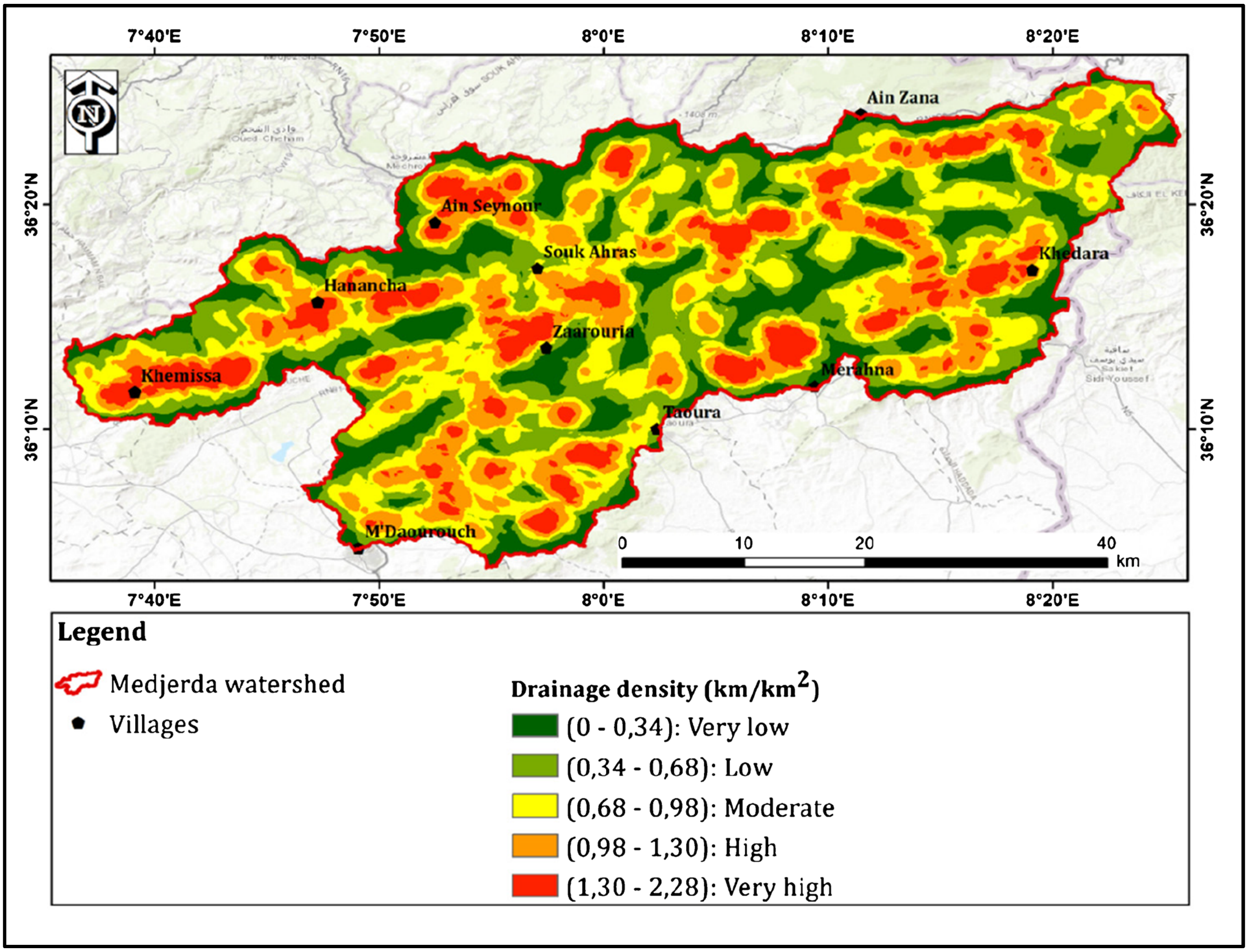

Fig. 5 Drainage density map of the study area

et al. 2018). The porosity of lithological formations plays an important role in the existence of groundwater reservoirs (Ganapuram et al. 2009; Ghorbani Nejad et al. 2017; Şener et al. 2018). Analysis of the final lithological map shows very complex geology including all geological formations and ranging from the oldest Trias formations to the most recent Quaternary layers represented by superficial formations such as alluvial formations.

The comparison between the different lithological formations was made on the basis of its hydrogeological interest for groundwater recharge and storage (Pinto et al. 2017). After analyzing the petrophysical characteristics of the geological formations in our study area (Fig. 6), the experts agreed that the recent quaternary alluvium received the highest weight (0.39) due to its high efficiency in the storage and passage of groundwater, followed by the slope scree (0.24) which is characterized by large pores that increase the velocity of water circulation. On the other hand, sandstone and limestone take medium weights (0.19 and 0.12) respectively. The other geological formations take low weights, and this is due to their low contribution to the recharge and replenishment of groundwater reservoirs.

Lineament density

The lineament density designates all linear structural alignments that are marked on geological or topographic maps. Lineaments are structural features that provide an indication of the existence of groundwater reservoirs (Langevin et al. 1989). They play a major role in delineating potential groundwater zones (Subba Rao et al. 2001; Şener et al. 2018). Lineaments often promote infiltration and secondary porosity and therefore potentially increase underground flow velocity (Nouayti et al. 2017). Remote sensing is one of the most effective techniques for detecting and mapping lineaments (Eric et al. 2014).

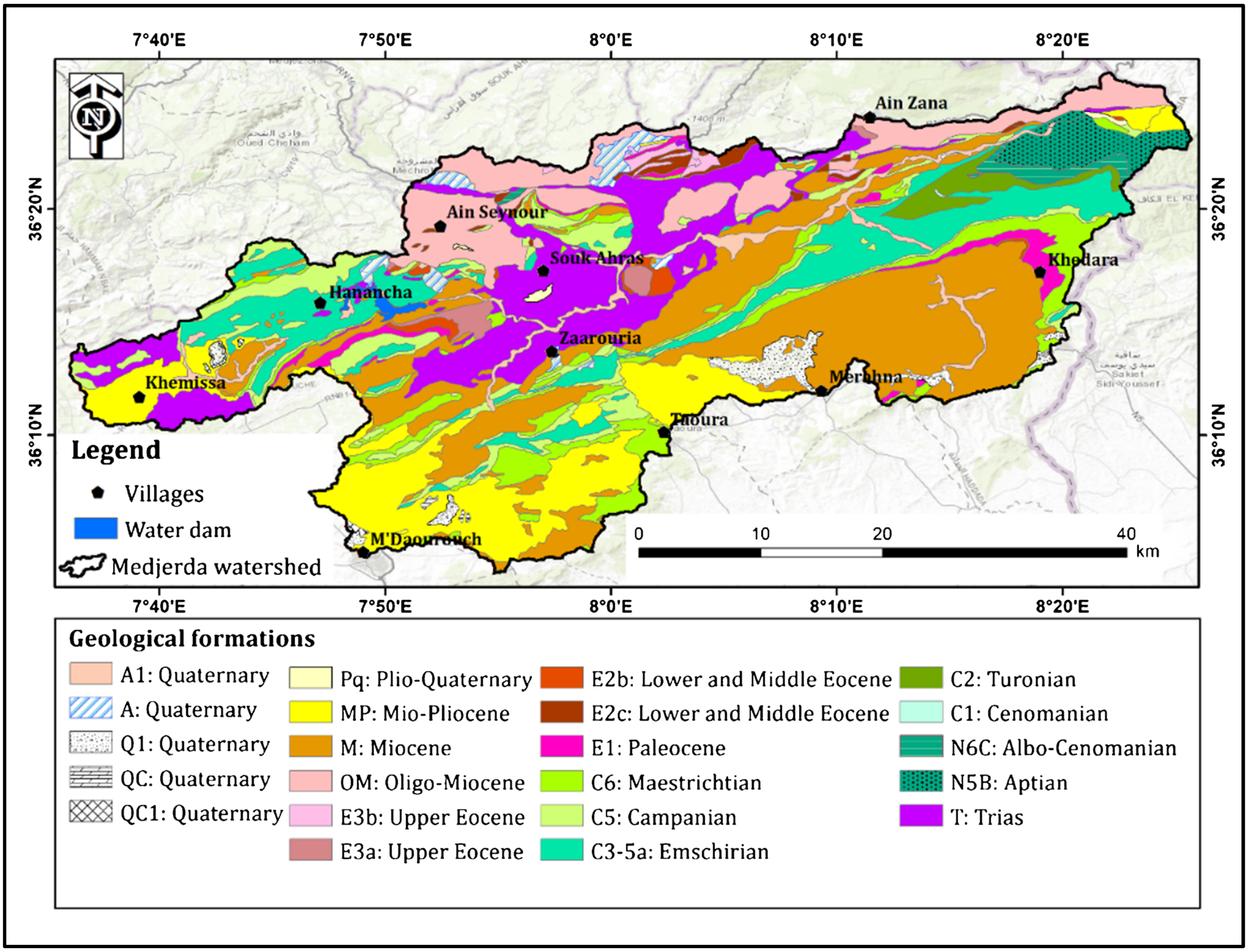

Fig. 6 Lithology map of the study area

The lineament density map (Fig. 7) reveals 5 classes from very low to very high with equal intervals. The zones of very high fracture density are located throughout the catchment area. They favor the existence of a potential reservoir (C. Langevin et al. 1989). Zones of low lineament density are recorded in the center of the watershed and characterized by low weight (0.03).

Rainfall

Rainfall is the main source of recharge to streams and groundwater reservoirs (Lakshmi & Reddy, 2018). The probability of finding aquifers with high groundwater potential increases in regions characterized by heavy rainfall (Şener et al. 2018).

The rainfall map (Fig. 8) was classified into five categories: (1) 550–570 mm/year, (2) 580–590 mm/year, (3) 600–610 mm/year, (4) 620–630 mm/year, and (5) 640–650 mm/year. The average annual rainfall over the last 29 years (1990–2019) for the whole region is 600 mm/year, with low rainfall in the southern and central parts of the sub-catchment. The northeastern and northwestern parts of the sub-catchment receive more heavy precipitation about 650 mm/year. A weight of 0.387 was assigned to the precipitation factor, which illustrates the importance of this factor for estimating groundwater potential.

Land use/cover

The land use/land cover (LU/LC) plays also an important role in identifying groundwater potential. The land use/cover map of our study area (Fig. 9) includes five classes: agricultural areas cover most of the watershed, representing 48.86% of the total area. This is followed by forests (28.87%), bare soil (21.3%), water surfaces (0.29%), and urban areas (1.93%).

The rank of LULC classes in the GWP map was defined as follows. The highest weights were assigned to agricultural

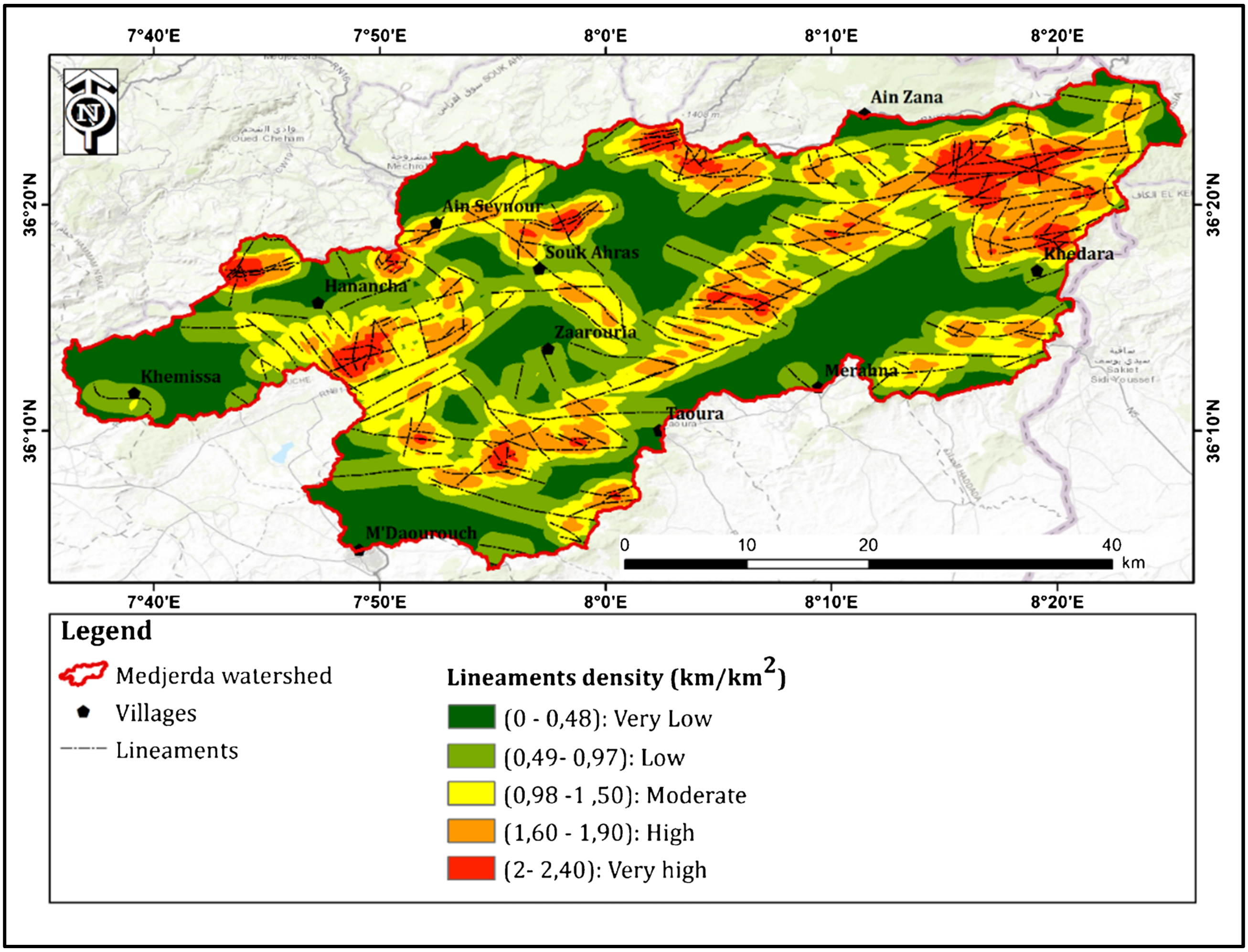

Fig. 7 Lineament density map of the study area

areas (0.53) and forests (0.26) because they promote infiltration and slow down the surface flow. Urban areas were characterized by low weight (0.04), as they are considered a direct obstacle to precipitation infiltration and thus prevent the recharge of groundwater reservoirs (Mandal et al. 2016).

Soil

The soil is the final factor that is considered in the groundwater potential model. The soil type strongly determines water infiltration and recharge. Seven main soil classes were considered (Fig. 10): the limestone soil represents the dominant type over almost the entire watershed (623.81 km^2 about 43.40%), followed by the solonetz soil associated with limestone (19.11%) concentrated in the southeastern part of Souk Ahras, Merahna, and neighboring communes, followed by the association of solonchak with limestone (173.89 km^2; 12.09%) that cover the central part of the city of Souk Ahras, followed by unsaturated soil (168.58 km^2; 11.73%), calcium soil (144.36 km^2, 10.04%), podzolic soil (31.05 km^2, 2.16%), and finally mother stone (20.72 km^2, 1.44%).

The pair comparison between these 7 soil classes allowed calculating the weight of each class based on the infiltration rate of each soil type (P. Kumar et al. 2016). Unsaturated soil received a high weight (0.35) because of its effective infiltration degree, while solonchak was characterized by a low weight (0.035) showing a low infiltration rate due to the very fine texture of the latter (Legros 2007).

Implementing the fuzzy-AHP method

The ranking and weighting values of subclasses within factors and normalized weights of factors for the fuzzy-AHP model are given in Table 4.

The normalized weight weights all factors that influence groundwater potential. The fuzzy-AHP weighting represents the weight of the subclasses of each factor. It represents the importance of each subclass of the major

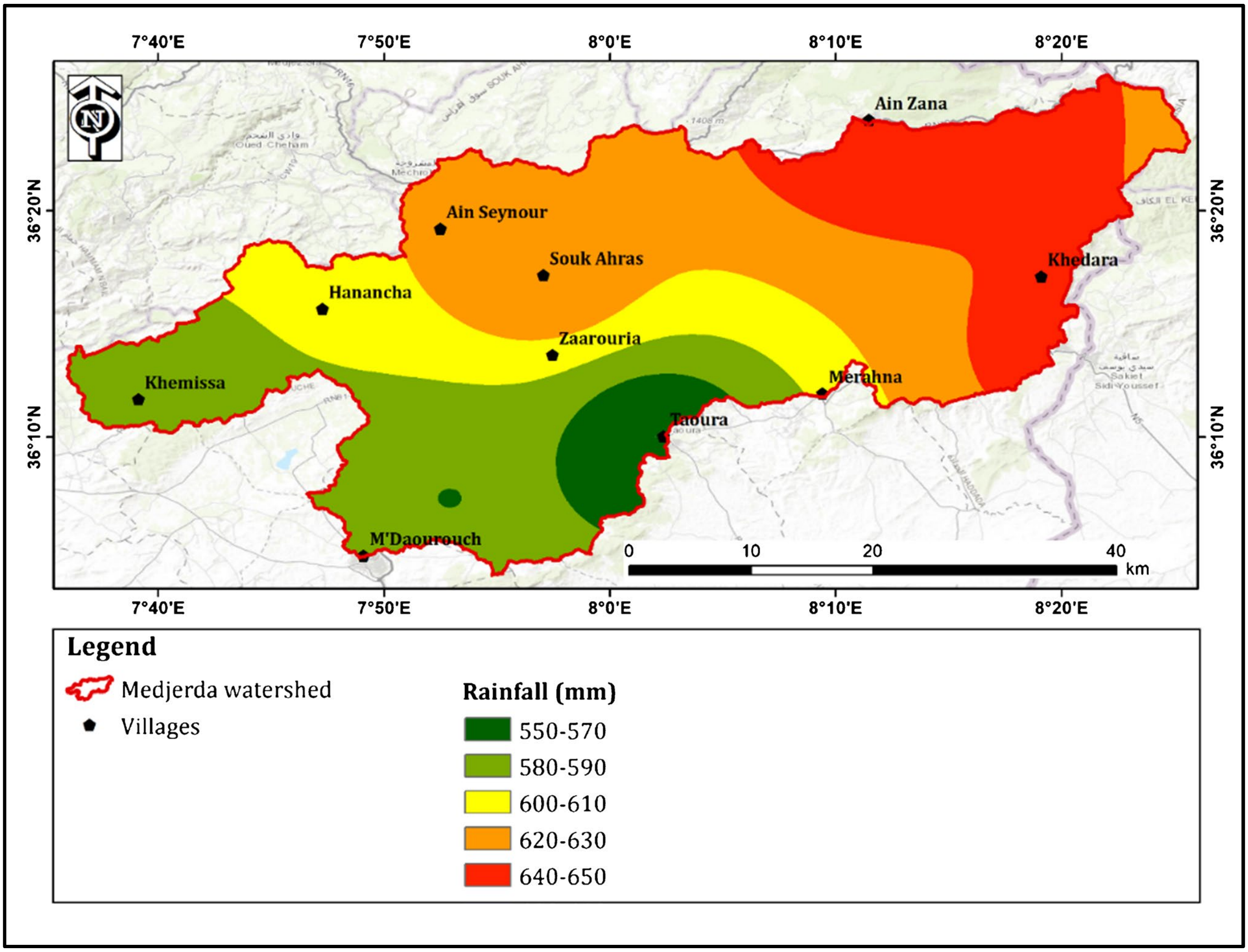

Fig. 8 Rainfall map of the study area

factors using a scale of 1–9. The values of 5–9 give the classes of high importance and which promote infiltration, groundwater recharge, and storage, while values of 1–5 are given for classes of low to moderate importance and therefore play an unfavorable role in groundwater recharge. These weights are obtained from the confusion matrices as established by expert consultation (see table 03 in annex). Results in Table 4 suggest that precipitation is the main factor contributing to groundwater potential. Indeed, precipitation received a very important weight (0.32) compared to other factors. Precipitation is followed by lineaments density (0.191) which plays a very important role in increasing infiltration capacity and accelerating the velocity of groundwater flow. Soil type (0.12) is further being considered as the third factor. For this factor, the permeable unsaturated soil type class receives a high weight (0.35) because these soil types strongly influence the recharge process of underground reservoirs. In contrast, the impervious saline soil type class receives the lowest weight (0.02). Indeed, saline soils are poorly structured and are often characterized by low infiltration capacities. Geology (0.13) is considered the fourth most important factor for groundwater potential, similar as observed in previous studies (Hussein et al., 2017; Nigussie et al., 2019). Land use and land cover (0.089) are only moderately important for groundwater potential in our watershed. The weighing of the subclasses for this factor is logical, with the attribution of low weight to urban surfaces, representing an obstacle to infiltration. The results show that the drainage density is a parameter of little importance compared to other factors with a weight (0.05).

Groundwater potential zones

The final groundwater potential map is given in Fig. 11. The analysis of the final potential map reveals three classes: low, moderate, and strong. The area of low potential occupies an

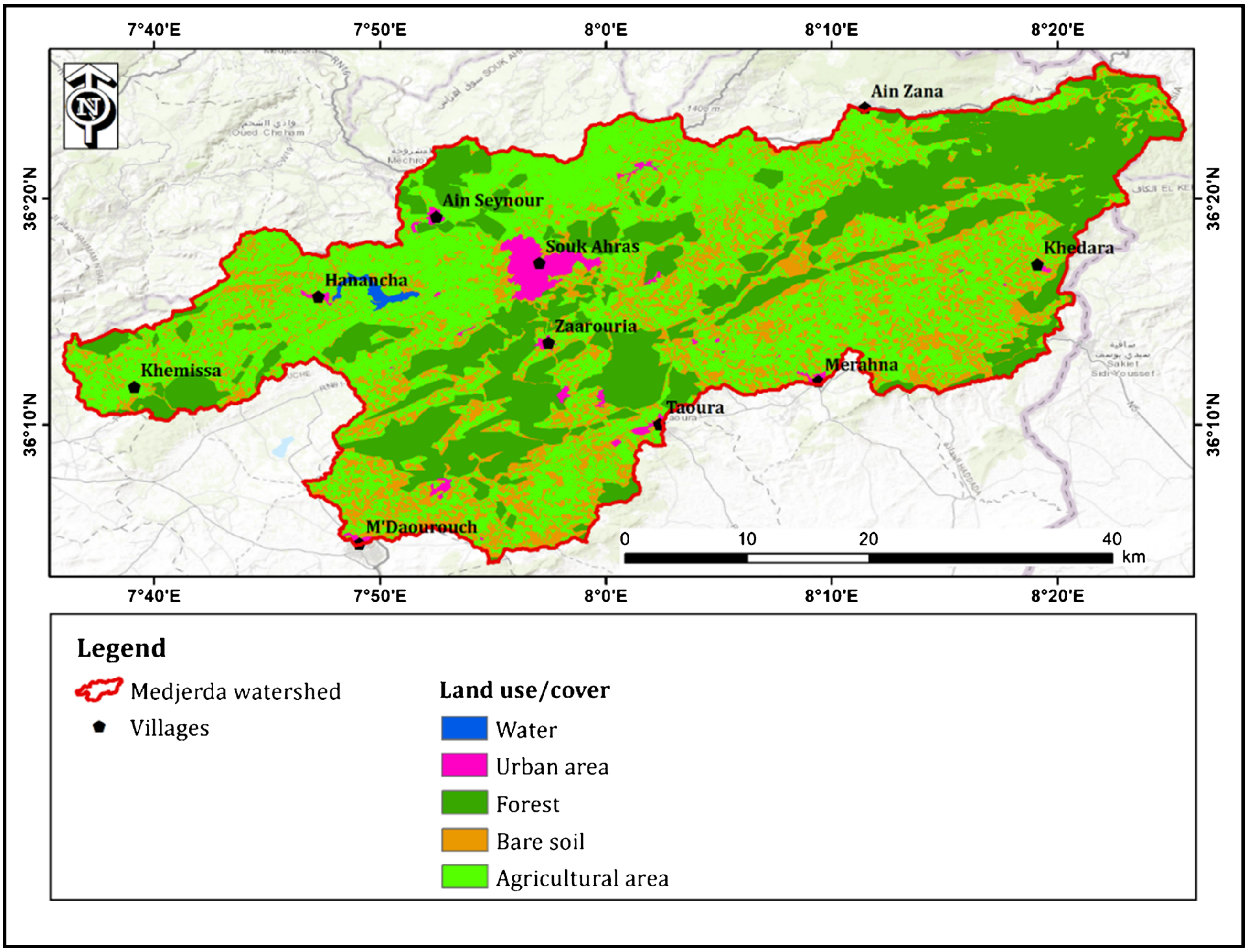

Fig. 9 Land use/cover map of the study area

area of 305.945 km^2 or 21% of the total area of the basin. The moderate zone has an area of 1022.174 km^2 or 71% of the area of the basin.

The zone of high potential has an area of 107.019 km^2 or 8% of the study area. High groundwater potential zones are located in alluvial plains and areas where there is a very high lineament density. Also, high GWP is mapped in the southeastern part of the watershed characterized by a low slope and limestone soil that favors infiltration. These limestone layers encompass often larger aquifers (David, 1956). The region of Mdaouroche up to the Tunisian borders is characterized by more dispersed aquifer systems. The urban areas and areas located in Triassic formations that are rich in gypsum and salt in the center of the Souk Ahras wilaya have been identified as having low GWP. The mountainous massif of the commune of Ouled Moumen is located in the northeast of the wilaya of Souk Ahras which in spite of its altitude reaches 1100 m, but it is characterized by a zone of strong potential; geologically, this region is characterized by the limestones of the Turonian which absorb a great quantity of water by the existing cracks.

From the hydrogeological point of view, the areas of high potential are characterized by more constant and more important aquifers located in the limestone formations of high density of lineaments. The Turonian limestones and the two bars of Senomanian limestones rest on marl formations; their surface is almost impermeable but absorbs a great quantity of water by innumerable cracks. Concerning the Quaternary of the high plains, the permeable alluvium of the low slope is often covered by a limestone crust which favors an important flow. The scree slopes are characterized by large blocks or rock fragments located in the north of the wilaya of Souk Ahras in the town of Ouled Driss also play a very important role in the evacuation of water through fractures to the groundwater. The region of Taoura located about 20 km southeast of the watershed belongs to the zone of high moderate potential. It is characterized by two types of aquifers. The first is in the fissured and porous limestones of the Campanian and Maastrichtian; their water

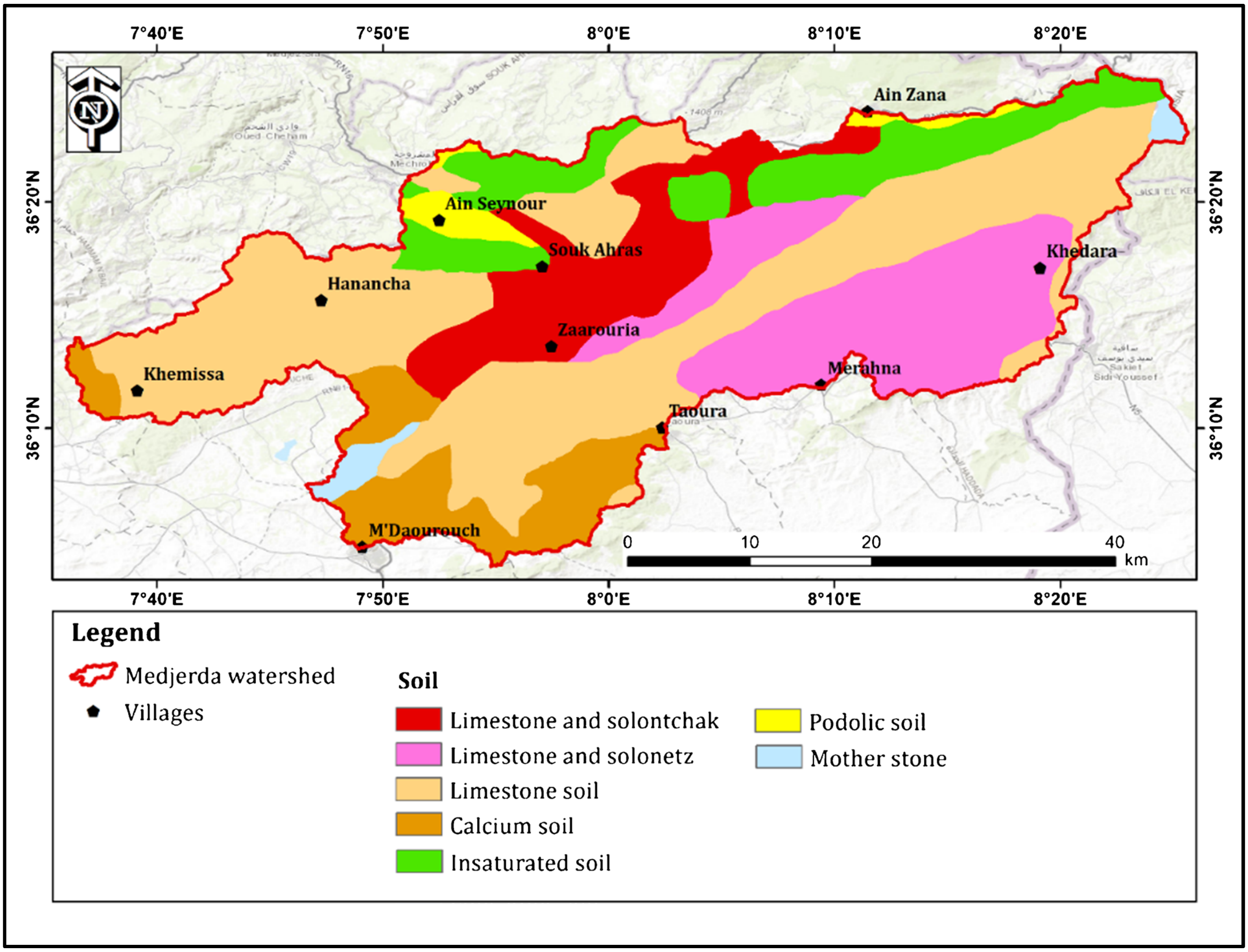

Fig. 10 Soil map of the study area

content is higher; the second is in the clays and marls of the Plio-Quaternary. What can be concluded is that the spatial variation of the groundwater potential is conditioned by the geological structure and the existence of cracks allowing an important groundwater flow without forgetting the precipitation, which remains the main source of aquifer recharge.

Validation

The validation of the groundwater potential map was carried out by analyzing the productivity of the wells located in the Medjerda sub-catchment. In total, 61 water production wells were identified and compared to the GWP map established using the FAHP model classification. Eleven wells are located in areas of low potential characterized by urban surfaces and impermeable saline soil. These wells have productivity ranging between (2.5 to 9 l/s). Thirty-four wells with productivity ranging between 10 to 20 l/s are located in areas characterized by moderate GWP. This class encompasses 71% of the total area of the basin and is situated in semi-permeable sedimentary formations and encompasses sandstone, sandy, or carbonate formations.

Sixteen high productivity wells (20–40 l/s) are located in areas of high potential. They are installed in the alluvial deposits of the Medjerda wadi or limestone formations with a high lineament density.

Overall, the consistency between GWP and well productivity was good. Occasionally high productivity wells are found in areas identified as having low GWP. This is depending on the depth and type of aquifer exploited. Sometimes, satisfying the needs of drinking water and irrigation in a region requires the capture of a surface or deep aquifer or both at the same time, which results in a high productivity despite the area being characterized by a low potential. Using the data of the 61 water production wells, we established the ROC curve. In the vast majority of cases, the ROC curve is used in medical diagnoses to know if high

Table 4 Ranking and weighting values of different factors conditioning the groundwater potential

Factor	Normalized weight (FAHP)	Classes	Weights (FAHP)	Rank
Soil	0.12	Is (Insaturated soils)	0.353	7
		Ps (Podolic soils)	0.083	4
		Ms (Mother stone)	0.056	3
		Cs (Calcium soils)	0.176	5
		Ls (Limestone soils)	0.271	6
		(Ls + Solonetz)	0.026	1
		(Ls + solontchak)	0.035	2
Slope	0.084	Class 1 (0–6)	0.497	9
		Class 2 (6–12)	0.281	6
		Class 3 (12–18)	0.130	4
		Class 4 (18–25)	0.060	3
		Class 5 (> 25)	0.033	1
Rainfall	0.32	Class 1 (< 560)	0.035	1
		Class 2 (560–590)	0.255	2
		Class 3 (590–610)	0.117	3
		Class 4 (610–630)	0.453	4
		Class 5 (> 630)	0.139	5
Land use/cover	0.089	Urban area	0.04	2
		Forest	0.26	6
		Bare soil	0.12	4
		Agricultural area	0.53	9
		Water	0.29	1
Drainage density	0.05	C1 (0–0.34)	0.471	9
		C2 (0.34–0.68)	0.301	6
		C3 (0.68–0.98)	0.134	4
		C4 (0.98–1.30)	0.058	3
		C5 (1.30–2.28)	0.036	1
Lineament density	0.19	C1 (0–0.08)	0.037	3
		C2 (0.08–0.24)	0.069	4
		C3 (0.24–0.40)	0.158	5
		C4 (0.40–0.65)	0.433	7
		C5 (> 0.65)	0.303	9
Geology	0.13	Alluvium	0.397	9
		Slope scree	0.248	7
		Sandstone	0.193	5
		Limestone	0.124	4
		Marls	0.038	3
		Stringers	0.025	2
		Clays	0.014	1
		Numidiens lay	0.052	2
		Gypsum	0.073	3

values in diagnostic tests correspond to sick individuals, while low values correspond to healthy individuals (Id, 2020). However, if we apply this idea in our study, we find the opposite where our objective is to know if high potential groundwater areas correspond to high productivity and low potential areas correspond to low productivity. In other words, the values (high or low) of productivity could define the class of groundwater potential. The ROC curve for the classification (Fig. 12) exhibits an AUC = 0.755. The accuracy of the prediction of the ROC model is therefore considered to be acceptable.

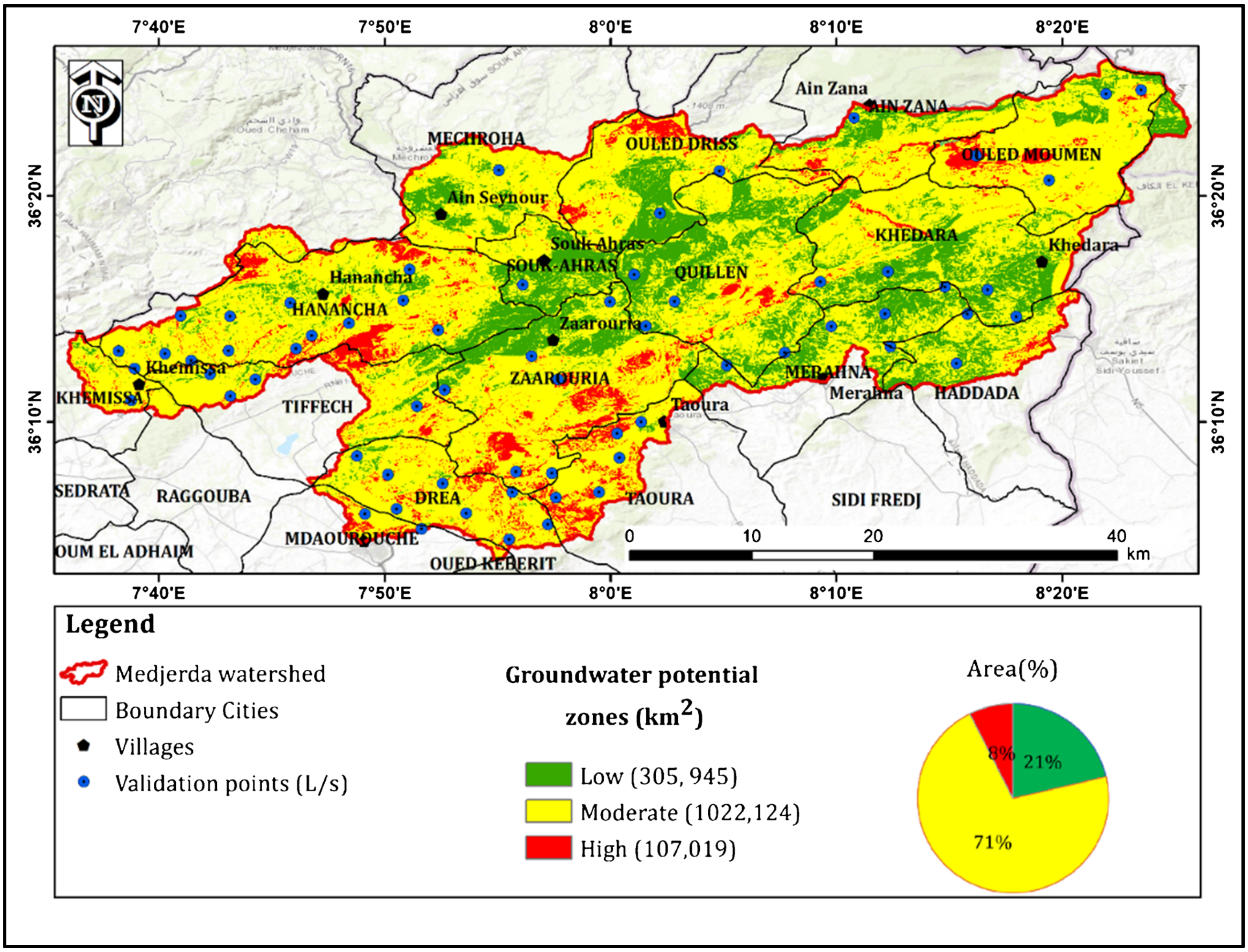

Fig. 11 Groundwater potential map of the study area

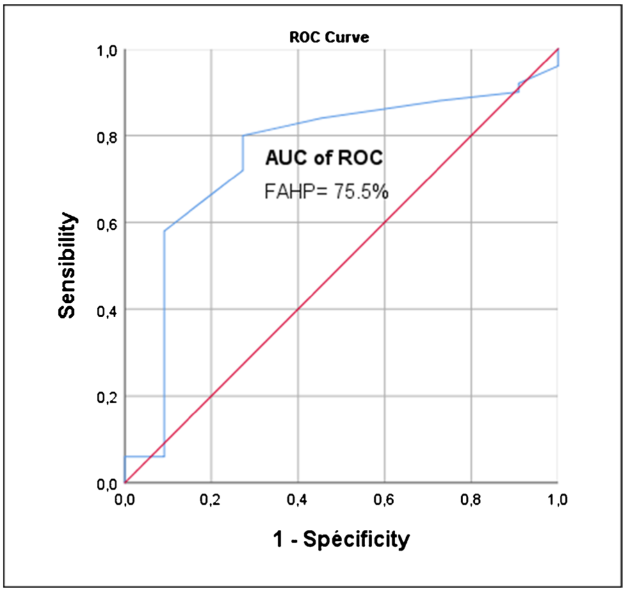

Fig. 12 ROC curve for the groundwater potential map

Conclusion

In this study, the GWP map was established for the Medjerda sub-catchment area of the northeastern part of Algeria. A weighted overlay model was used to map GWP based on seven dominating factors: soil, geology, precipitation, slope, land use/cover, lineament density, and drainage density. The fuzzy-AHP method was used to calculate the weight of each factor and their classes in the GWP model, based on expert judgments. Precipitation was judged by the experts as the dominating factor determining groundwater recharge and hence GWP. Subsequently, the following ranking of controlling factors was obtained: lineaments density (0.168), soil (0.131), geology (0.11), slope and land cover (0.078), and drainage density (0.044). The consistency ratio (CR) was calculated to verify consistency between the judgments of the experts and was considered of being acceptable (0.68).

The values of calculated GWP were reclassified using 3 classes: low (21%), moderate (71%), and high (8%). The high GWP zones are located in alluvial and calcareous formations with high lineament density, allowing for a significant recharge and rapid over-circulation of the quantities of water infiltrated. Furthermore, a strong effect of low slope surfaces and soil type has been observed on the map. Zones of low potential are located in areas of a steep slope, urban areas, and gypsum Triassic formations. Finally, the GWP map was validated using data on the productivity of wells located in the basin. The AUC of the ROC curve (0.755) was considered very good. The established GWP map is considered an important tool for designing groundwater management strategies in the Medjerda watershed. It could contribute significantly to the protection of groundwater quality. Considering that high potential areas are characterized by high infiltration, high density of lineaments, and low slope, this leads to a significant infiltration of pollutants associated with various processes, especially the intensive use of pesticides in agricultural areas, as well as the installation of landfill sites upstream of recharge areas and stream which leads to contamination of shallow alluvial aquifers by toxic, hazardous, or domestic waste. Given these considerations, it can be concluded that based on this study, water resource and environmental managers understand that monitoring pesticide use as well as developing a controlled discharge site is therefore very important to protect groundwater in order to ensure a sustainable supply of drinking water and also to preserve the health of local populations in these areas.

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Author contribution Conceptualization: Mohammed Bouklab. Material preparation, data collection: Mohammed Bouklab, Larbi Djabri, Nabil Bougherira, Mokrane Kadir. Methodology: Mohammed Bouklab, Marnik Vanclooster, Mokrane Kadir. Software: Mohammed Bouklab. Validation: Mohammed Bouklab. Writing, review, and editing: Mohammed Bouklab, Marnik Vanclooster. Supervision: Nabil Bougherira, Larbi Djabri, Marnik Vanclooster.

Declarations

Competing interests The authors declare no competing interests.

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