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ORIGINAL ARTICLE

Integrating remote sensing, GIS-based, and AHP techniques to delineate groundwater potential zones in the Moulouya Basin, North-East Morocco

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Abstract

Groundwater is a valuable shared resource in the Moulouya Basin, but it has been in decline due to recent years of low rainfall and rapid population growth. To support socio-economic development, there is increased demand for this precious resource. This paper presents a standard methodology for delimiting potential groundwater zones using geographic information systems (GIS), an integrated analytical hierarchy process (AHP), and remote sensing techniques. Seven parameters that monitor the presence and mobility of groundwater, including drainage density, lithology, slope, precipitation, land use/land cover, distance to river, and lineament density, were incorporated into a raster data model using ArcGIS software. AHP-based expert knowledge was used to prepare a groundwater potential index and assign weights to the thematic layers. The study classified the area into five zones of varying groundwater potential: very high (26%), high (51%), moderate (13%), poor (9%), and very poor (1%). The accuracy of the model was validated by comparing the Groundwater Potential Zones map with data from 96 wells and boreholes across the basin. The validity of the results was confirmed by comparing them with the specific yield of the aquifer in the study area, yielding a high correlation coefficient (R^2) of 0.79. The analysis revealed that 89.5% of the boreholes were situated in the high and very high potential zones, demonstrating the reliability and robustness of the employed approach. These findings can aid decision-making and planning for sustainable groundwater use in the water-stressed region.

Keywords GWPZ · AHP · Sustainable groundwater use · Moulouya Basin · Morocco

Introduction

Water is essential for human survival and has been recognized as a crucial resource worldwide (e.g., Jha et al. 2007; Hilal et al. 2018; Bouadila et al. 2019, 2023; Kostyuchenko et al. 2022; El Yousfi et al. 2022, 2023a,b; Aqnouy et al. 2018, 2019, 2021, 2023; Abioui et al. 2023; Khaddari et al. 2023; Ikirri et al. 2023). Groundwater, in particular, plays a vital role in supporting the growth and development of both rural and urban areas and is crucial for agriculture, industrial activities, and ensuring a safe and clean water supply for communities. As population growth and changing land-use patterns increase water demand, the sustainable management and use of groundwater resources become increasingly important to ensure a secure future for communities and the environment. Groundwater is a finite resource and its availability and quality are threatened by over-extraction, contamination, and climate change. Therefore, the responsible use and management of groundwater are crucial for sustainable development (Jha et al. 2007; Ahmed et al. 2021; Elbadaoui et al. 2023).

Morocco is vulnerable to frequent droughts, particularly in its four main basins including the Moulouya basin (Bouizrou et al. 2022, 2023). This region has experienced a widespread rainfall deficit that has led to a decline of up to 50% in some climate stations. This shortage is a result of both prolonged drought and excessive extraction of groundwater resources, posing a significant threat to the socio-economic development of the area. In this sense, and according to Nouayti et al. (2019), 65% of irrigation water comes from groundwater, and therefore the demand for groundwater is

Extended author information available on the last page of the article becoming increasingly important. This high demand pushes researchers and managers to seek efficient and economical methods of exploration, evaluation, and development of groundwater to ensure more resources to cover the needs.

Conventional methods used for identifying and mapping groundwater typically involve drilling, geological assessments, hydrogeological studies, geophysical techniques, and field surveys. These approaches necessitate significant labor and resources, including time, finances, and the involvement of specialized professionals, especially during exploration activities (Shao et al. 2020; Nhamo et al. 2020). However, modern alternative approaches such as multi-criteria analysis methods, geographic information system (GIS), and remote sensing (RS) have shown promising results in identifying groundwater potential (Magesh et al. 2012; Ferozu et al. 2019; Khan et al. 2020), offering encouraging and promoting outcomes. Faced with this situation, establishing an assessment and ensuring optimal management of water resources in these areas has become essential and to achieve this, water managers need very precise information on the conditions of recharge and exploitation at the level of each hydrogeological basin. The quantification of groundwater recharge is one of the most relevant topics, but also the most difficult to estimate because it is controlled by parameters and contexts that vary in time and space.

Different approaches have been considered for its estimation such as: the geochemical method based on the use of the chloride balance (Cl^-), the direct method which consists in estimating the infiltration using in situ measuring devices, the isotopic method which exploits the ratios of the tritium (^3H) contents of the waters of the aquifers compared to those of the precipitations (Allison 1988), the climatic method of Turc (1955) and the physical method which takes into consideration the humidity and soil pressure (Allison 1988). Many authors have faced the task to identify GWPZ using several knowledge and data-driven models (Table 1), but the use and insertion of the parameters that control groundwater recharge constitute an important starting point for

Table 1 A review of literature on using thematic layers to identify areas with potential for groundwater

Author(s)	Year	Ge	Lt	So	Rf	DEM	Sl	DD	LD	LU	DR
Dar et al. (2011)	2011	✓	✓					✓	✓	✓	
Hutti and Nijagunappa (2011)	2011	✓	✓	✓			✓	✓			
Magesh et al. (2012)	2012		✓	✓	✓		✓	✓	✓	✓	
Mukherjee et al. (2012)	2012	✓	✓	✓		✓	✓	✓	✓	✓	
Agarwal et al. (2013)	2013	✓	✓	✓	✓		✓	✓	✓	✓	
Awawdeh et al. (2013)	2013	✓	✓	✓	✓	✓	✓	✓	✓		
Fashae et al. (2014)	2014	✓	✓	✓	✓		✓	✓	✓	✓	
Kaliraj et al. (2014)	2014	✓	✓	✓	✓		✓	✓	✓		
Kumar et al. (2014)	2014		✓	✓	✓		✓	✓	✓	✓	
Ghosh et al. (2016)	2016		✓	✓			✓	✓	✓	✓	
Hussein et al. (2017)	2017	✓	✓	✓	✓		✓	✓	✓	✓	
Yeh et al. (2016)	2016		✓				✓	✓	✓	✓	
Maity and Mandal (2017)	2017	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pinto et al. (2017)	2017		✓	✓	✓	✓	✓	✓	✓	✓	
Gnanachandrasamy et al. (2018)	2018	✓	✓	✓	✓		✓	✓	✓		
Nasir et al. (2018)	2018		✓	✓	✓		✓	✓	✓	✓	
Patra et al. (2018)	2018	✓	✓	✓	✓	✓	✓	✓		✓	
Arulbalaji et al. (2019)	2019	✓	✓	✓	✓		✓	✓	✓	✓	
Das et al. (2019)	2019		✓	✓	✓		✓		✓	✓	
Choubin et al. (2019)	2019		✓			✓		✓	✓	✓	✓
Etikala et al. (2019)	2019	✓	✓	✓	✓		✓	✓	✓	✓	
Kanagaraj et al. (2019)	2019	✓	✓	✓	✓		✓	✓	✓	✓	
Siddi Raju et al. (2019)	2019	✓	✓	✓	✓		✓	✓	✓	✓	
Arshad et al. (2020)	2020	✓		✓	✓			✓		✓	
Kolli et al. (2020)	2020	✓		✓	✓		✓	✓	✓	✓	
Ajay Kumar et al. (2020)	2020	✓	✓	✓			✓	✓	✓	✓	
Dar et al. (2021)	2021	✓	✓	✓	✓		✓	✓	✓	✓	
Benjmel et al. (2022)	2022		✓				✓	✓	✓		

Ge geomorphology; *Lt* lithology; *So* soil; *Rf* rainfall; *DEM* digital elevation model; *Sl* slope; *DD* drainage density; *LD* lineament density; *LU* land use; *WT* water table depth; *DR* distance to river the mapping of GWPZs because the climatic, geological, hydrogeological and structural contexts are relative to each geographical area and can change from one area to another. The technique of multi-criteria analysis is a method that considers algorithms and that makes it possible to guide a choice based on several common criteria. This method is primarily intended for understanding and solving decision-making problems (Heywood et al. 1995). A specific weight is attributed to the different parameters to enhance and quantify their relative contribution in the multi-criteria analysis technique. Thus, to have an idea of the situation, the determining parameters must be treated and integrated by giving a specific weight to a particular domain.

Our research builds upon and enhances existing methodologies for groundwater potential mapping in the study area. While Saadi et al. (2021) utilized a cartographic approach with five key parameters, including lithology, rainfall, drainage, lineaments, and slope, we have made substantial contributions by introducing two additional critical parameters, namely the distance to the river and land use. These additions were motivated by their significant roles in influencing aquifer recharge processes, which were not fully accounted for in previous studies. Similarly, in the work conducted by Benjmel et al. (2022) in an arid region of southwest Morocco, precipitation was not considered a determining factor. However, in our research, we acknowledge the vital role of precipitation in our study area and integrate it as one of the key parameters for groundwater potential mapping. By doing so, we provide a more comprehensive understanding of the complex interactions between various hydrological and geological factors that influence groundwater occurrence.

Various estimation methods have been applied to evaluate the GWPZ. These methods include single-factor analysis (Xin-feng et al. 2012), multi-influence factor techniques (Nasir et al. 2021), fuzzy clustering (Tükel et al. 2021), brittle rock proportion (Singaraja et al. 2015), Fuzzy-AHP indices (e.g., Rajasekhar et al. 2019; Echogdali et al. 2022a; Sinha et al. 2023; Bhagya et al. 2023) and GIS information fusion (Arnous et al. 2020). In this particular study, the delineation of GWPZs is conducted using the analytic hierarchy process (AHP) (Saaty 1989) and RS-GIS methods. The identification of GWPZs is based on seven factors, which include drainage density, lithology, slope, precipitation, land use/land cover, distance to river, and lineament density.

The Hierarchical Analysis Process (AHP) is a multi-criteria decision-making tool that structures a complex problem into a hierarchical system. The approach is based on 2-to-2 comparisons of elements, grouped into comparison tables, at each level of the hierarchy (Wind and Saaty 1980). The user starts by defining the criteria comparison table at level 0, followed by sub-criteria comparison tables at level 1 (if it's a 2-level problem) or alternatives on the criteria at level 1. Finally, at level 2, the comparison tables of alternatives on criteria and/or sub-criteria are defined. The result is a comprehensive experimental plan for AHP analysis. The utilization of the AHP approach in evaluating the significance of selected parameters within a hydrogeological model has been adopted by numerous researchers (e.g., Hajkowicz and Higgins 2008). AHP is recognized as a robust decision-making method that takes into account multiple factors, as supported by studies conducted by Mohammadi et al. (2018) and Pinto et al. (2017).

This study aims to harness the potential of AHP, GIS, and remote sensing techniques to identify and map the Groundwater Potential Zones (GWPZ) in the Moulouya basin, located in North-East Morocco. Through the integration of geospatial methods and consideration of various influencing factors, the study seeks to decipher and statistically validate the groundwater potential zones. The ultimate objective is to offer decision-makers a dependable hydrogeological tool for the selection and implementation of future water wells. By doing so, this approach aims to reduce the expenses associated with geophysical investigations and promote sustainable groundwater management practices.

Materials and methods

Study area

The Moulouya basin is the largest Mediterranean basin in Morocco and Northwest Africa with an area of 55,500 km^2. Geographically, it is located in the Northeast of Morocco and extends between the parallels 32° 18′ and 35° 9′ North and the meridians 1° 10′ and 5° 40′ West. It is limited to the northwest by the Mediterranean coastal basins, to the west by the basins of Sebou and Oum Rbia, and to the south by the basins of Ziz and Guir, while to the east it extends into the Algerian territory (Fig. 1). The Moulouya basin in Morocco boasts a Mediterranean climate, marked by low and unpredictable annual rainfall amounts (ranging from 200 to 400 mm). Its shape, stretching from the South to the North and slightly slanting to the East, allows it to benefit from the humid Mediterranean winds while being exposed to scorching and dry winds from the South. This region boasts a highly concentrated hydrographic network. The Moulouya River, as the main collector, drains a large number of tributaries along its course, the main ones forming the large sub-basins of the area and which are: Za, Msoun, Melloulou, and Ansegmir wadis.

The geological formations in the Moulouya basin range in age from the Paleozoic to the Quaternary. The Paleozoic era is primarily composed of shale and granite, covering 2.59% of the basin's area (Ahamrouni 1996). In Upper Moulouya,

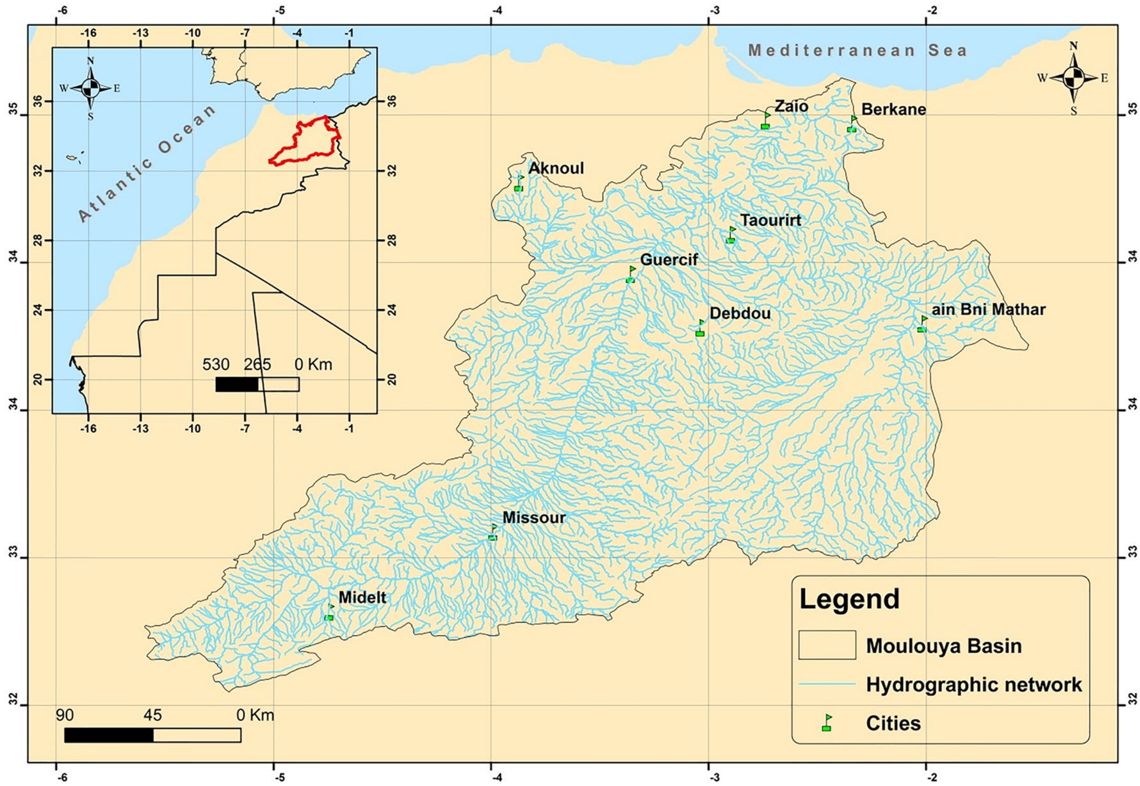


Fig. 1 Map of Moulouya basin showcasing the Moulouya River and its key tributaries

these rocks form primary massifs such as Boumia and Ahouli and are found as schists that make up most of the region's metamorphic series. The Triassic formations outcrop unconformably on the old massifs of Upper Moulouya, and are made up of marls, clays, and altered basalts (Riad 2003). The Jurassic is marked by calcareous-dolomitic facies and red terrigenous paleosol deposits that form the Upper Moulouya. The carbonate formations are found on the borders of the Middle and High Atlas and to the west of the highlands (Riad 2003).

The Cretaceous is characterized by marls, red sandstone, and white limestone, and outcrops mainly along the High Atlas between the Aouli massif and the High Atlas and to the east of Midelt. It begins with conglomerates, followed by marls and limestones that have deposited evaporitic series, particularly gypsum (Nasloubi 1993). The Quaternary formations, which are the most recent, are deposited above all previous formations and consist of fluvial terraces in the form of nested series, covered with silt and conglomeratic deposits (Amrani 2007). The study basin is located within a NE-SW shear zone from a tectonic perspective. The dominant fault structures in the area are oriented in two main directions: E–W and NW–SW, which can be identified as Riedel fractures. The structural evolution of the area is complex due to the varying directions of deformation axes from the Upper Eocene to the present day (Labbassi 1991).

Parameters controlling groundwater recharge

The selection of thematic layers used for determining groundwater recharge in the study area is based on the parameters that affect it. The hydrological conditions in the area, which significantly impact the presence of groundwater, are largely influenced by these thematic layers. Using these layers provides a solid foundation for accurately predicting the groundwater potential of a region. Saadi et al. (2021) found that factors affecting recharge in the middle Moulouya basin include slope, drainage, precipitation, lithology, and fracture lineaments. Guo et al. (2019) reported that proximity to rivers greatly impacts precipitation infiltration, with a 50% effect. Siddik et al. (2022) also highlighted the significant impact of Land Use/Land Cover (LU/LC) changes on groundwater recharge. The study took both of these findings into account by including "Distance to river" and "LU/LC" as parameters in the applied model.

The overlapping layers must possess comparable cartographic features, such as equivalent resolution, geographical extent, length units, and projection system. This requirement ensures that calculations are carried out on a consistent matrix or mesh size (Fig. 2).

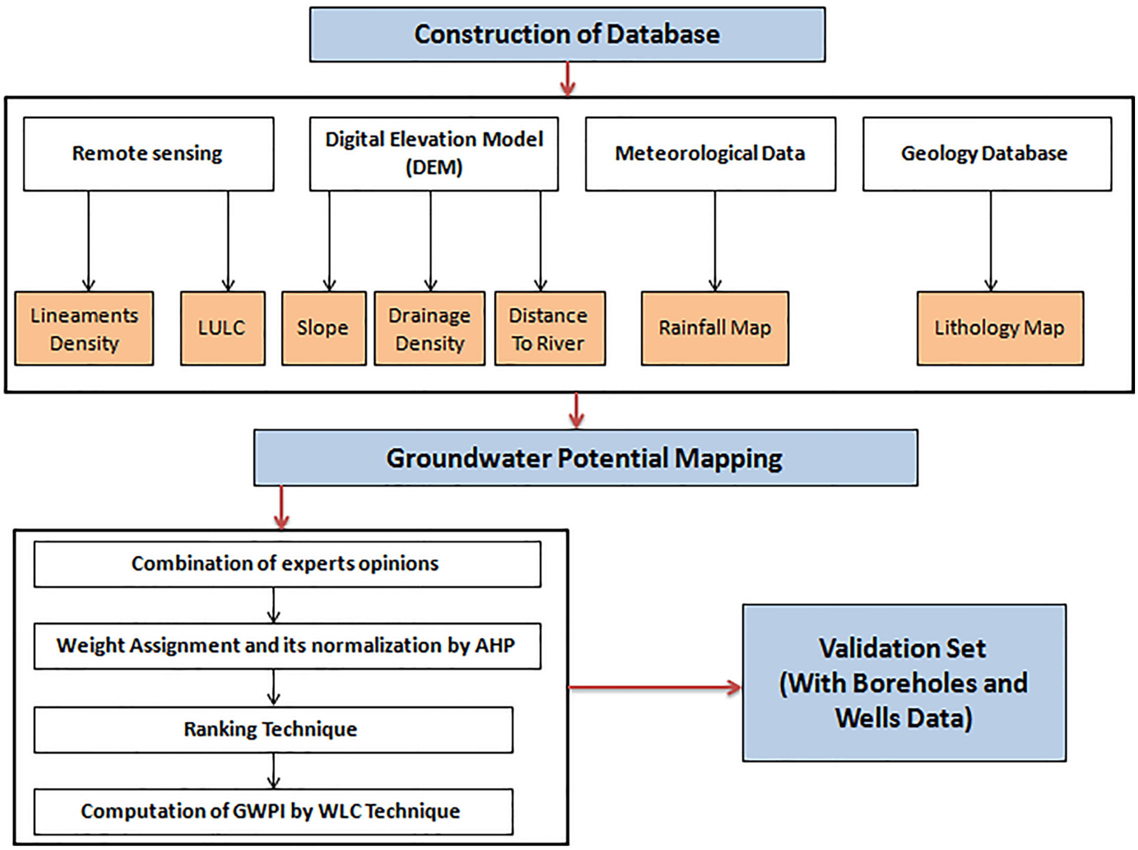


Fig. 2 Flowchart outlining the methodology utilized in mapping the groundwater potential zones in the Moulouya basin

Rainfall (Rf)

The recharge of groundwater is monitored by various parameters of which precipitation is the main source of groundwater recharge (e.g., Aswathi et al. 2022; Echogdali et al. 2022b). Precipitation intensity is one of the key factors controlling the recharge-runoff relationship. Average annual precipitation from 2010 to 2021 in the study area was obtained at stations located in the basin. Subsequently, they were spatially interpolated in ArcGIS 10.4.1 to obtain a rainfall contour map. The resulting map was categorized into five main groups: < 100 mm/year (Very low), 100–200 mm/year (low), 200–300 mm/year (Moderate), 300–400 mm/year (High) and > 400 mm/year (Very high) (Fig. 3a). The map shows that the rainfall varies from 220 to more than 350 mm/year. It increases from south to north.

In our adopted cartographic approach, we considered precipitation as a determining parameter influencing groundwater recharge, and we integrated historical data on its trends to assess its impact on groundwater recharge in the region. Additionally, we conducted prospective analyses to project future water needs, taking into account estimates of the local demographics, which increased from 2,102,781 inhabitants in 2004 to 2,505,730 in 2020 and is projected to reach 2,725,106 by 2030, according to the report of the (HCP 2021).

The remarkable expansion of irrigated agricultural areas in the Moulouya basin, which increased from 65,400 hectares in 1986 to 133,721 hectares in 2022, as reported by HCP (2021), along with the number of wells exceeding 2200 (Saadi 2021), was considered in evaluating their implications on groundwater resources. The combination of historical precipitation data, statistical modeling, and demographic projections thus provided a solid foundation for understanding the high water demand and addressing the complex interactions between human activities, climate, and groundwater availability in the region.

Lithology (Lt)

The lithological characterization of soils essentially aims to highlight the classes of soils concerning their runoff capacity. The infiltration of water depends on the permeability of the rock, by porosity or by fracturing, and on the resistance to erosion of the rock itself or of the ground cover which is present above. It provides information on permeability and influences not only groundwater flow but also surface runoff. According to Shaban et al. (2006), the rock

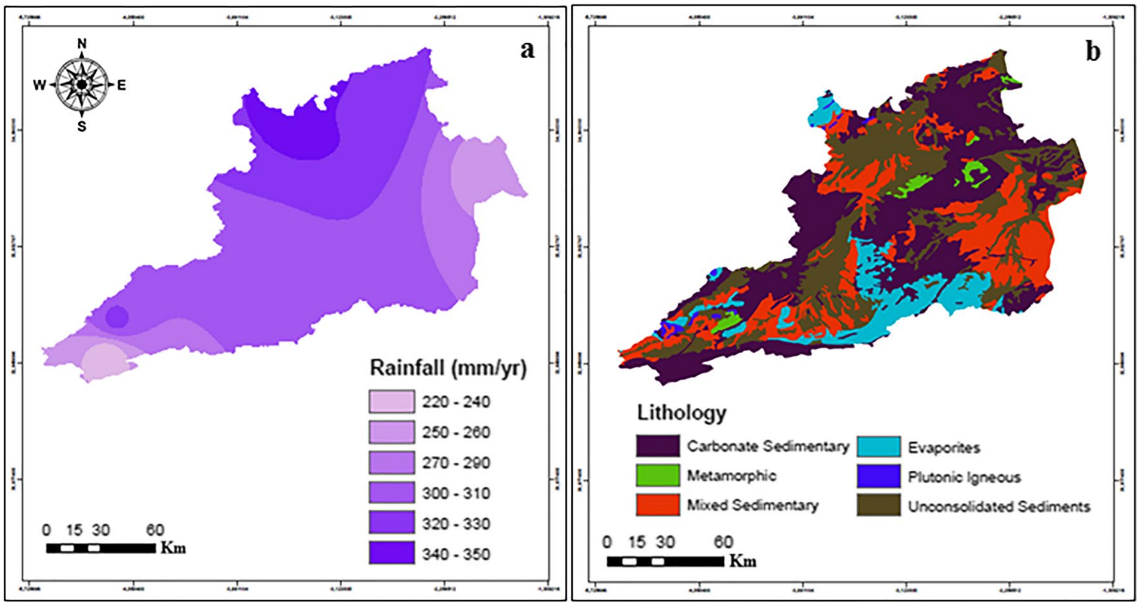


Fig. 3 **a** Spatial variation of rainfall. **b** lithological map

type can significantly influence the GWPZ. Similarly, El-Baz and Himida (1995) found that lithology affects recharge by controlling water percolation. Some authors like Arshad et al. (2020) and Kolli et al. (2020) ignored the lithological component in GWP mapping by taking into account drainage characteristics and lineament density as the main factors for measuring porosity. Information on the lithology of the Moulouya basin is obtained by combining the supervised classification of Landsat 8 images with geological maps and technical borehole sections. The lithology thematic map is distinguished into seven lithological units: Carbonate Sedimentary, Unconsolidated Sediments, Mixed Sedimentary, Evaporites, Metamorphic, Plutonic Igneous, and Siliciclastic Sedimentary (Fig. 3b). The major part of the Moulouya is occupied by carbonate sedimentary formations from the Lias and the Middle Jurassic, especially the dolomitic series with 39%, also there are fluvial deposits from the Middle Holocene with 26%, while 21% of the area of the basin is taken by series of gypsum and clayey limestone with deposits of conglomerates (21%), without neglecting the presence of evaporites and siliciclastic sediments with minimal percentages (Birot 1963).

Slope (Sl)

This factor is involved in increasing the velocity of water flow with a subsequent decrease in vertical infiltration and thus influencing the recharge process. The steeper the slope, the faster the surface water circulates and the less the groundwater recharges (Satapathy and Syed 2015). We note that the highest slopes are located mainly on the lines of the ridges of the basin and in the Moroccan High Atlas and part of the Middle Atlas, while the very low class represents the reservoirs of dams and water lakes. The other classes (between 10, 20, and 30°) are generally dispersed in the center of the basin (Fig. 4a).

LU/LC

Land Use/Land cover is the result of physical-geographical factors (relief, lithology, and climate) which are added to the anthropogenic factor via clearing and cultivation as well as reforestation. The LC map was produced using the supervised classification method of the Landsat8 image using the "maximum likelihood" algorithm. The image processing was carried out using ENVI 5.3 software and ArcGIS 10.4.1 by applying the supervised classification technique coupled with field observations, which gave the thematic LULC map (Fig. 4b).

Drainage density (DD)

The hydrographic network is characterized by its drainage density, which expresses different physical phenomena: the relative share of surface flows and underground flows. This criterion, by favoring the drainage of the slopes, makes it possible to understand the importance of surface drainage. This is defined as the average length of the hydrographic network per kilometer. Land that has a dense drainage system has a high recharge rate and the opposite is also true. In this work, drainage density was computed using the Line Density tool in ArcGIS 10.4.1 (Fig. 4c). The very low class (> 3 km/Km^2) occupies 57% of the area, followed by the low class (3–2.25 km/km^2) with 27%, the moderate class (2.25–1.5 km/km^2) with 11 0.5%, the high class (1.5–0.75 km^2) With 3% and finally the Very High class (< 0.75 km/km^2) which is the smallest and represents 0.84% of the area of the basin.

Distance to the river (DR)

The distance to hydrographic networks is a critical factor in hydrogeology, as it indicates the presence of alluvial aquifers, especially in semi-arid regions, which is the focus of our study (Benjmel et al. 2022). To determine the distance to rivers parameter, we utilized the Euclidean Distance tool in ArcGIS 10.4.1 on the major river network. Based on the spatial distribution of the distance to rivers, we identified two classes: the very low class covering 47% of the basin area and the very high class covering 53% (Fig. 4d).

Lineaments density (Ld)

The mapping of structural objects (lineaments, fractures, faults, lithological limit, etc.) plays an essential role in the different phases of prospecting for underground water resources (Karimoune et al. 1990; Biémie 1992; Shaban 2003; Abdou Ali 2018). As an application in hydrogeology, we can cite for example obtaining and determining from satellite images, information on the nature of the soil and other structural objects such as fractures which sometimes play the role of a drain thus participating in the recharge of groundwater. For Shaban (2003), connected lineaments create a subterranean pathway for groundwater flow. This makes them an indicative parameter of groundwater transport and therefore an analysis criterion in the production of maps of potential water recharge areas (Teeuw 1994; El-Baz and Himida 1995). Lineament density (Ld) is calculated based on the following equation (where $\sum i = 1 i = n$ denotes the length of lineament lines, and A denotes the area):

$$\text{Ld} = \frac{\sum_{i=1}^{i=n} \text{Li}}{A} \tag{1}$$

To obtain the lineament map, we used the PCI GEOMATICA software to extract it from Landsat 8 images. Lineament densities in the basin range from < 0.0028 to 1.02 km/km^2 (Fig. 4e). The density of lineaments on the groundwater potential map indicates the potentiality of groundwater in a particular area. Areas with higher lineament density are likely to have higher groundwater potential, whereas lower lineament density suggests lower potential. The highest lineament density is commonly found in the western and northwestern parts of the basin, and it appears to be elongated in a northeast-southwest direction. These findings are consistent with those reported by Chennouf et al. (2007).

Analytical hierarchy process (AHP) model

The Analytical Hierarchy Process (AHP) was first introduced by Saaty (1989), and it was used to determine the weights of the thematic layers. This approach involves four fundamental steps: (1) Standardization of the evaluation parameters, (2) Preparation of a pairwise comparison matrix, (3) verification of the inconsistency of the criteria developed, and (4) Aggregation of the weighting results (Allafta et al. 2020).

Pairwise comparison matrix

The Pairwise Comparison Method is a statistical technique that determines the relative importance of each factor in the decision-making process. It is done by comparing the factors pairwise, creating square matrices, and then calculating the weighting coefficients based on the eigenvectors of these matrices. This method provides an objective determination of the weights or weighting coefficients, ensuring a systematic approach to the decision-making process.

The weights of each parameter were determined taking into account the importance of each parameter in the characterization of groundwater potential. This comparison was based on Saaty's 1 to 9 scale (Saaty 1989) in Tables 2 and 3.

Assessing matrix consistency

In this hierarchical classification approach, it is possible to verify the consistency of our method by determining the coherence or consistency ratio (CR). The latter constitutes an acceptance test of the weights of the different criteria. This step aims to identify any inconsistencies in the comparison of the significance of each pair of criteria. The CR is calculated as follows:

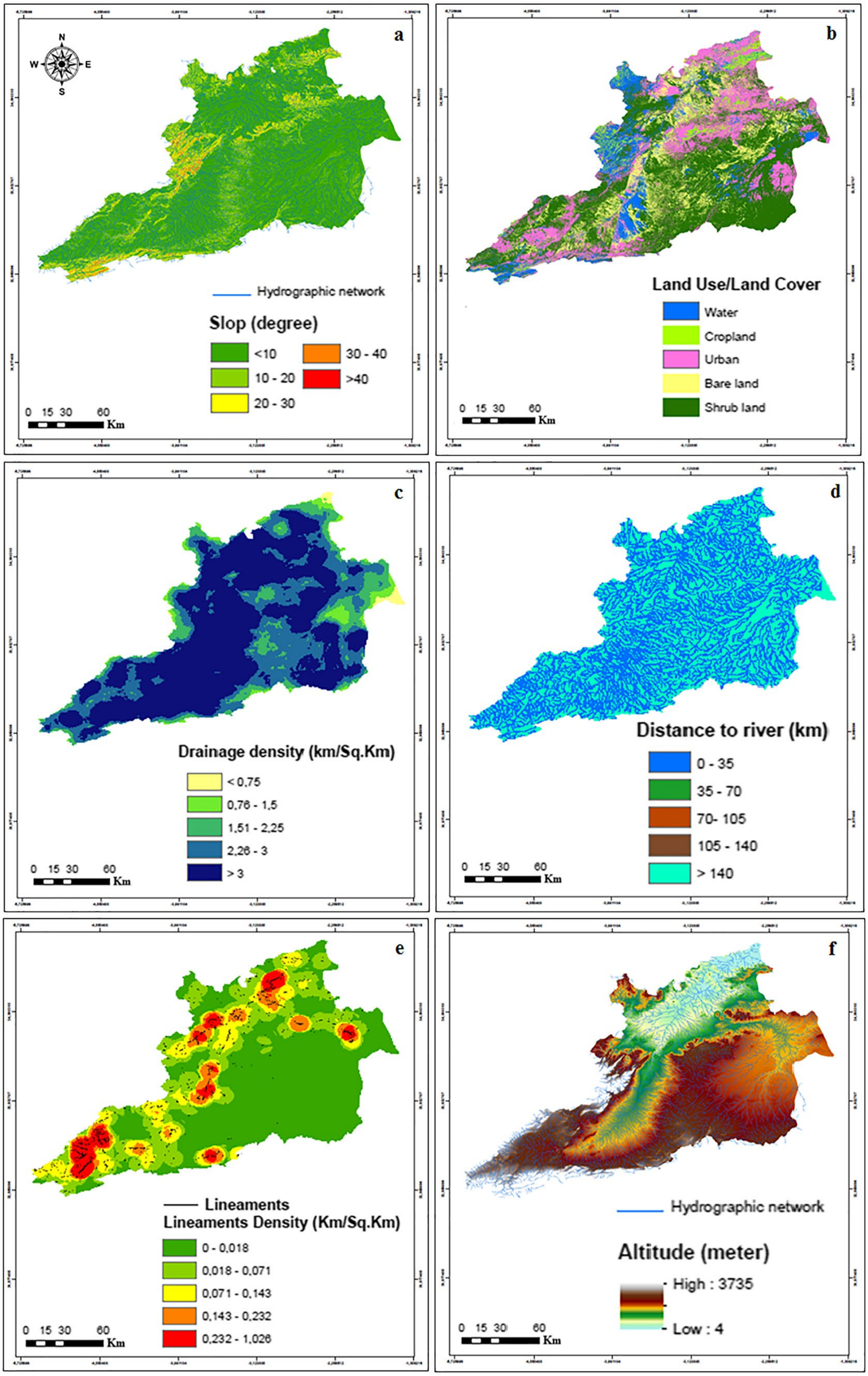
$$\text{CI} = \frac{\lambda \max - n}{n - 1} \tag{2}$$

The CI in this study is represented by the equation where λmax stands for the major eigenvalue and n signifies the number of parameters involved:

$$\text{CI} = \frac{7.37123 - 7}{7 - 1} = 0.06187167 \tag{3}$$

The principal eigenvalue (λmax) of Table 4 was calculated by adding the products of the sum of the columns of parameters and the eigenvectors of Table 3.

To check the consistency (CR) of the decision of the selected parameters, the following equation is used:


a
N
W
E
S
Hydrographic network
Slop (degree)
<10
10 - 20
20 - 30
30 - 40
>40
0 15 30 60
Km
b
Land Use/Land Cover
Water
Cropland
Urban
Bare land
Shrub land
0 15 30 60
Km
c
Drainage density (km/Sq.Km)
< 0,75
0,76 - 1,5
1,51 - 2,25
2,26 - 3
> 3
0 15 30 60
Km
d
Distance to river (km)
0 - 35
35 - 70
70- 105
105 - 140
> 140
0 15 30 60
Km
e
Lineaments
Lineaments Density (Km/Sq.Km)
0 - 0,018
0,018 - 0,071
0,071 - 0,143
0,143 - 0,232
0,232 - 1,026
0 15 30 60
Km
f
Hydrographic network
Altitude (meter)
High : 3735
Low : 4
0 15 30 60
Km

◂**Fig. 4** Factors controlling groundwater recharge used in the study: **a** slope, **b** land use/land cover, **c** drainage density, **d** distance to the rivers, **e** lineament density, **f** DEM

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}'} \tag{4}$$

where RI represents the random index which is given in Table 5 for different n values. In the current study, RI equals 1.32 for seven parameters. Therefore, CR is:

$$\mathrm{CR} = \frac{0.06187167}{1.32} = 0.046 = 4.6\% \tag{5}$$

The obtained CR of 4.6% (less than 10%) is eligible to overlay weighted parameters for GWPZ mapping. The CR value should be lower than 0.1 to confirm that the pairwise comparison judgments are compatible. However, if the CR value is higher than 0.1, the coefficients of the matrix are inconsistent and are not usable for further processing (Wong and Li 2007).

GWPI definition

Groundwater Potential Index (GWPI) is a method of predicting areas of high groundwater potential in a region. Once the thematic layers of the different parameters are prepared with their weights (Table 5), the groundwater potential index (GWPI) is calculated based on the linear combination method indicated by Malczewski (1999):

$$\mathrm{GWPI} = \sum_{w=1}^{m} \sum_{i=1}^{n} (Wi \times Xj) \tag{6}$$

where Wi is the standardized weight of the thematic layer i, Xj is the ranking of each class for layer j, m is the total set of thematic layers and n is the total set of classes in a thematic layer.

$$\mathrm{GWPI} = 0.34 \times \mathrm{Rainfall} + 0.22 \times \mathrm{Lithology} + 0.16 \times \mathrm{Lineament\ density} + 0.10 \times \mathrm{Slope} + 0.09 \times \mathrm{Drainage\ density} + 0.05 \times \mathrm{LULC} + 0.04 \times \mathrm{Distance\ to\ river} \tag{7}$$

The model's accuracy was assessed through validation against data from 96 wells and boreholes distributed across the Moulouya basin. The statistical comparison was made using the correlation coefficient to evaluate the accuracy of the Groundwater Potential Zones (GWPZ) map (Table 6).

Results

Identification of GWPZ

The development of the groundwater potential map involved the application of formula (6) through a GIS environment, with all parameters chosen based on AHP techniques. The resulting groundwater potential index values were then classified into five distinct (GWPZ): very poor, poor, moderate, high, and very high. These zones covered different percentages of the study area, with the very poor zone covering 60.54 km^2 (1%) and the very high zone covering 13,560.59 km^2 (26%). The poor, moderate, and high zones covered 4669.09 km^2 (9%), 6692.22 km^2 (13%), and 26,135.07 km^2 (51%), respectively (Figs. 5, 6).

The distribution of groundwater potential in the study area is influenced by various geological and hydrological factors, including rock types, rainfall, and the presence of lineaments. The areas with high groundwater potential are typically associated with favorable conditions for water recharge and storage. For example, the presence of permeable rock formations, such as limestone and dolomitic limestone, in these areas allows for water to percolate and accumulate in the subsurface. Additionally, the moderate annual average rainfall in these areas helps to replenish the groundwater aquifers. The presence of lineaments, or linear fractures in the rock formations, can also contribute to the high groundwater potential by providing pathways for water to penetrate deeper into the subsurface. On the other hand, areas with low groundwater potential are typically associated with unfavorable conditions such as steep slopes, high altitudes, and low densities of lineaments. Areas of very high to high underground water potential are located in the central and northeastern parts and small patches in the southwestern part of the basin (Fig. 6).

These areas are dominated by limestone and dolomitic limestone from the lower to middle Lias influenced by the presence of lineaments, they are characterized by moderate annual average rainfall. Similar observations were also noted by Benjmel et al. (2022). Additionally, the study found that the distribution of different land use and land cover (LULC) types can also greatly impact the groundwater potential in the study area. Das et al. (2019) have demonstrated that

Table 2 The one-to-nine scale of parameters significance (Saaty1989)

Strength of Significance	Explanation
1	Equal significance
3	Medium significance
5	Strong
7	Very strong significance
9	Maximum significance
2, 4, 6, and 8	Interim number between two adjacent numbers

Table 3 Pairwise comparison matrix for the AHP process

	Rf	Lt	Ld	Sl	Dd	LULC	DR	Normalized principal eigenvector (%)
Rf	1	2	3	4	4	5	5	33.7
Lt	1/2	1	2	3	3	4	4	22.2
Ld	1/3	1/2	1	3	2	3	5	16.3
Sl	1/4	1/3	1/3	1	2	3	3	10.3
Dd	1/4	1/3	1/2	1/2	1	3	3	8.7
LULC	1/5	1/4	1/3	1/3	1/3	1	2	5.0
DR	1/5	1/4	1/5	1/3	1/3	1/2	1	3.8
Sum	2.7	4.7	7.4	12.2	12.7	19.5	23.0	100

Table 4 Computation of the principal eigenvalue (λmax)

	Column sums	Eigenvectors	Parameter rank
Rf	2.7	0.34	0.92001
Lt	4.7	0.22	1.03452
Ld	7.4	0.16	1.2062
Sl	12.2	0.10	1.2566
DD	12.7	0.09	1.1049
LULC	19.5	0.05	0.975
DR	23.0	0.04	0.874
			7.37123

wetlands, vegetation, and cropland are associated with good groundwater potential. This is in line with the findings of the present study, where it was confirmed that these LULC types play a crucial role in determining the high to moderate groundwater potential areas. This highlights the interplay between LU/LC and hydrological processes and how they impact slope stability. Thus, it is crucial to consider LU/LC when assessing the groundwater potential and its distribution.

The areas of poor to very poor groundwater potential can be found in the southern region of the basin near the high Moulouya limit. These areas are characterized by steep slopes with inclinations greater than 40 degrees and high elevations in the Moroccan High Atlas mountain range, where the density of lineaments is less than 0.018 km/km^2. Despite this challenging landscape, the methodology employed in this study still managed to produce relevant results for predicting groundwater potential, without relying solely on expert opinions.

Results validation

The results were cross-validated with the specific yield of the aquifer within the study area (Fig. 7). The analysis revealed a robust positive correlation with a coefficient ($R^2 = 0.79$) between areas exhibiting excellent groundwater potential and high specific yield. Conversely, areas with poor potential showed a weakening correlation as their specific yield decreased.

The results of the study showed that 89.5% (86 out of 96 wells) of the wells were situated in areas with very high to high groundwater potential. The flow rate of these wells was observed to vary significantly, ranging from 1 L per second (l/s) for shallow boreholes (less than 100 m) that tap into alluvial aquifers to over 90 l/s for deep boreholes (exceeding 500 m) that tap into the dolomitic limestone of the Jurassic aquifer. These findings are consistent with the findings reported by Bouazza et al. (2013).

The groundwater depth is found to be variable and depends on the local hydrogeological and geological conditions. Factors such as topography, slope, land use, and underlying sediments play a crucial role in determining the groundwater recharge rate and hence the depth of the groundwater. The central part of the basin, characterized by flat topography, low slopes, and bare land use with unconsolidated sediments, is more favorable for groundwater recharge, leading to shallow groundwater depths as seen in the research by Saadi et al. (2021). Conversely, in other areas, particularly in the eastern part of the basin, the groundwater depth is found to be relatively deep and confined, with a slow rate of recharge. These findings highlight the importance of understanding the regional variations in groundwater conditions to make informed

Table 5 Ratio index (RI) for various n scores (Saaty 1989)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

Table 6 Weightage of different factors and subclass ranking pattern

Factor	Class	Groundwater Potentiality	Parameter Weight	Class Rank
Rainfall (mm/year)	< 100–200	Low	0.34	1
	200–300	Moderate		15
	300–400	High		25
	400–500	Very high		34
Lithology	Evaporites	Very low	0.22	1
	Metamorphic	low		4.5
	Plutonic Igneous	Low		8
	Volcanic Igneous	Low		11.5
	Siliciclastic Sedimentary	Moderate		15
	Mixed Sedimentary	High		17.5
	Carbonate Sedimentary	High		20
	Unconsolidated Sediments	Very high		22
Lineament density (km/km^2)	< 0.018	Very low	0.16	1
	0.018–0.071	Low		4.75
	0.071–0.143	Moderate		7.5
	0.143–0.232	High		11
	0.232–0.391	Very high		16
Slope (degree)	< 10	Very high	0.10	10
	10–20	High		7
	20–30	Moderate		5
	30–40	Low		3
	> 40	Very low		1
Drainage density (km/km^2)	< 0.75	Very high	0.09	9
	0.75–1.5	High		7
	1.5–2.25	Moderate		5
	2.25–3	Low		3
	> 3	Very low		1
Land use/land cover	Urban	Very low	0.05	1
	Shrub land	Low		3
	Cropland	Moderate		4
	Bare land	High		5
	Water	Very high		6
Distance to river	0–35	Very high	0.04	9
	35–70	High		7
	70–105	Moderate		5
	105–140	Low		3
	> 140	Very low		1

decisions about groundwater management and resource utilization.

Groundwater sustainability plans

As with any methodology, our approach involves certain assumptions and simplifications. One of the key assumptions is that the factors considered in our GIS model have equal importance, and their weights defined by the Analytic Hierarchy Process (AHP) remain constant both spatially and temporally. These simplifications may have implications for the accuracy of the results over time and space, as hydrological characteristics can vary significantly from one region to another due to factors such as geology, topography, and climate. Consequently, the methodology may not fully account for this local variability, potentially limiting its relevance in certain specific areas. Moreover, our methodology assigns a significant weight to precipitation (34%), which could pose a limitation in extremely arid and dry regions. While rainfall is the most influential factor in mapping, prompting us to prioritize the protection and proper management of recharge areas,

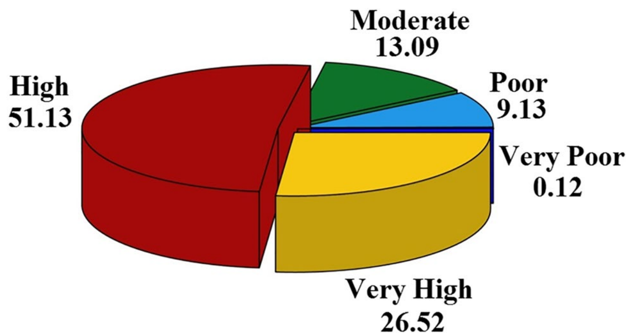


Fig. 5 Percentage (%) of the areal distribution of the groundwater potential zones

it is essential to consider local conditions and adjust the weightings of factors accordingly.

According to IAEA (2010), the recharge zones of the Moulouya basin are situated in the Beni Snassen and Jbel Hamra mountains, at altitudes ranging between 700 and 1200 m. However, most of the groundwater in the basin originates from recent recharge, as indicated by their tritium and carbon-14 content (IAEA 2010). This highlights the recharge ability of the aquifers while also emphasizing their vulnerability to contamination. To safeguard these crucial recharge areas, the following measures are recommended:

- Establishment of strict regulations for activities that may potentially pollute the groundwater, such as intensive agriculture, chemical industries, or waste disposal.
- Implementation of adequate infrastructure for the collection and treatment of rainwater to prevent direct infiltration into groundwater recharge areas.
- Regular monitoring of groundwater quality and the condition of recharge areas. This enables the rapid identification of potential issues and the implementation of appropriate corrective measures.

Encouraging water conservation and promoting efficient water use practices can reduce the overall demand for groundwater and sustainable practices can foster a culture of responsible water use. Implementing technologies such as drip irrigation and rainwater harvesting can help optimize water use and reduce reliance on groundwater. Raising awareness among local communities, stakeholders,

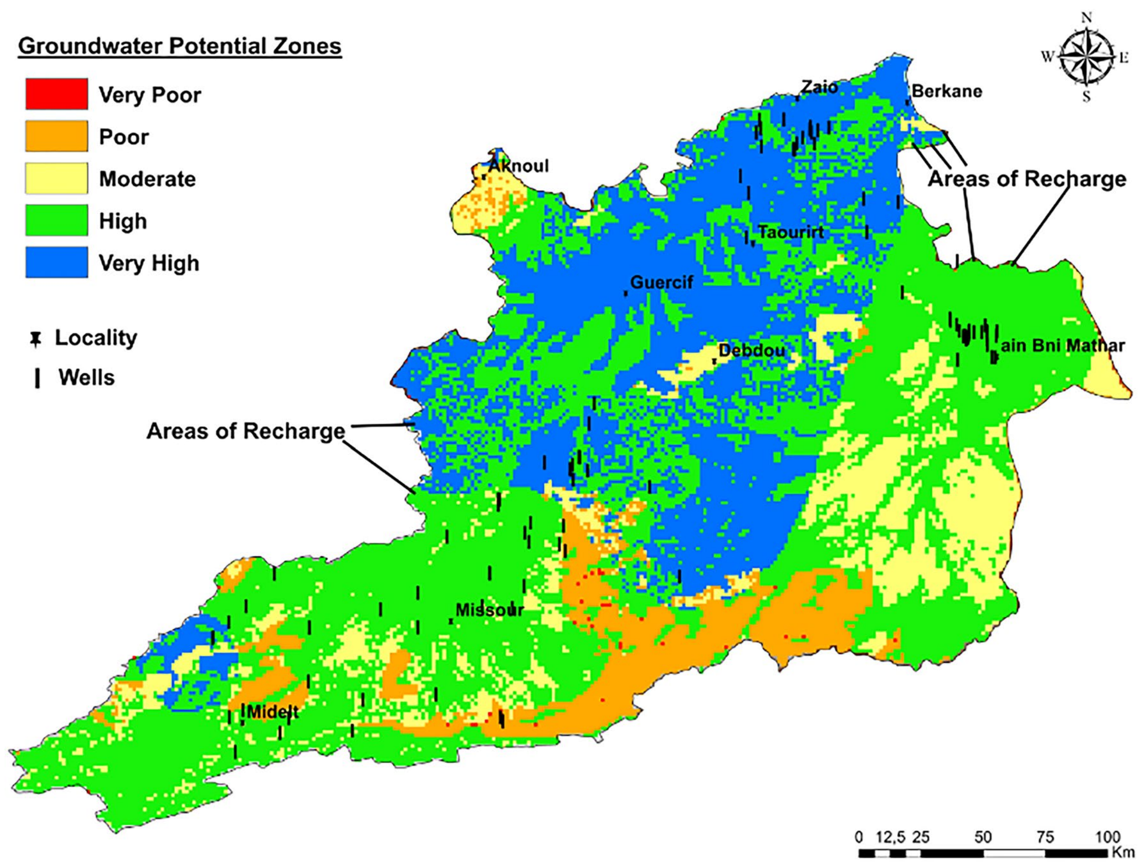


Fig. 6 Spatially distributed groundwater potential zones and wells locations

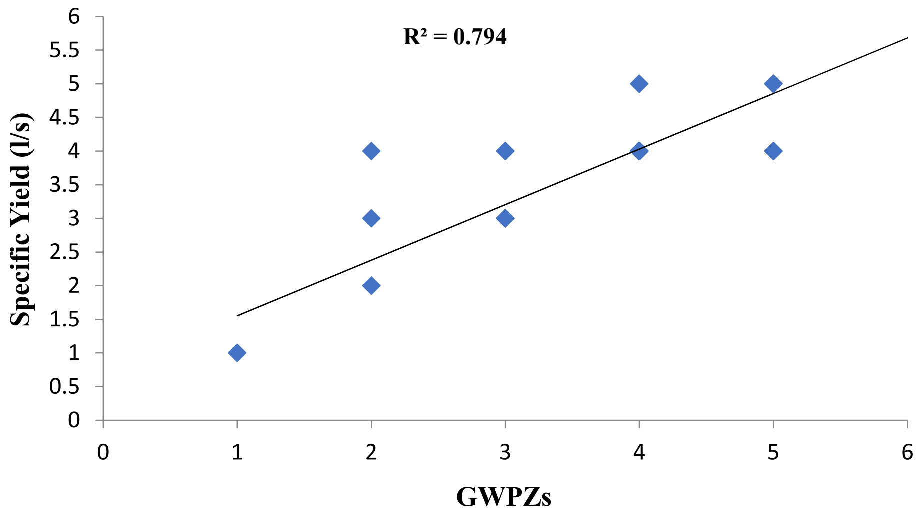


Fig. 7 Relationship between specific yield and GWPZs

and decision-makers about the importance of sustainable groundwater management is essential. By incorporating these strategies, decision-makers can enhance sustainable groundwater management, protecting the vital recharge areas and ensuring the availability of clean and reliable groundwater resources for present and future generations.

Conclusions

This study focuses on the identification of GWPZ using GIS, AHP, and RS techniques in the Moulouya, one of the principal basins of Morocco. Thematic layers of lithology, rainfall, LU and LC, drainage and lineament density, slope, and distance to rivers were created using conventional data, such as topographic maps and remote sensing data. Also, the weight assigned to individual themes and their reciprocal classes applying the AHP technique. The implementation of all the thematic layers in the GIS model created a potential groundwater map of the study area. According to the GWPZ map, the study area is categorized into five different zones, namely a zone of very high water potential (13,560.59 km^2), high (26,135.07 km^2), moderate (6692. 22 km^2), poor (4669.09 km^2) and very poor (60.54 km^2). The obtained results were validated by comparing them with the specific yield of the aquifers, yielding a correlation coefficient (R^2) of 0.79.

The results of the study demonstrate that AHP-based GIS and remote sensing is a viable approach for groundwater potential mapping, and the generated groundwater potential maps can serve as valuable resources for water resource management decision-makers. This research highlights the importance of conducting comprehensive groundwater evaluations and explorations, which could help minimize the high costs of geological surveys and contribute to the success of future water resource planning.

Future research could explore the applicability of advanced modeling techniques, including machine learning algorithms, artificial neural networks, and fuzzy logic, to further improve the accuracy of groundwater potential mapping. Additionally, future studies could focus on analyzing the temporal variability of groundwater potential in the Moulouya Basin by using historical data and trends coupled with the results of isotopic analyses. Understanding the dynamics of groundwater potential over time will provide valuable insights for developing effective groundwater management strategies.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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