https://doi.org/10.7494/geom.2024.18.6.47

Abdessamad Mazzourh[1], Morad Taher[2], Abdellah Ouhadi[3], Houria Dakak[4], Hinde Cherkaoui Dekkaki[5]

Mapping Groundwater-Potential Zones Using Geospatial and Decision-Making Approaches: Case Study of Ghiss-Nekkour Watershed in Northeastern Morocco

Abstract: Accelerated population growth has led to a heightened demand for water resources, resulting in a notable decline in underground water storage – especially in coastal areas. To effectively manage this crucial resource, the objective of this research work is to identify potential groundwater recharge areas in the Ghiss-Nekkour watershed using Saaty's multi-criteria analysis combined with GIS and remote-sensing techniques. Initially, this work involved gathering spatial information that was related to the various parameters that govern recharge and express it in thematic maps: slope, altitude, geology, rainfall, soil, land cover, and drainage density. A reclassification was made according to their degrees of involvement in the recharge process by Saaty's analytical hierarchy process (AHP); this was followed by a weighting of these parameters. These were subsequently integrated into a GIS in order to establish a map of potential groundwater recharge zones in the Ghiss-Nekkour watershed. The groundwater-potential map resulted in five classes:

- good (165 km^2) and excellent (0.9 km^2) aquifer recharge potentials – situated in north and southwest portions of study area;
- moderate (617 km^2) aquifer recharge potentials – located in western and southern parts of watershed;
- fair (551 km^2) and poor (44 km^2) aquifer recharge potentials – located in central zone and southeastern part of Ghiss-Nekkour watershed.

Field surveys that were conducted in November 2022 and October 2023 validated the obtained results.

Keywords: watershed, analytical hierarchy process, geospatial, remote sensing, Morocco

Received: June 12, 2024; accepted: November 12, 2024

[1] Abdelmalek Essaâdi University, Faculty of Science and Technology of Al Hoceima, Tétouan, Morocco, email: amazzourh@uae.ac.ma, https://orcid.org/0009-0002-0160-2559

[2] Abdelmalek Essaâdi University, Faculty of Science and Technology of Al Hoceima, Tétouan, Morocco, email: m.taher@uae.ac.ma (corresponding author), https://orcid.org/0000-0002-9273-2764

[3] Abdelmalek Essaâdi University, Faculty of Science and Technology of Al Hoceima, Tétouan, Morocco, email: aouhadi@uae.ac.ma

[4] Research Unit on Environment and Conservation of Natural Resources, Regional Center of Rabat, National Institute of Agricultural Research (INRA), Rabat, Morocco, email: houria.dakak@inra.ma, https://orcid.org/0000-0002-8550-7710

[5] Abdelmalek Essaâdi University, Faculty of Science and Technology of Al Hoceima, Tétouan, Morocco, email: hcherkaouidekkaki@uae.ac.ma, https://orcid.org/0000-0002-7501-0604

1. Introduction

Water is crucial for life, as all living beings require water in order to simply exist. This natural resource is sometimes decisive for socio-economic challenges [1]. Groundwater is a form of water that occupies all of the voids of a geological stratum. Aquifer formations exist in the Earth's crust and are primarily considered to be transmission channels and reservoirs for water storage [2]. Groundwater constitutes a main part of the hydrological cycle; this is a precious natural resource that is a primary source of water for agricultural, industrial, and domestic activities around the world [3, 4]. Faced with the strong growth in water demand in urban and rural areas, groundwater has become a vital resource [5].

Groundwater has undergone a drop in terms of its levels due to overexploitation; consequently, an ever-increasing pressure on this type of water is obvious in several regions of the world [6]. In Morocco, water is, in fact, one of the strategic sectors that is affected by the effects of climate change [7]. With around 1.2 billion people living in areas of water scarcity globally, Morocco is one of those countries whose economies mainly depend on water; this is why its impact is becoming more serious [8].

Along with population growth and climate change (which can have negative effects on the availability of groundwater), there is also the poor management of this water – especially in the agricultural sector. In Morocco, groundwater has gradually taken a more important role in the irrigation of agricultural territories [9].

The impact of the expected pressures that will be caused by global climate change calls for an urgent need for quantitative strategies that allow for assessing the groundwater production of aquifers; there also should be effective management and sustainable uses of groundwater resources [10].

Located in the northeastern part of Morocco, the coastal watershed of Ghiss-Nekkour serves as a significant water reservoir that provides for the drinking water needs of the city of Al Hoceima and its peripheral areas. This watershed is the subject of our study. Currently, the coastal watershed of Ghiss-Nekkour faces significant pressure due to limitations in mobilizing water resources. This pressure is further exacerbated by the siltation of the Mohamed Ben Abdelkrim Khattabi Dam [11] – particularly, in the Rif belt. Soil erosion is considered to be a primary factor that contributes to dam siltation and the subsequent reduction in storage capacity [12].

The study area is known for its limited available groundwater resources – particularly in the main aquifer of Ghiss-Nekkour (which is located to the north of the watershed). This water source is characterized by easy exploitation and vulnerability to pollution [13].

GIS techniques and integrated remote-sensing data were used to detect groundwater availability [14]. Additionally, the analytical hierarchy process (AHP) is an effective tool that was introduced by Thomas L. Saaty in 1980 for dealing with complex decision-making in groundwater-related fields. The tool simplifies complex decisions into pairwise comparisons, thus synthesizing the results [15]. The proposed

AHP methodology could prove to be useful for decision-makers and practicing hydrogeologists who are involved in the effective planning and management of vital groundwater resources [16, 17].

In terms of the sustainability of these water resources in the Ghiss-Nekkour watershed and in order to ensure local water security, we applied a combination of GIS and remote-sensing techniques with a multi-criteria analysis of Saaty to identify and delimit any groundwater-potential zones.

2. Study Area

The Ghiss-Nekkour watershed is located in the northeastern part of Morocco; it is open to the north and faces the Mediterranean Sea via the Ghiss-Nekkour alluvial plain (Fig. 1); this basin extends over an area of nearly 1,367 km^2. The basin is drained by the various tributaries of two bodies: the Ghiss River (approximately 80 km in length and flowing from the southwest to the northeast), and the Nekkour River (which is 76 km long (Fig. 2) and distinguished by a hydrological regime with a pluvial nature; the floods here are brutal due to the very high slopes and an annual rainfall regime that varies between 120 and 450 mm/year).

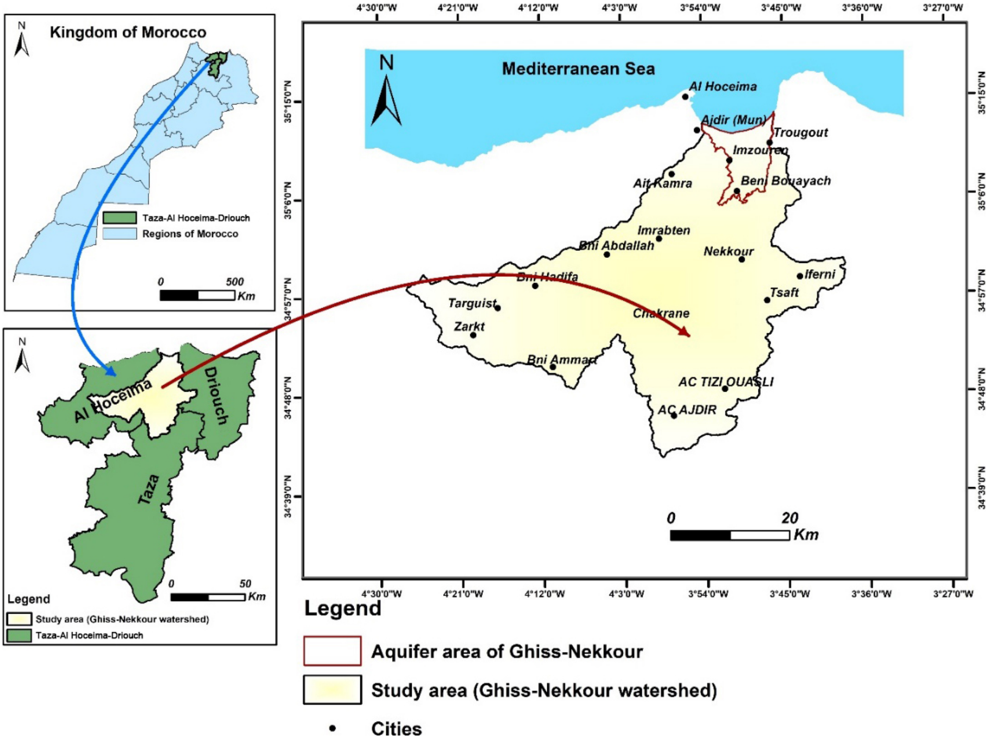

Fig. 1. Geographical location of Ghiss-Nekkour watershed

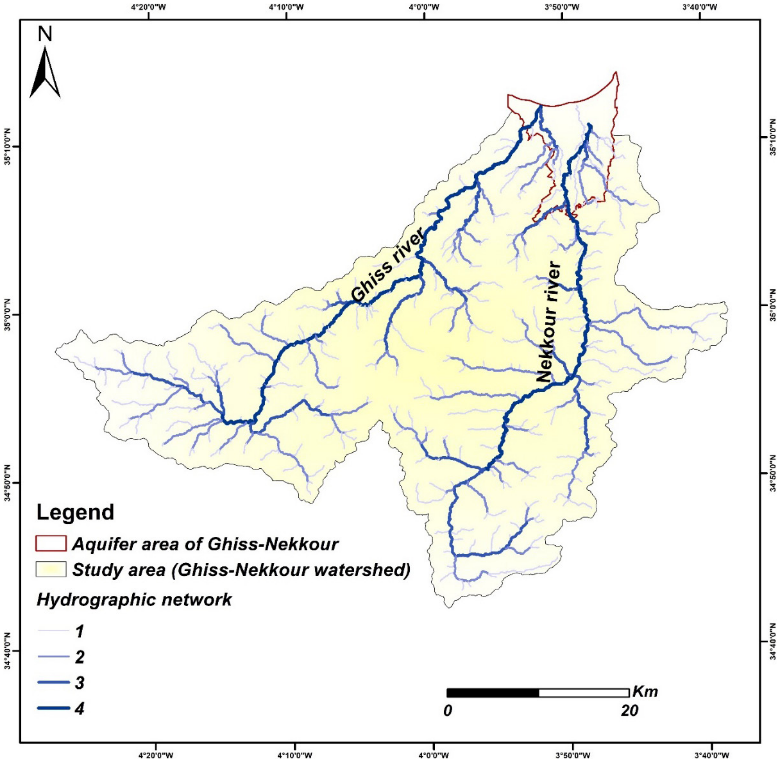

Fig. 2. Extent of hydrographic network

The downstream areas of the Ghiss and Nekkour Rivers correspond to two ponds or wetlands in the bay of Al Hoceima (which is separated from the seashore by a thin dune ribbon).

The Ghiss-Nekkour watershed submits to the climate of the Mediterranean Sea, which is distinguished by dry and hot summers and moderate winters. In general, the average temperatures represent variations that are strong because of the noticeable changes of seasons (which are characterized by extremely cold winters and summers that are extremely hot). The annual temperature average rises to above 30°C. In terms of the temperatures, there are two distinguished seasons; specifically speaking, there is a hot season in July and August and a cold season in January. When the temperatures reach 35°C during the month of August, they lower in a gradual way; by January, they can sometimes reach lows of 3°C [18].

From a hydrogeological point of view, the Ghiss-Nekkour coastal aquifer is considered to be the most productive groundwater source in the Ghiss-Nekkour watershed because of its favorable properties of storage and transmission [19]. This aquifer receives water from various sources, including the infiltration of rainfalls, river water from the Ghiss and Nekkour Rivers in the downstream parts, a lateral flow, and the infiltration of irrigation water [20].

3. Materials and Adopted Approach

The AHP method was developed by Thomas L. Saaty in the 1980s; it's aim was to refine the decision-making process by examining the coherence and logic of the decision-maker's preferences [21]. The methodology adopted in the current study is shown in Figure 3.

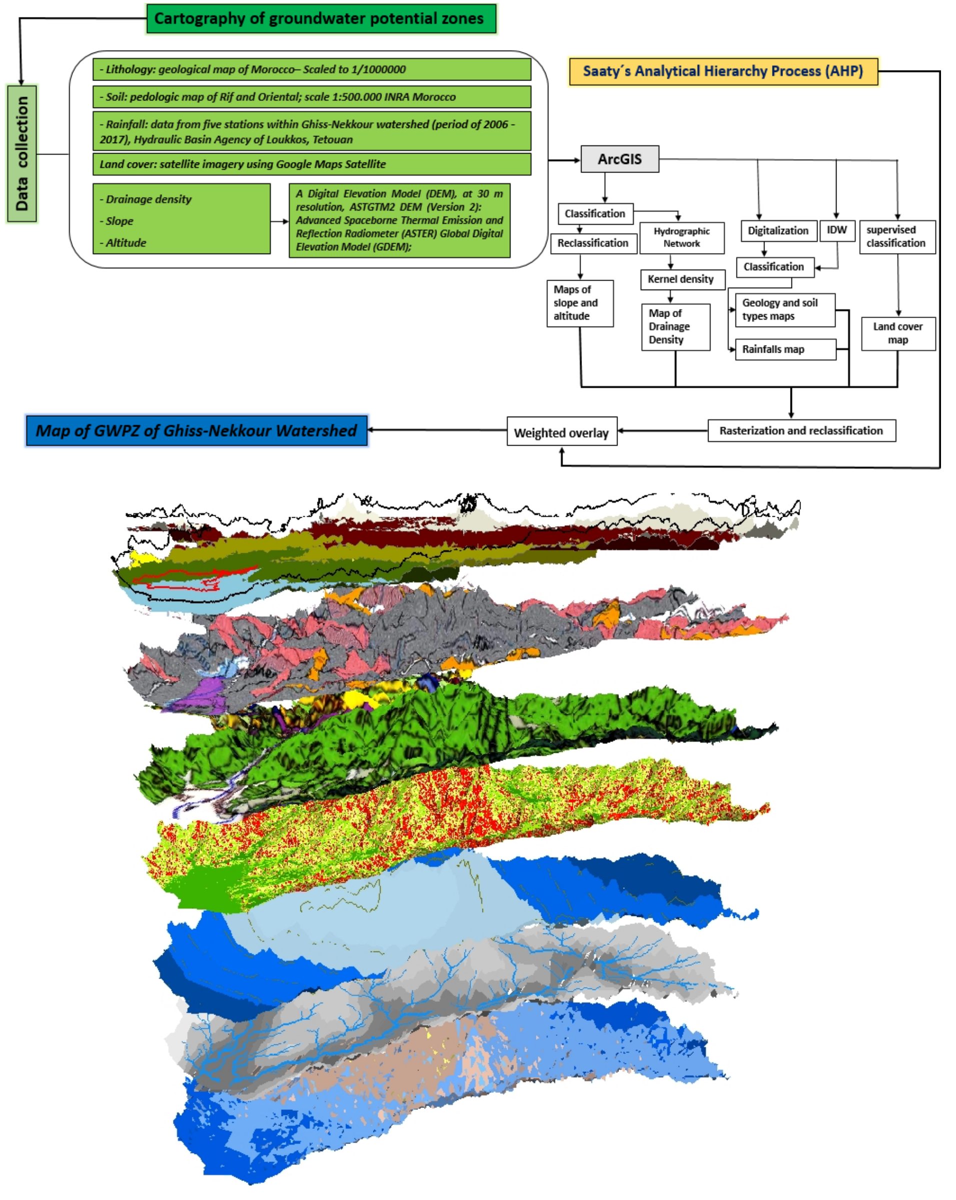

Fig. 3. Explanatory schema of adopted method as part of our research work

AHP is a multicriteria analysis method that depends on an approach that is structured and complementary for orderly analyzing all of the data that pertains to both evaluating and providing a resolution for a problem. This method necessitates the inclusion of various factors that control the dynamics of groundwater in locating potential groundwater-storage zones [22].

In the hierarchical analysis process, the relative importance of component or criterion (*i*) in relation to component (*j*) is determined by the Saaty scale (Table 1) and is assigned to the (*i*, *j*)th position of the paired comparison matrix [23].

Table 1. Saaty's relative importance scale (from 1 to 9)

Scale	Importance
1	equal importance
2	weak
4	moderate plus
5	strong importance
6	strong plus
7	very strong importance
8, 9	extreme importance

The procedure that was adapted for this work consisted of a very precise combination of work between everything that was cartographic and work in the field for validating the results in order to identify potential groundwater zones in the Ghiss-Nekkour watershed.

In the context of the AHP approach, it is valid to check the coherence of the judgments, which allows for the construction of the hierarchy matrix. This is done by calculating the consistency ratio (which can be considered to be an acceptance index) in order to verify the logic of the weights that are assigned to different criteria. This is calculated using the following formula:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{1}$$

where CI is the consistency index, and RI is the randomized index (Table 2).

The consistency index is calculated as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

where $\lambda_{\max}$ is the maximum eigenvalue, and n is the number of criteria.

Table 2. Random consistency index

Matrix size	3	4	5	6	7	8	9	10
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: [23]

At the beginning of realizing the three relative matrices, the first one required a paired comparison of seven criteria; the second calculated the division result of each comparison in the first matrix by the sum of each column of that matrix.

To complete the third matrix, we needed to determine the criteria weights by calculating the mean of each row of the second matrix. Subsequently, we multiplied the criterion weights of each row of the second matrix by each column of the first matrix that corresponded (Tables 3, 4).

Table 3. Matrix resulting from comparisons of different parameters

Rank	Factor	Rainfall	Slope	Soil	Elevation	Land cover	Drainage density	Geology	Criteria weights	Weighted sum value	Ratio	Normalized weight [%]
1	Rainfall	1	2	5	4	7	6	8	0.4193	2.9356	7.0011	42
2	Slope	1/2	1	5/2	4/2	7/2	6/2	8/2	0.2097	1.4678	6.9995	21
5	Soil	1/5	2/5	1	4/5	7/5	6/5	8/5	0.0839	0.5871	6.9976	9
4	Elevation	1/4	2/4	5/4	1	7/4	6/4	8/4	0.1049	0.9435	8.9942	10
7	Land cover	1/7	2/7	5/7	4/7	1	6/7	8/7	0.0599	0.4193	7.0000	6
6	Drainage density	1/6	2/6	5/6	4/6	7/6	1	8/6	0.0699	0.4892	6.9985	7
8	Geology	1/8	2/8	5/8	4/8	7/8	6/8	1	0.0524	0.3669	7.0019	5
	TOTAL								1			100

Table 4. Normalized weights relating to different thematic layers and their corresponding classes

Influencing factors	Class interval	Reclass	Overlay	NW	NW%
Rainfall	90–244	1	1	0.4193	42
	245–346	2	2		
	347–429	3	3		
	430–520	4	4		
	521–683	5	5		
Slope	0–7	1	5	0.2097	21
	8–14	2	4		
	15–20	3	3		
	21–28	4	2		
	29–62	5	1		
Soil	Slightly developed soil	1	7	0.0839	9
	Iron sesquioxide soils	2	4		
	Calcimagnesic soils	3	5		
	Brown soils	4	4		
	Raw mineral soils	5	2		
	Isohumic soils	6	6		
	Sodic soils	7	3		
	Sand dune	8	8		
Elevation	15–411	1	5	0.1049	10
	411–807	2	4		
	807–1203	3	3		
	1,203–1,599	4	2		
	1,599–1,995	5	1		
Land cover	Waters	1	9	0.0599	6
	Forest	2	7		
	Agricultural land	3	6		
	Building	4	1		
	Uncultivated space	5	4		
	Bare space	6	3		
Drainage density	0.039–0.575	1	5	0.0699	7
	0.576–1.111	2	4		
	1.112–1.646	3	3		
	1.647–2.182	4	2		
	2.183–2.718	5	1		
Geology	Modern alluvium (limes)	1	9	0.0524	5
	Sericiteous shale	2	2		
	Marly shale	3	4		
	Flysch or molasses	4	7		
	Gypsum breaches	5	2		
	Grey calc-schist	6	4		
	Massive white limestones and secondary dolomites	7	4		
	Calcareous limestone slabs in large benches	8	4		
	Marl	9	7		
	Conglomerate (sandstone and silt)	10	2		
	Marl-limestone-sandstone flysch	11	6		

Let's calculate the consistency index according to Equation (2), assuming that the maximum eigenvalue $\lambda_{max} = 7.2846$:

$$CI = \frac{(7.2846 - 7)}{7 - 1},$$

$$CI = 0.04761.$$

Consistency ratio according to Equation (1) equals:

$$CR = \frac{0.04762}{1.32},$$

$$CR = 0.03606.$$

CR is less than 0.1, which confirmed the consistency of the judgments at the matrix level.

4. Results

4.1. Thematic Layers

Table 5 presents the parameters utilized in this study, which were selected based on a comprehensive review of the existing literature. These parameters were carefully chosen to align with established research and best practices in the field, ensuring the robustness and relevance of the study's methodology.

Table 5. Summary of employed factors for delineating GWPZ

Parameter	Authors who used same parameter
Rainfall	[28]
Slope	[29, 30]
Soil	[31, 32]
Elevation	[28]
Land cover	[33, 34]
Drainage density	[29, 34, 35]
Geology	[15, 31, 36, 37]

Rainfall (Fig. 4). The impact of rainfall is very important as a factor that influences groundwater recharge and distribution; therefore, high groundwater recharge is mainly linked to high rainfall levels.

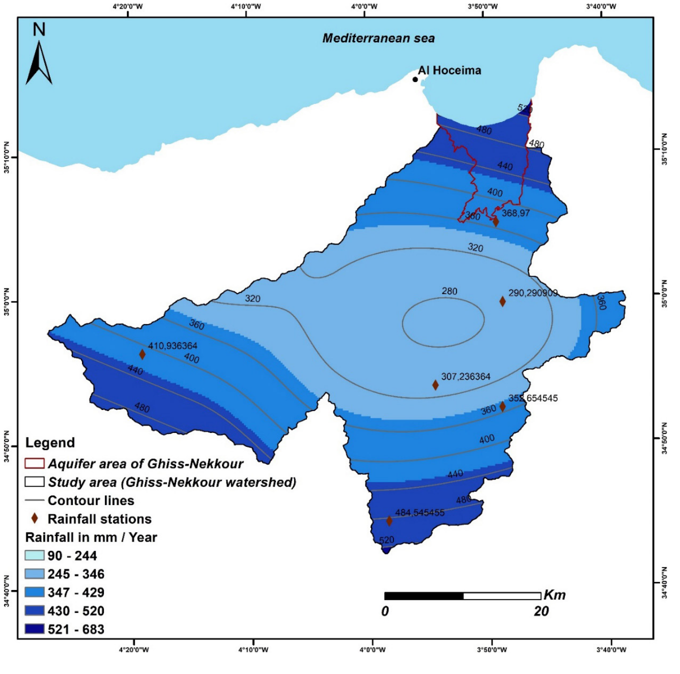

Fig. 4. Annual mean of rainfall (2006–2017)

Rainfall data from six rainfall stations within the Ghiss-Nekkour watershed (2006–2017) were used to calculate and establish a map of the annual mean of the rainfall for each station. As a result, high weights are attributed to heavy rainfall, and low weights are related to low rainfall.

Slope and Altitude (Figs. 5, 6). These two factors strongly condition the runoff at the level of a watershed. Topographic parameters are crucial for ensuring groundwater recharge; therefore, the rate of groundwater recharge increases as they decrease.

Soil (Fig. 7). Soil as one of the resources in nature; it is a significant parameter that determines potential groundwater zones. Additionally, soil plays a crucial role in the recharge of groundwater and meets the basic requirement for agricultural production. A soil's characteristics effectively control the penetration of surface water into the groundwater system. Besides, they are directly related to infiltration, percolation, and permeability rates [24].

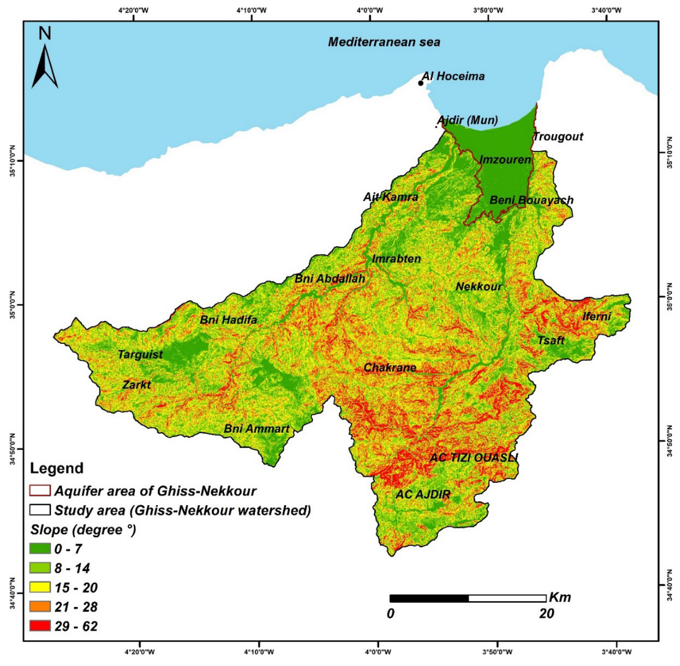

Fig. 5. Spatial distribution of slopes

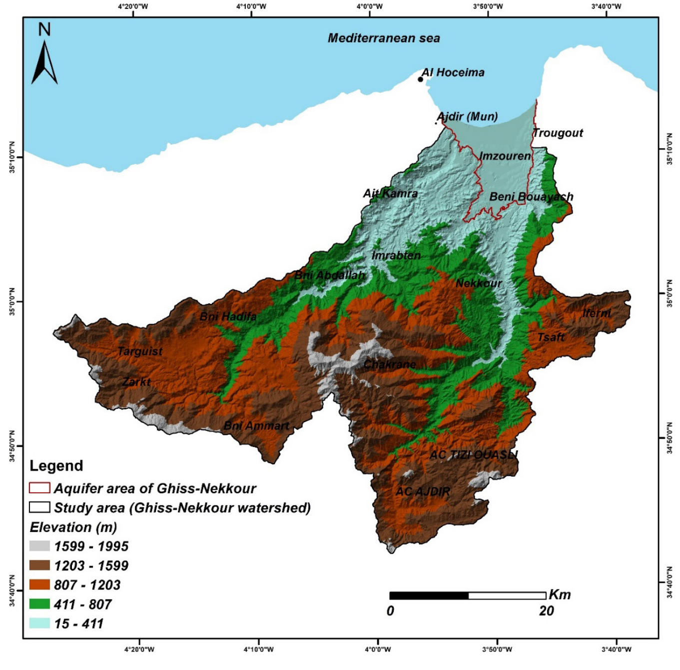

Fig. 6. Spatial distribution of altitudes

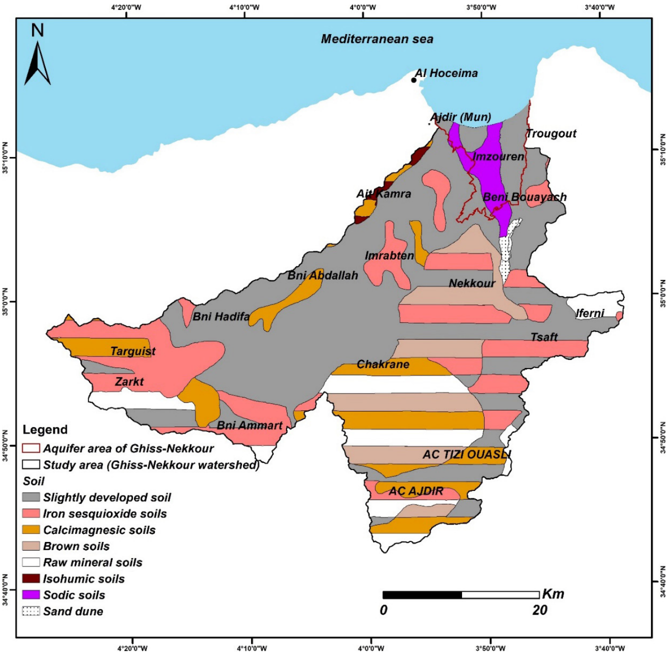

Fig. 7. Soil map

Similarly, soils with a more clayey grain-size component contribute to the swelling of the soil and the closing of pores, while soils with a dominant loamy or loamy-sandy grain size better ensure the interaction between the soil and the porosity [25].

A map of the soil types was obtained through digitalization using the pedological map of the Rif and the Oriental regions at a scale of 1:500,000; this data was provided by the National Institute for Agronomic Research in Morocco.

Land cover (Fig. 8). The study of land cover can lead to the extractions of important indicators that are related to the distribution and recharge of groundwater. Furthermore, it serves as an important indicator for selecting potential sites for groundwater recharge.

The characteristics of the elaborated land cover map include the following: 1) water surface; 2) forest; 3) agricultural land; 4) building; 5) uncultivated soil; and 6) bare soil.

Drainage density (Fig. 9). Drainage density D_d is the result of the sum of the lengths of the watercourses of a watershed $\sum L$ to the surface area of the same basin A [26].

According to Arthur N. Strahler (1957, as cited in [27]), drainage density quantitatively measures the total length of the watercourses within a square kilometer area. Areas that are characterized by high drainage densities indicate higher potentials for surface runoff, thus resulting in limited groundwater development.

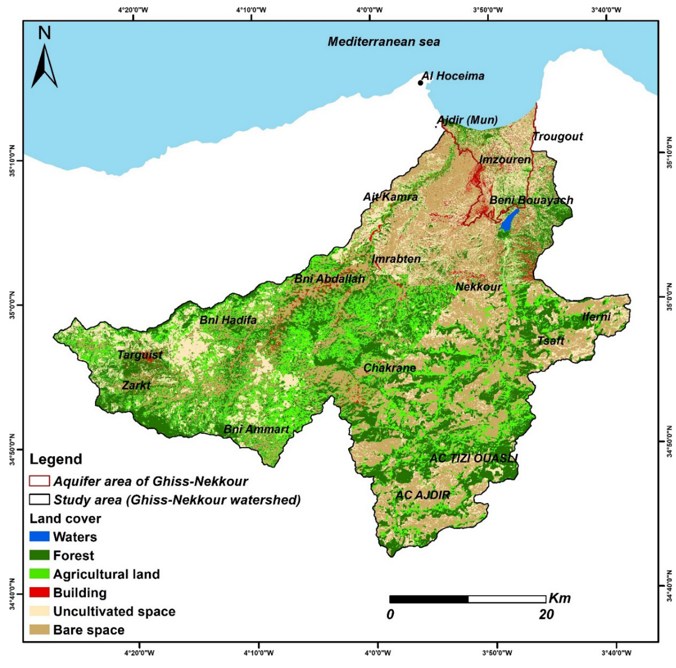

Fig. 8. Land cover

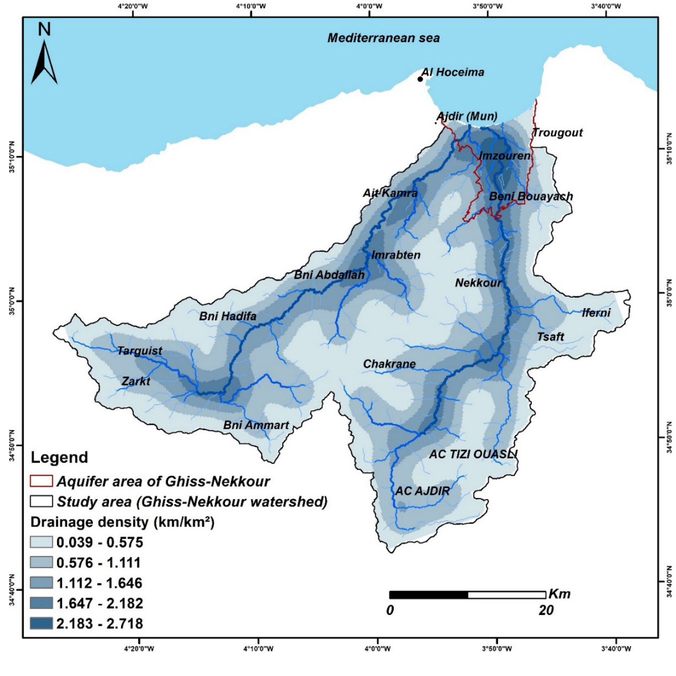

Fig. 9. Drainage density

The drainage-density map was established starting from the hydrographic network of the watershed that was obtained by using the digital elevation model (DEM). The map presents five classes of density, with high densities around watercourses and tributary crossings. The density values varied from 0.039 to 2.718 km/km^2.

Geology (Fig. 10). The geological nature of a field plays a primordial role in the recharge of groundwater. At with the Ghiss-Nekkour watershed, the Ghiss-Nekkour plain constitutes an intermontane valley. Below this plain (which is drained by the tributaries of the two main rivers), the Ghiss-Nekkour coastal aquifer circulates.

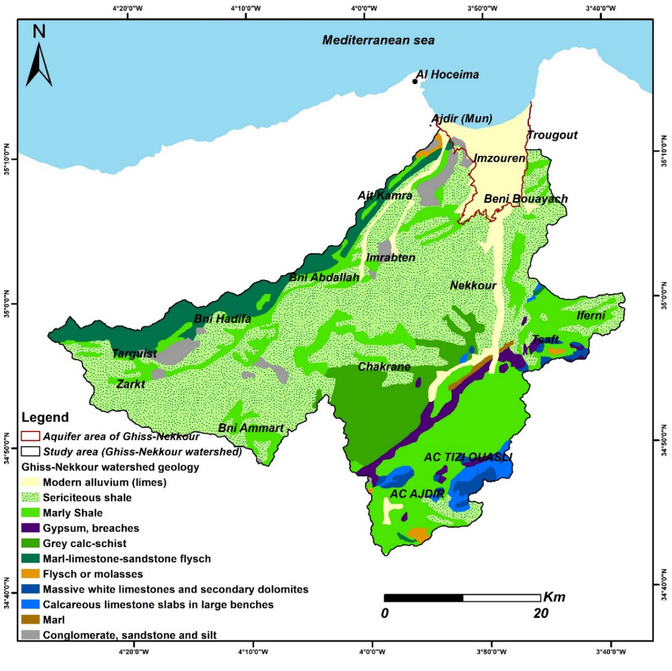

Fig. 10. Geological map

The geological map was created through the digitalization of a paper geological map of Morocco (scaled to 1:1,000,000); thus, we identified the following lithological formations according to the geological map of the Ghiss-Nekkour watershed:

- Alluvium (upper Pleistocene and Holocene),
- Melloussa-facies “flysch” aquifer (lower Cretaceous),
- Lacustrine facies,
- Malaria or dune (lower Pleistocene “Villafranchian”),
- Oligocene to lower Miocene,
- Formation of Mecmen (lower Paleocene-Eocene),
- Detrital facies (mid Cretaceous),
- Callovo-Oxfordian with flysh sandstone facies (upper Jurassic),

- Lias,
- Numidian sandstone aquifer,
- Detrital facies (upper Cretaceous),
- Lower Sebtides units (upper Paleozoic),
- Detrital facies (lower Cretaceous),
- Barremo-Albian – with “flysch” facies of Rif (upper Cretaceous).

4.2. Groundwater-Potential Zones

According to Figure 11 and Table 6, five classes of the recharge degree were extracted from the map of potential recharge zones.

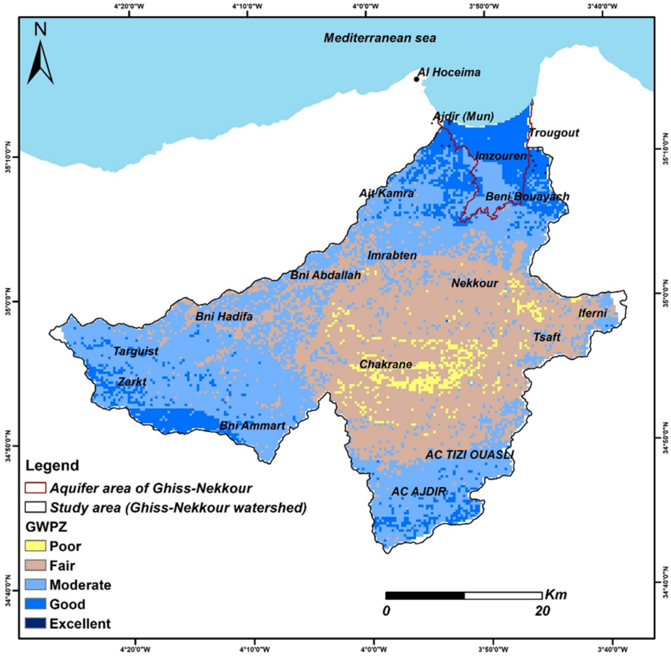

Fig. 11. Map of groundwater-potential zones

Table 6. Area of potential zones of groundwater recharge

Potential zone	Area [km^2]	Percentage [%]
Poor	44.8	3.24
Fair	551.3	39.94
Moderate	617.8	44.76
Good	165.3	11.97
Excellent	0.9	0.06

Poor and Fair. These two classes covered 44.8 and 551.3 km^2 of the mapped areas that were generally located in the central and southeastern parts of the Ghiss-Nekkour watershed, respectively. It was necessary to take into consideration that the highest altitudes and extreme slopes were located in these two mapped parts, which resulted in disadvantages in the recharge levels in these areas. In addition, the recorded mean rainfall was the lowest (90–240 mm/year) as compared to the other areas (according to the rainfall map).

Moderate. This represented almost half of the study area (617.8 km^2); it was the dominant class. This was located in the western and southern parts of the studied watershed (in addition to the south of the Ghiss-Nekkour aquifer). This modest degree of recharge was attributed to a medium-to-low slope class (0°–20°) and average rainfalls of 360–400 mm/year.

Good. This occupied 165.3 km^2 of the area studied and was predominantly located in the north (specifically, between the Ajdir and Trougout communes) and southwest (particularly, between the Zarkt and Bni Ammart communes). The slopes that were recorded in these two areas (especially in the north [0°–7°]) covered a part of the southern zone of the watershed (in the commune of Ajdir, Taza Province).

In the northern zone (where the Ghiss-Nekkour aquifer is located), the recorded mean rainfall was the highest (521 mm/year) according to the rainfall map. In addition, there was a significant vegetation cover (forest, cultivated land) that characterized the southwestern part.

From a geological point of view, the area that is located to the north was characterized by the presence of alluvium (upper Pleistocene alluvium has a strong infiltration capacity), which was formed by recent loads from the valleys; these modern alluviums presented great porosity that facilitated rainwater infiltration more effectively.

Excellent. This represented only 0.9 km^2 and was located specifically in the far east (around the Trougout fault) and the west of the Ghiss-Nekkour aquifer.

4.3. Validation of Groundwater-Potential Zones

From Figure 12, one can observe that most of the water-sampling points (wells and boreholes) were located in those areas with good groundwater-recharge potentials (specifically, around the Ghiss-Nekkour alluvial aquifer). The catchment area of the Ghiss and Nekkour Rivers plays a significant role in supplying drinking water to the study area. The Ghiss area was comprised of two boreholes (1805/5, 1677/5) and two wells (385/5 and 1768/5), with a total flow rate of 135 l/s. Similarly, the capture area of the Nekkour area was composed of three boreholes (573/5, 576/5, and 1971/5) and was equipped with a total flow rate of 160 l/s [13].

Based on our texture study of the soil samples (Fig. 12, Table 7), we observed a predominance of sandy and silty textures (sandy-clayey, sandy-silty, sandy-clayey) to the north of the Ghiss-Nekkour watershed (particularly, around the Ghiss-Nekkour aquifer). These sand-silt textures inherently provide favorable permeability for water.

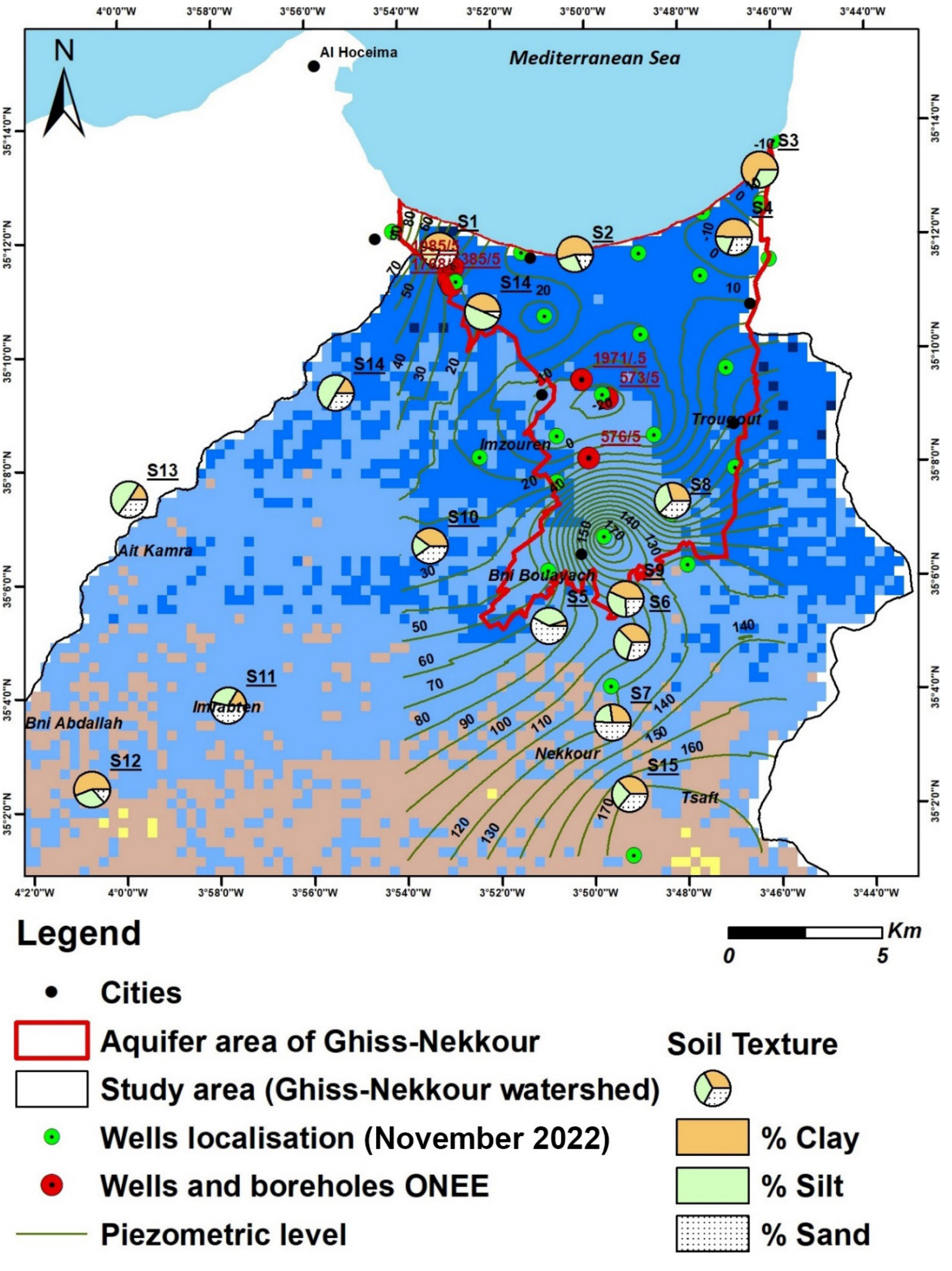

Fig. 12. Textures and piezometry of northern part of watershed (Ghiss-Nekkour aquifer) (ONEE – Office National de l'Électricité et de l'Eau Potable [National Office of Electricity and Drinking Water])

Table 7. List of analyzed soil samples (own data from field study – October 2023)

Sample	Latitude	Longitude	Clay [%]	Silt [%]	Sand [%]
S1	35.19666667	−3.885916667	46.6	22.6	30.8
S2	35.19283333	−3.837694444	54.6	27.6	17.8
S3	35.21888889	−3.771222222	67.5	31.6	0.9
S4	35.19927778	−3.780833333	49.6	19.3	31.1
S5	35.08613889	−3.848805556	5.3	37	57.7
S6	35.08427778	−3.819361111	37.4	33.1	29.4
S7	35.05752778	−3.826638889	27.2	21.9	50.9
S8	35.11844444	−3.804222222	29.9	32.4	37.8
S9	35.09369444	−3.821388889	43.3	32.1	24.6
S10	35.11008333	−3.890833333	40.4	19.8	39.9
S11	35.06408333	−3.963500000	16.9	29.4	53.7
S12	35.04338889	−4.012416667	55.8	30.9	13.3
S13	35.12497222	−3.997916667	16.1	48.7	35.3
S14	35.15533333	−3.923638889	15.9	51.2	32.9
S15	35.17852778	−3.870861111	43.7	49.9	6.4
S16	35.03650000	−3.820916667	36.4	27.6	36.0

The perturbation that can be observed in the piezometric levels (our own data from the field study – November 2022) was due to hydrogeological depressions that were linked to the overexploitation of the Ghiss-Nekkour aquifer. This aquifer supplies drinking water and irrigation for agricultural lands (olive trees, tomatoes, melons, etc.). It was detected that zero piezometric level receded in some locations instead of advancing toward the outlet of the aquifer. Additionally, one can observe in Figure 12 that there was a case of a localized recharge of the aquifer (the altitude of the water body = 170); this was likely favored by the existence of permeable soil (sand, silt) around this southern part of the Ghiss-Nekkour aquifer.

5. Discussion

Numerous investigations have been undertaken in order to delineate the groundwater resources within the region of the study area; they have employed similar approaches (AHP) while utilizing different factors. Bourjila et al. [28] used 11 thematic layers that were known to be of high importance in the demarcations of groundwater-potential zones in the Nekkour basin. The analysis was conducted through GIS and identified 15.56% of the area as having poor groundwater potential, with 63.95% exhibiting moderate potential. Conversely, those regions that were characterized by good and very good groundwater potentials accounted for only 20.48% of the basin. Additionally, the same author used the same number of thematic layers for mapping the groundwater in the Ghiss basin [38]. The analysis was conducted through GIS and utilized multiple thematic layers; it indicated that those areas that were classified as having "poor" and "moderate" groundwater potentials covered 7% (58.59 km^2) and 55% (460.35 km^2) of the total area, respectively. Conversely, those regions that were designated as having good and very good groundwater potential encompassed 35% (292.95 km^2) and 3% (25.11 km^2) of the total area, respectively. Consequently, we revealed 10.75% for the poor, 59% for the moderate, and 29% for the good classes by combining the two studies. In contrast, our study revealed that both the poor and good classes had the lowest percentages. In both studies, the moderate class presented the highest percentage. This variability in groundwater potentiality can be attributed to those factors that are related to groundwater-recharge potentiality, which is the main limitation of the AHP approach. Furthermore, Taher et al. [31] adopted many different scenarios to delineate the groundwater in the Boudinar basin using the AHP method; for each scenario, different results were obtained. Therefore, it appears that an elaboration of the map of potential groundwater zones requires a good choice of factors at the beginning to better refine the results – either in the elaborations of the matrices or when assembling these different spatial parameters in a geographic information system (GIS). Likewise, those areas that represent high and very high degrees of groundwater-potential zones are often linked to the presence of significant values of factors such as rainfall (high), slope (low), and soil (favorable permeability).

The results of several studies that have been conducted in the different regions of Morocco using the AHP method for groundwater-potential mapping have shown varied classifications of the potential zones. While applying the same methodology, these studies have reflected the regional differences in groundwater availability:

- Ifni basin (2023). The groundwater potential in this study was categorized into four zones: very high (15.22%), high (20.17%), moderate (30.96%), and low (33.65%) [39].
- Ighrem region (2020). This study identified three categories: favorable (17%), medium (64%), and unfavorable (18%) [1].

– Tata basin (2022). Five categories were defined: very low (8.67%), low (17.74%), moderate (46.77%), high (19.95%), and very high (6.87%) [40].
– Central Middle Atlas (2020). The classification revealed very good (3.88%), good (17.22%), moderate (20.20%), poor (29.89%), very poor (18.60%), and non-potential (10.49%) zones [41].

These studies have demonstrated the application of the AHP method in diverse regions, resulting in a range of groundwater-potential classifications that have reflected the varying hydrogeological and climatic conditions of each area.

The disadvantages that elaborating the map of potential groundwater zones may present are mostly in the spatial analysis of those factors that are obtained through interpolation (such as drainage density). In other words, the interpolation can lead to errors in the preparation of the maps of these factors.

The use of the multi-criteria method can be considered to be a technical and reliable solution for avoiding the massive creation of the random drilling of boreholes and wells without a planned hydrogeological study. Besides, this method positively influences the preservation and sustainability of the water resources in the study area in the medium and long terms.

6. Conclusion

The application of the analytical hierarchy process (AHP), including the selection of factors, matrix development, and calculation of CI and CR, facilitates the creation of groundwater-potential maps via GIS. This technique enables a deeper comprehension of the hydrological and hydrogeological characteristics of an area.

This combination of operations in the present study serves to classify zones that are favorable for recharging. As a result, five classes were extracted; the good class reached 165.3 km^2 and was found to be distributed in the majority in the north and southwest areas of the Ghiss-Nekkour watershed.

The map of the groundwater-potential zones can be considered to be a recommended reference sheet that provides information that can be relied upon by experts, researchers, and decision-makers in the water sector to ensure effective water-resource management.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CRediT Author Contribution

A. M.: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing.

M. T.: methodology, writing, review.

A. O.: methodology, validation, data curation.
H. D.: data curation, methodology.
H.C.D.: methodology, data curation, supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

Acknowledgment

We would like to express our sincere gratitude to the editor and reviewers for their thoughtful and constructive comments on our manuscript. We appreciate the time and effort that they have dedicated to the review process, which has greatly contributed to improving the rigor and impact of our study.

References

[1] Benjmel K., Amraoui F., Boutaleb S., Ouchchen M., Tahiri A., Touab A.: *Mapping of groundwater potential zones in crystalline terrain using remote sensing, GIS techniques, and multicriteria data analysis (case of the Ighrem Region, Western Anti-Atlas, Morocco)*. Water, vol. 12(2), 2020, 471. https://doi.org/10.3390/w12020471.

[2] Ganapuram S., Kumar G.T.V., Krishna I.V.M., Kahya E., Demirel M.C.: *Mapping of groundwater potential zones in the Musi basin using remote sensing data and GIS*. Advances in Engineering Software, vol. 40(7), 2009, pp. 506–518. https://doi.org/10.1016/j.advengsoft.2008.10.001.

[3] Treidel H., Martin-Bordes J.L., Gurdak J.J. (eds.): *Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations*. International Contributions to Hydrogeology, vol. 27, CRC Press – Balkema, Leiden, Netherlands – Boca Raton 2012.

[4] Zolekar R.B., Todmal R.S., Bhagat V.S., Bhailume S.A., Korade M.S., Das S.: *Hydro-chemical characterization and geospatial analysis of groundwater for drinking and agricultural usage in Nashik district in Maharashtra, India*. Environment, Development and Sustainability, vol. 23(3), 2021, pp. 4433–4452. https://doi.org/10.1007/s10668-020-00782-2.

[5] Faye C., Solly B., Dièye S., Fall A.: *Evaluation des zones potentielles d'eaux souterraines avec l'utilisation des SIG et de la télédétection Cas du sous-bassin de la Sandougou (bassin de la Gambie)* [*Evaluating of the potential groundwater zones using GIS and remote sensing Case study of Sandougou sub-basin (Gambia Basin)*]. African Journal of Land Policy and Geospatial Sciences, vol. 4(1), 2021, pp. 53–75. https://doi.org/10.22004/ag.econ.334427.

[6] Singh L.K., Jha M.K., Chowdary V.M.: *Assessing the accuracy of GIS-based Multi-Criteria Decision Analysis approaches for mapping groundwater potential*. Ecological Indicators, vol. 91, 2018, pp. 24–37. https://doi.org/10.1016/j.ecolind.2018.03.070.

[7] El Assaoui N., Sadok A., Merimi I.: *Impacts of climate change on Moroccan's groundwater resources: State of art and development prospects*. Materials Today: Proceedings, vol. 45(part 8), 2021, pp. 7690–7696. https://doi.org/10.1016/j.matpr.2021.03.220.

[8] Echogdali F.Z., Boutaleb S., Abioui M., Aadraoui M., Bendarma A., Kpan R., Ikirri M., El Mekkaoui M., Essoussi S., El Ayady H., Abdelrahman K., Fnais M.S.: *Spatial mapping of groundwater potentiality applying geometric average and fractal models: A sustainable approach.* Water, vol. 15(2), 2023, 336. https://doi.org/10.3390/w15020336.

[9] Del Vecchio K., Kuper M.: *La mise en visibilité des eaux souterraines au Maroc: un processus historiquement lié aux politiques de développement de l'irrigation.* Développement Durable et Territoires, vol. 12(3), 2021. https://doi.org/10.4000/developpementdurable.19675.

[10] Oh H., Kim Y.S., Choi J.K., Park E., Lee S.: *GIS mapping of regional probabilistic groundwater potential in the area of Pohang City, Korea*. Journal of Hydrology, vol. 399(3–4), 2011, pp. 158–172. https://doi.org/10.1016/j.jhydrol.2010.12.027.

[11] Arrebei N., Sabir M., Naimi M., Chikhaoui M., Raclot D.: *Reconstitution des données historiques et diagnostic de l'état actuel des aménagements antiérosifs dans le bassin versant Nekor*. Revue Marocaine des Sciences Agronomiques et Vétérinaires, vol. 7(2), 2019, pp. 313–322. https://hal.science/hal-02893733.

[12] Taher M., Mourabit T., Bourjila A., Saadi O., Errahmouni A., El Marzkioui F., El Mousaoui M.: *An estimation of soil erosion rate hot spots by integrated USLE and GIS methods: A case study of the Ghiss Dam and Basin in Northeastern Morocco*. Geomatics and Environmental Engineering, vol. 16(2), pp. 95–110. https://doi.org/10.7494/geom.2022.16.2.95.

[13] ONEE, Direction Technique et Ingénierie: *Renforcement de l'AEP d'Al Hoceima à partir du barrage Oued Ghiss. Plan de Gestion Environnementale et Sociale.* Royaume du Maroc Office National de l'Électricité et de l'Eau Potable Branche Eau, 2020. http://www.onep.ma/grands-projets/2020/PPSAE-BAD14-PGES-AlHoceima.pdf [access: 30.08.2024].

[14] Abdalla F.: *Mapping of groundwater prospective zones using remote sensing and GIS techniques: A case study from the Central Eastern Desert, Egypt*. Journal

of African Earth Sciences, vol. 70, 2012, pp. 8–17. https://doi.org/10.1016/j.jafrearsci.2012.05.003.

[15] Arulbalaji P., Padmalal D., Sreelash K.: *GIS and AHP techniques based delineation of groundwater potential zones: A case study from Southern Western Ghats, India*. Scientific Reports, vol. 9, 2019, 2082. https://doi.org/10.1038/s41598-019-38567-x.

[16] Chowdhury A., Jha M.K., Chowdary V.M.: *Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques*. Environmental Earth Sciences, vol. 59(6), 2010, pp. 1209–1222. https://doi.org/10.1007/s12665-009-0110-9.

[17] Doke A.B., Zolekar R.B., Patel H., Das S.: *Geospatial mapping of groundwater potential zones using multi-criteria decision-making AHP approach in a hardrock basaltic terrain in India*. Ecological Indicators, vol. 127, 2021, 107685. https://doi.org/10.1016/j.ecolind.2021.107685.

[18] Nouayti N., El Khahil C., Algarra M., Pola M.L., Fernández S., Nouayti A., Esteves da Silva J.C.G., Driss K., Samlani N., Hilali M., El Mustapha A., Krawczyk D.A., Rodero A.: *Determination of physicochemical water quality of the Ghis-Nekor Aquifer (Al Hoceima, Morocco) using hydrochemistry, multiple isotopic tracers, and the Geographical Information System (GIS)*. Water, vol. 14(4), 2022, 606. https://doi.org/10.3390/w14040606.

[19] Chafouq D., El Mandour A., Elgettafi M., Himi M., Chouikri I., Casas A.: *Hydrochemical and isotopic characterization of groundwater in the Ghis-Nekor plain (Northern Morocco).* Journal of African Earth Sciences, vol. 139, 2017, pp. 1–13. https://doi.org/10.1016/j.jafrearsci.2017.11.007.

[20] Bourjila A.: *Modélisation hydrochimique de l'intrusion marine dans l'aquifère côtier de Ghiss-Nekor et caractérisation des zones potentielles en eaux souterraines dans les bassins versants de Ghiss et Nekor (Maroc) à l'aide des méthodes géospatiales*. Université Abdelmalek Essaâdi, Tétouan, 2023 [PHD thesis]. https://hal.science/tel-04553629v1.

[21] Caillet R.: *Analyse multicritère : Étude de comparaison des méthodes existantes en vue d'une application en analyse de cycle de vie.* Centre Interuniversitaire de Recherche en Analyse des Organisations (CIRANO), Montreal 2003. https://depot.erudit.org/id/000057dd.

[22] Abdelouhed F., Algouti A., Algouti A., Baiddane Y., Ifkirne M.: *Using GIS and remote sensing for the mapping of potential groundwater zones in fractured environments in the CHAOUIA-Morocco area.* Remote Sensing Applications: Society and Environment, vol. 23, 2021, 100571. https://doi.org/10.1016/j.rsase.2021.100571.

[23] Jeddou M.B., Kalboussi W.B., Dhouibi A.: *Application de la méthode AHP pour le choix multicritère des fournisseurs.* Revue Marocaine de recherche en management et marketing, no. 12, 2015, pp. 60–71. https://doi.org/10.48376/IMIST.PRSM/remarem-v0i12.3772.

[24] Savita R.S., Mitta H.K., Satishkumar U., Singh P.K., Yadav K.K., Jain H.K., Mathur S.M., Davande S.: *Delineation of groundwater potential zones using remote sensing and GIS techniques in Kanakanala Reservoir Subwatershed, Karnataka, India.* International Journal of Current Microbiology and Applied Sciences (IJCMAS), vol. 7(1), pp. 273–288. https://doi.org/10.20546/ijcmas.2018.701.030.

[25] Akkari D.: *L'apport du système d'information géographique (SIG) dans la définition des zones de potentielhydrique dans le bassin versant Abou Ali (Liban Nord)*. Journal of Alpine Research – Revue de Géographie Alpine, no. 110-4, 2022, pp. 1–27. https://doi.org/10.4000/rga.10015.

[26] Rambert B.: *Recherche sur la signification hydrogéologique de la densité du drainage. Application à la détermination et à la cartographie de l'écouelement souterrain*. Bureau de Recherches Géologiques et Minières (BRGM), Orléans 1973. http://infoterre.brgm.fr/rapports/73-SGN-422-AME.pdf.

[27] Dinesh Kumar P.K., Gopinath G., Seralathan P.: *Application of remote sensing and GIS for the demarcation of groundwater potential zones of a river basin in Kerala, southwest coast of India*. International Journal of Remote Sensing, vol. 28(24), 2007, pp. 5583–5601. https://doi.org/10.1080/01431160601086050.

[28] Bourjila A., Dimane F., Nouayti N., Taher M., El Ouarghi H.: *Use of GIS, remote sensing and AHP techniques to delineate groundwater potential zones in the Nekor Basin, Central Rif of Morocco*. [in:] *GEOIT4W-2020: 4th Edition of International Conference on IT, Geospatial Technologies and Water Resources in Mediterranean Region: March 11 & 12, 2020, ENSAH, Al Hoceima*, Association for Computing Machinery, New York 2020, art. no. 13, pp. 1–7. https://doi.org/10.1145/3399205.3399219.

[29] Argaz A., Ouahman B., Darkaoui A., Bikhtar H., Yabsa Y., Laghzal A.: *Application of remote sensing techniques and GIS-multicriteria decision analysis for groundwater potential mapping in Souss Watershed, Morocco*. Journal of Materials and Environmental Sciences, vol. 10(5), 2019, pp. 411–421.

[30] Ahmadi H., Kaya O.A., Babadagi E., Savas T., Pekkan E.: *GIS-based groundwater potentiality mapping using AHP and FR models in Central Antalya, Turkey*. Environmental Sciences Proceedings, vol. 5(1), 11. https://doi.org/10.3390/IECG2020-08741.

[31] Taher M., Mourabit T., Etebaai I., Dekkaki H.C., Amarjouf N., Amine A., Abdelhak B., Errahmouni A., Azzouzi S.: *Identification of groundwater potential zones (GWPZ) using geospatial techniques and AHP method: A case study of the Boudinar Basin, Rif Belt (Morocco)*. Geomatics and Environmental Engineering, vol. 17(3), 2023, pp. 83–105. https://doi.org/10.7494/geom.2023.17.3.83.

[32] Ahmed A., Ranasinghe-Arachchilage C., Alrajhi A., Hewa G.: *Comparison of multicriteria decision-making techniques for groundwater recharge potential zonation: Case study of the Willochra Basin, South Australia*. Water, vol. 13(4), 2021, 525. https://doi.org/10.3390/w13040525.

[33] Melese T., Belay T.: *Groundwater potential zone mapping using analytical hierarchy process and GIS in Muga Watershed, Abay Basin, Ethiopia*. Global Challenges, vol. 6(1), 2022, vol. 6(1), 2100068. https://doi.org/10.1002/gch2.202100068.

[34] Singh P., Hasnat M., Rao M., Singh P.: *Fuzzy analytical hierarchy process based GIS modelling for groundwater prospective zones in Prayagraj, India.* Groundwater for Sustainable Development, vol. 12, 2021, 100530. https://doi.org/10.1016/j.gsd.2020.100530.

[35] Kumar M., Singh S.K., Kundu A., Tyagi K., Menon J., Frederick A., et al. *GIS-based multi-criteria approach to delineate groundwater prospect zone and its sensitivity analysis*. Applied Water Science, vol. 12(4), 2022, 71. https://doi.org/10.1007/s13201-022-01585-8.

[36] Ake G.E., Kouame K., Koffi A., Jourda J.: *Cartographie des zones potentielles de recharge de la nappe de Bonoua (sud-est de la Côte d'Ivoire)*. Revue des Sciences de l'Eau – Journal of Water Science, vol. 31(2), 2018, pp. 129–144. https://doi.org/10.7202/1051696ar.

[37] Dar T., Rai N., Bhat A.: *Delineation of potential groundwater recharge zones using analytical hierarchy process (AHP)*. Geology, Ecology, and Landscapes, vol. 5(4), pp. 292–307. https://doi.org//10.1080/24749508.2020.1726562.

[38] Bourjila A., Dimane F., El Ouarghi H., Nouayti N., Taher M., El Hammoudani Y., Saadi O., Bensiali A.: *Groundwater potential zones mapping by applying GIS, remote sensing and multi-criteria decision analysis in the Ghiss basin, northern Morocco.* Groundwater for Sustainable Development, vol. 15, 2021, 100693. https://doi.org/10.1016/j.gsd.2021.100693.

[39] Ikirri M., Boutaleb S., Ibraheem I.M., Abioui M., Echogdali F.Z., Abdelrahman K., Id-Belqas M., Abu-Alam T., El Ayady H., Essoussi S., Faik F.: *Delineation of groundwater potential area using an AHP, remote sensing, and GIS techniques in the Ifni Basin, Western Anti-Atlas, Morocco*. Water, vol. 15(7), 2023, 1436. https://doi.org/10.3390/w15071436.

[40] Echogdali F.Z., Boutaleb S., Bendarma A., Saidi M.E., Aadraoui M., Abioui M., Ouchchen M., Abdelrahman K., Fnais M.S., Sajinkumar K.S.: *Application of analytical hierarchy process and geophysical method for groundwater potential mapping in the Tata Basin, Morocco*. Water, 14(15), 2022, 2393. https://doi.org/10.3390/w14152393.

[41] Hamdani N., Baali A.: *Characterization of groundwater potential zones using analytic hierarchy process and integrated geomatic techniques in Central Middle Atlas (Morocco)*. Applied Geomatics, vol. 12(3), 2020, pp. 323–335. https://doi.org/10.1007/s12518-020-00300-z.