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Research paper

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Identification of potential groundwater zones using the analytical hierarchical process technique: Case study of the region of Constantine – Northeastern Algeria

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Summary

This study presents an integrated approach for identifying groundwater potential zones in the Constantine region, northeastern Algeria, by combining the Analytical Hierarchical Process (AHP) with Geographic Information Systems (GIS). The methodology incorporates a multi-criteria analysis based on seven critical parameters: geomorphology, slope, drainage density, fault density, land use, lithology, and soil types. Each parameter was weighted using the AHP technique to quantify its relative influence on groundwater accumulation. Subsequently, areas were classified into zones of varying groundwater potential, ranging from 'very poor' to 'excellent'.
Field verification was conducted to validate the model's results, demonstrating its effectiveness. Specifically, 80% of the 22 drilled wells in 'good' potential zones were found to exhibit reliable performance and sustainability. In contrast, wells located in areas classified as 'poor' potential

zones were non-performing. These findings highlight the practical reliability of the AHP-GIS methodology in delineating groundwater-rich areas and its potential application in strategic water resource management.

Moreover, the results reinforce the utility of this approach in addressing water scarcity challenges prevalent in arid and semi-arid regions. By accurately mapping groundwater concentration zones, this method offers a valuable tool for resource planners. The study also emphasizes its broader implications, including drought risk mitigation, particularly in regions where sustainable water management is critical for economic and environmental resilience.

Keywords

remote sensing • Constantine • geomorphology • Analytical Hierarchical Process (AHP) • potential of groundwater

1. Introduction

'And we have made water for all living beings' [Surah al-Anbiya, verse 30]. From this point of view, water is the most important element for life, which becomes especially true when water resources decrease, since groundwater provides fresh water for consumption, domestic use, watering and irrigation [Taylor et al. 2013, Agarwal and Garg 2016, Andualem et al. 2019, Roy et al. 2020, Thakuriah 2023, Dali et al. 2023, Rehman et al. 2024]. The irrational use of surface water resulted in its depletion, which in turn has led an hurried search for groundwater, especially in dry and semi-dry areas. In dry areas annual precipitation is low or almost nonexistent [Bhunia et al. 2012, Andualem et al. 2019, Roy et al. 2020, Saranya and Saravanan 2020, Kumar et al. 2022, Derdour et al. 2023, Upadhya et al. 2023]. In such regions, groundwater is the only source of water for consumption, agriculture, industry and other domestic uses [Reddy et al. 1996, Roy et al. 2020]. At the global level, and according to statistics of the year 2022, about 42% of groundwater is directed to the agricultural sector [Mukherjee and Banerjee 2009, Roy et al. 2020, Kumar et al. 2022, Thakuriah 2023, Upadhya et al. 2023, Rehman et al. 2024]. It has been proven throughout history that there can be no economic growth without water, and it has proven that groundwater is the most reliable source of economic growth [Milly 1994, Milly and Dunne 1994, Sehgal 1998, Mukherjee and Banerjee 2009, Roy et al. 2020, Thakuriah 2023, Derdour et al. 2023, Rehman et al. 2024].

In Algeria, water resources are crucial, especially in agricultural areas. Moreover, in Algeria, more than 70% of the rural population depends on groundwater for their needs, while 30% of the urban population [Negm et al. 2020]. The northeastern part of Algeria is experiencing unusual temperatures as well as abnormal irregularities in precipitation. Agriculture in this part of Algeria depends on rainwater. The main problem that this research aims to solve is the difficulty of identifying potential areas for the concentration of groundwater, and another problem is the cost of the search, whether through geophysical roads or searching by drilling, which is very expensive. According to the statistics provided by the Water Resources Bureau of the Constantine province, due to the fact that the province of Constantine relies on the Bani Haroun Dam, the majority of the inhabitants of the Constantine province suffer from a varying degree of water shortage. The crisis in the agricultural sector is even greater because the Directorate of Water Resources does not grant permits to exploit groundwater on the one hand, and the difficulty and cost of research for the farmer on the other. The study area has low water retention capacity, excessive drainage and significant surface runoff. These characteristics contribute to high soil erosion and make the study area very vulnerable to changes in meteorological parameters [Guemmaz et al. 2020]. Studies have shown that the Constantine area is often affected by irregular rainfall and frequent droughts, especially in the summer. Groundwater is the only source of water supply in times of water stress. Therefore, identifying the groundwater in the Constantine region and ensuring their sustainability is necessary to support soil productivity, ensure food crops in cultivated lands and meet domestic needs [Negm et al. 2020, Guemmaz et al. 2020, Saranya and Saravanan 2020, Bouklab et al. 2022, Maizi et al. 2023, Rehman et al. 2024].

To make better use of groundwater research, several methods were used by the researchers to determine potential groundwater areas, such as the logistic regression model and frequency ratio [Mukherjee and Patil 2013, Ghosh and Jana 2018, Roy et al. 2020, Saranya and Saravanan 2020, Bouklab et al. 2022, Derdour et al. 2022, Maizi et al. 2023, Rehman et al. 2024]. In this context, the analytical hierarchical process based on RS and embedded in GIS is considered to be the minimum costly and most effective technology [Sehgal 1998, Mukherjee and Banerjee 2009, Mukherjee and Patil 2013, Roy et al. 2020, Kumar et al. 2022]. Many studies have been conducted worldwide to identify potential groundwater areas [Todd 1980, Roscoe Moss Company 1990]. This is the case with the assessment of groundwater resources in the eastern central desert, Egypt, Burdur, Turkey, Ghana, the Maknassy Basin, Tunisia and the Kurdistan region, Iran, West Bengal (India) and Bangladesh [Patra et al. 2018, Nsiah et al. 2018, Magesh et al. 2012, Singh et al. 2018, Ferozur et al. 2018]. Some studies have been conducted in India by Jasrotia et al. [2016], Kumar et al. [2022] in sub-mountainous regions, [Mallick et al. 2015] in New Delhi [Madrucci et al. 2008] in the Udaipur district, Rajasthan, Paschim Medinipur district, West Bengal [Bhunia et al. 2012, Roy et al. 2020, Derdour et al. 2022, Upadhya et al. 2023] Theni district, Tamil Nadu [Magesh et al. 2012] and Unnao Uttar Pradesh district [Agarwal et al. 2013]. Waikar and Nilawar [2014] used the analytical hierarchical process to identify potential groundwater areas in the Parbhani district of Maharashtra. Ndatuwong et al. [2014] used hydrogeological factors combined with remote sensing and GIS techniques to delineate potential groundwater areas in the Uttar Pradesh Vindhyan Basin. Jaiswal et al. [2003] used these techniques to identify prospective groundwater areas for rural development [Prasad et al. 2008]. The geomorphology and density of lineaments was taken into account by Prasad et al. [2008], Roy et al. [2020] to determine potential groundwater areas in the Nalgonda district, Andhra Pradesh. In India, a micro-scale assessment of potential groundwater areas has been tried with great success. Ibrahim-Bathis and Ahmed [2016] used soil cover, geomorphology, drainage density, slope and lineament density to identify potential groundwater areas in the Krishna watershed [Patra et al. 2018, Nsiah et al. 2018, Magesh et al. 2012, Singh et al. 2018, Ferozur et al. 2018, Roy et al. 2020, Dali et al. 2023]. Similar parameters were used to identify potential groundwater areas in the Bairasagara watershed, Kolar district, Karnataka [Chandra et al. 2006] and Kattankulathur Block in Kancheepuram district, Tamil Nadu [Nagarajan and Singh 2009, Kumar et al. 2022, Thakuriah 2023, Derdour et al. 2023, Upadhya et al. 2023]. A new study was conducted by Singh et al. [2018], Roy et al. [2020], Kumar et al. [2022] to classify potential groundwater areas in the red and laterite areas of West Bengal, India.

To obtain a map of the groundwater centralization areas, which will help identify where wells may be set up and thereby limit research costs through ancient methods is one of the key objectives of these studies. The Constantine region has a large sedimentary basin called Ain Samara, which can be a reservoir of groundwater due to the nature of its geological composition.

In context of lack of studies using this approach in northeastern Algeria, this study is a contribution to the localization of potential groundwater areas based on parameters such as geomorphology, fault density, slope, drainage density, lithology, and soils as determining factors [Vila 1980, Bouillin 1977].

2. Area of study

2.1. Location of study area

The study area is situated in the northeast of Algeria and forms part of the Tell Constantinois region. This region includes the city of Constantine and its surrounding areas [Chadi 1991, Benabbas 2006, Rebouh et al. 2021, Rebouh and Khiari 2022, Rebouh et al. 2024]. Geographically, Constantine is located at approximately 36.23°N latitude and 7.35°E longitude, positioning it centrally within eastern Algeria [Chadi 1991, Benabbas 2006, Rebouh and Khiari 2022].

The city lies 430 km east of the capital, Algiers, 90 km southeast of Skikda, 235 km northeast of Biskra, and 245 km from the Algerian-Tunisian border [Aris 1994]. These distances highlight Constantine's strategic location as a regional hub (Fig. 1A).

2.2. Geology of study area

The study area lies within the Alpine chain of northeastern Algeria, a region marked by complex geological formations and significant tectonic activity. The main geological formations in the area include:

- **Quaternary deposits**: These are primarily composed of wadi alluvium (silt, gravel, and rounded pebbles) and scree, which are extensively developed along the edges of reliefs, such as terraces and glacis with low slopes [Bouillin 1977].
- **Mio-Pliocene formations**: Covering a substantial portion of the study area, these formations consist mainly of red clays [Benabbas 2006, Rebouh et al. 2021, 2022, 2024].
- **Numidian formations**: These formations comprise highly fractured argilo-sandstone units. The sandstones are characterized by their clear appearance at break,

with brown, tawny, or purplish patinas. They are interbedded with thin, less visible clayey layers [Hadjem 2010].

- **Tellian formations**: Predominantly marly and limestone in composition, these formations date from the Senonian to Lutetian periods [Lahondère 1987].
- **Peni-Tellian formation**: This consists of alternating materials ranging from the Lias to the Senonian periods [Vila 1980].
- **Neritic Constantine formation**: This limestone formation defines many of the region's prominent reliefs, including Chettaba, Feltene, Sekoum, Salem, Meimel, Friktia, Garne Chouf, and Toukouia [Raoult 1972].

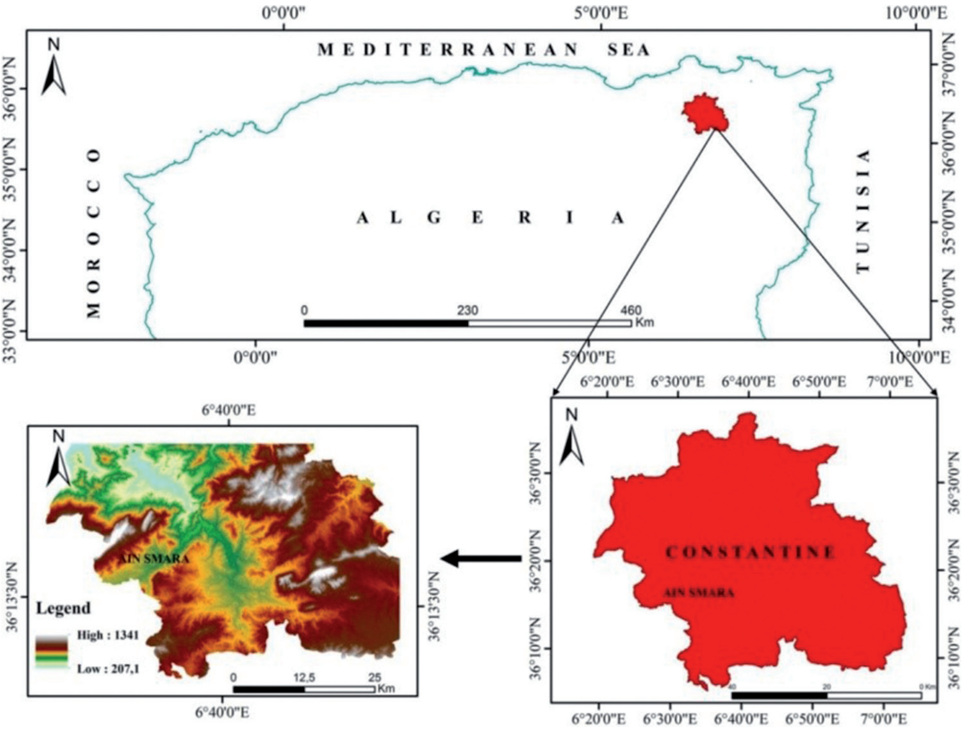

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Fig. 1A. Location of study area

To further contextualize the geological framework, the study analyzed faults and lineaments using data extracted from geological maps and supported by field observations. Geospatial tools such as Geomatica (PCI-LINE) and ArcGIS 10.2 were used to delineate lineaments, which were subsequently classified into four primary orientations: NE-SW, NW-SE, N-S, and E-W.

Statistical analysis using RockWorks 16 generated rose diagrams to illustrate variations in the directional distribution and density of the lineaments. The predominant fault orientations (NE-SW and NW-SE) correlate with active neotectonic structures in the region, particularly in the Constantine, Ain Smara, and Chettaba areas. These orientations align with known tectonic activity within the Tellian Atlas, highlighting zones of stress accumulation that influence groundwater potential through fault-controlled permeability pathways.

Additionally, the N-S orientation, observed predominantly in the Constantine area, underscores the role of tectonic influences in shaping groundwater distribution. The combined analysis of fault orientations and geological formations reveals a significant structural control on groundwater accumulation and distribution within the Constantine region, thereby supporting the delineation of potential groundwater zones.

This integration of geological and tectonic data provides a clearer understanding of how lithological and structural variations influence groundwater potential, offering valuable insights for future resource management in the study area.

3. Data and methods

3.1. Data used

In this study, seven types of thematic maps were utilized, namely geomorphological, lithological, fault, slope, soil, land use, and drainage maps.

The geomorphological, fault density, lithological, and soil maps were derived from existing maps of the study area and through the analysis of satellite data. The slope, drainage, and land use maps were generated using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM) with a 30 m spatial resolution, which was downloaded from the United States Geological Survey Earth Explorer platform (earthexplorer.usgs.gov). The land use map was specifically created using LandSat OLI8 images.

The selection of criteria for assigning ranks in this research was informed by the geological characteristics of the study area. Among these criteria, geomorphological factors are deemed the most influential, as demonstrated in studies by Roy et al. [2020] and Thakuriah [2023]. Lithology, regression, and soil type hold slightly less significance compared to geomorphology, a hierarchy supported by findings from previous studies [Agarwal et al. 2013, Roy et al. 2020].

Land use and land cover were ranked lower than the aforementioned criteria, as these factors have been shown to exert a relatively lesser influence on groundwater potential, as indicated in studies by Nag and Kundu [2016] and Roy et al. [2020] Drainage density occupies the lowest rank among the criteria due to its inverse relationship with groundwater potential. High drainage density in the study area reduces infiltration capacity, thereby limiting groundwater potential compared to areas with lower drainage density [Nag and Kundu 2016, Roy et al. 2020, Thakuriah 2023].

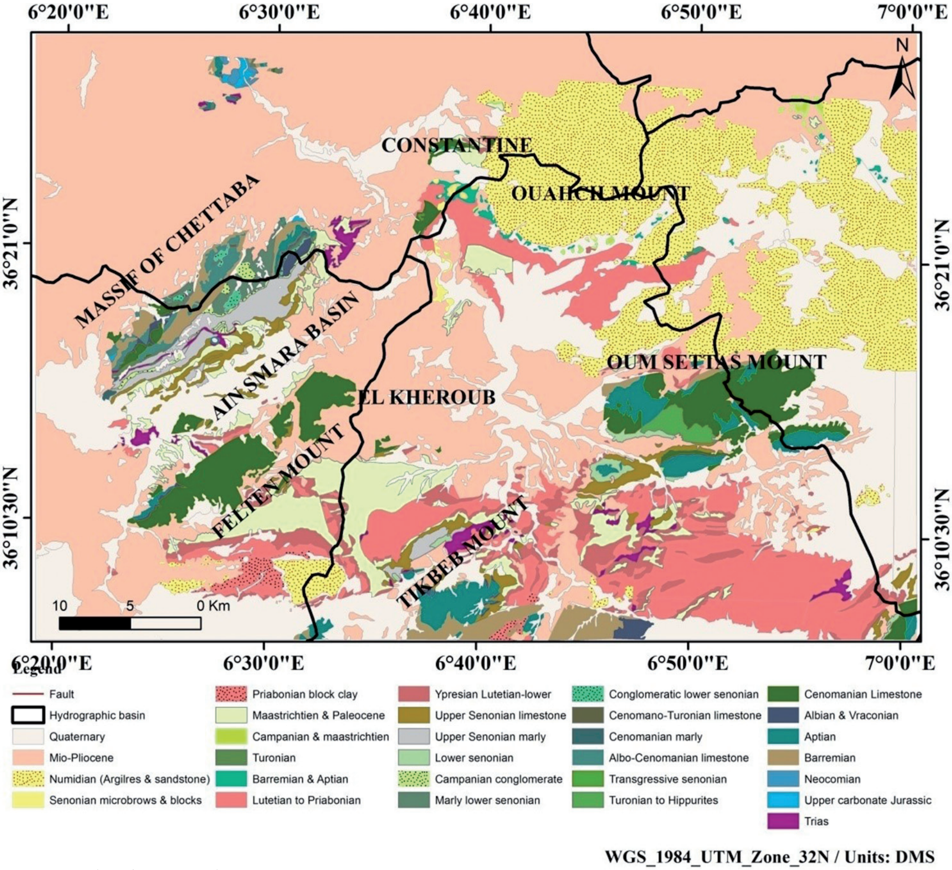

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Fig. 1B. Geology of study area

3.2. Assignment of ranking and weighting

The map of potential groundwater areas was developed by integrating all spatial layers using the weighted overlay method. Prior to the overlay, the spatial layers were uniformly reclassified on a scale from 1 to 5, where 1 represents very low groundwater potential, and 5 represents excellent potential [Krishnamurthy et al. 1996, Saraf and Choudhury 1998, Waikar and Nilawar 2014, Saranya and Saravanan 2020].

Weighting values for each layer were determined using a pairwise comparison matrix based on the analytical hierarchical process (AHP) technique (Table 1). These rankings were assigned according to the parameters, taking into account field observations, stakeholder consultations, expert opinion surveys, and a review of existing studies and reports.

Among the parameters, geomorphology and fault density were given the highest weights, reflecting their significant influence on groundwater potential. Moderate weights were assigned to slope, lithology, and soils, while land use and drainage density were given lower weights (Table 2). After weighting the parameters, individual rankings were assigned to the sub-variables associated with each parameter [Butler et al. 2002, Asadi et al. 2007, Yammani 2007, Saranya and Saravanan 2020, Thakuriah 2023].

Finally, the maximum values were used to characterize areas with the highest groundwater potential, while the minimum values indicated areas with the lowest potential.

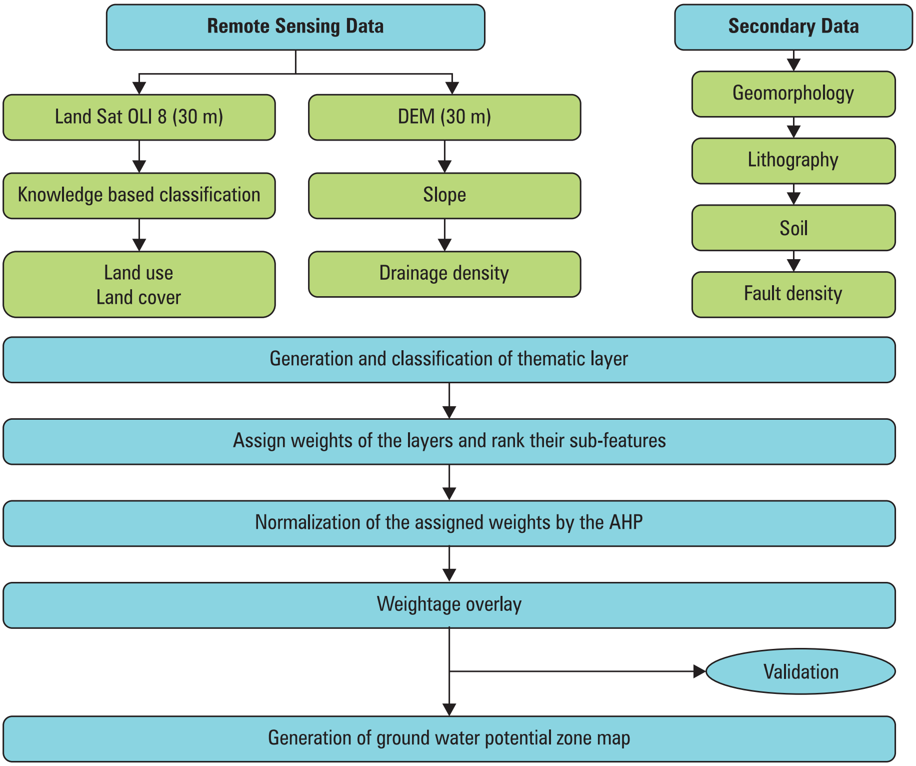

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Fig. 2. Flow chart of methodology

Table 1. Normalized pairwise comparison matrix (seven layers) developed for AHP based groundwater potential zoning

Factors	Geomorphology	FD	Lithology	Slope	Soil	Lu-Lc	DD	Weight
Geomorphology	7	6	5	4	3	2	1	**0.38**
Fault density	7/2	6/2	5/2	4/2	3/2	2/2	1/2	**0.19**
Lithology	7/3	6/3	5/3	4/3	3/3	2/3	1/3	**0.12**
Slope	7/4	6/4	5/4	4/4	3/4	2/4	1/4	**0.10**

Soil	7/5	6/5	5/5	4/5	3/5	2/5	1/5	**0.08**
Lu-Lc	7/6	6/6	5/6	4/6	3/6	2/6	1/6	**0.066**
DD	7/7	6/7	5/7	4/7	3/7	2/7	1/7	**0.064**
Total								**1**

Table 2. Weights assigned for different groundwater control parameters in the study

Factors	Weight	Rank	Over all
Geomorphology			
Alluvial plain	38	5	190
Valley fills		4	152
Buried pediment moderate		3	114
Mud flat		2	76
Structural hills		1	38
Fault density			
Very high	19	5	95
High		4	76
Medium		3	57
Low		2	38
Very low		1	19
Lithology			
Fluvial	12	4	48
Limestone		3	36
Sandstone		2	24
Clay		2	24
Slope			
0–1	10	5	50
1–2		4	40
2–3		3	30
3–5		2	20
>5		1	10

Table 2. cont.

Soil			
Alluvial soils	8	5	40
Limestone soils		4	32
Limestone and solonetz soils		3	24
Podzolic soils		2	16
Unsaturated soils		2	16
Limestone rocks		1	8
Lu-Lc			
Fallow land	6.6	5	33
Vegetation		4	26.4
River		3	19.8
Build-up land		2	13.2
Agricultural land		2	13.2
Drainage density			
Very high	6.4	1	6.4
High		2	12.8
Medium		3	19.2
Low		4	25.6
Very low		5	32

4. Results

The Analytical Hierarchical Process (AHP) is a robust multi-criteria decision-making tool that enables the ranking of variables by their relative importance, which is essential when assessing groundwater potential across a region. In this study, AHP has been employed to prioritize geographical factor such as geomorphology, fault density, slope, drainage density, lithology, land use, and soil types that directly influence groundwater availability and distribution. Each parameter was weighted according to its influence on groundwater potential, allowing for a precise classification of zones based on these factors. AHP derives a detailed map that categorizes the study area into zones of varying groundwater potential: 'excellent,' 'good,' 'fair,' 'poor,' and 'very poor.' These classifications, defined in geographic terms, highlight areas with the highest likelihood of groundwater reserves based on the interaction of local geological structures and geomorphological features. For instance, areas with high fault density and specific lithological compositions, such as permeable alluvial plains and fault-aligned valleys, are identified as having higher groundwater potential. Conversely, regions characterized by high slope gradients and low drainage density typical of structurally elevated landforms – are classified as lower-potential zones due to limited infiltration and high runoff.

4.1. Geomorphology

The geomorphology of the region of Constantine is influenced by the neritic relief, the specific limestone lithology and the structure of the slumping basins, which are filled with Mio-Pliocene Quaternary deposits. In turn, these factors significantly control the potential and perspective of groundwater (Fig. 3).

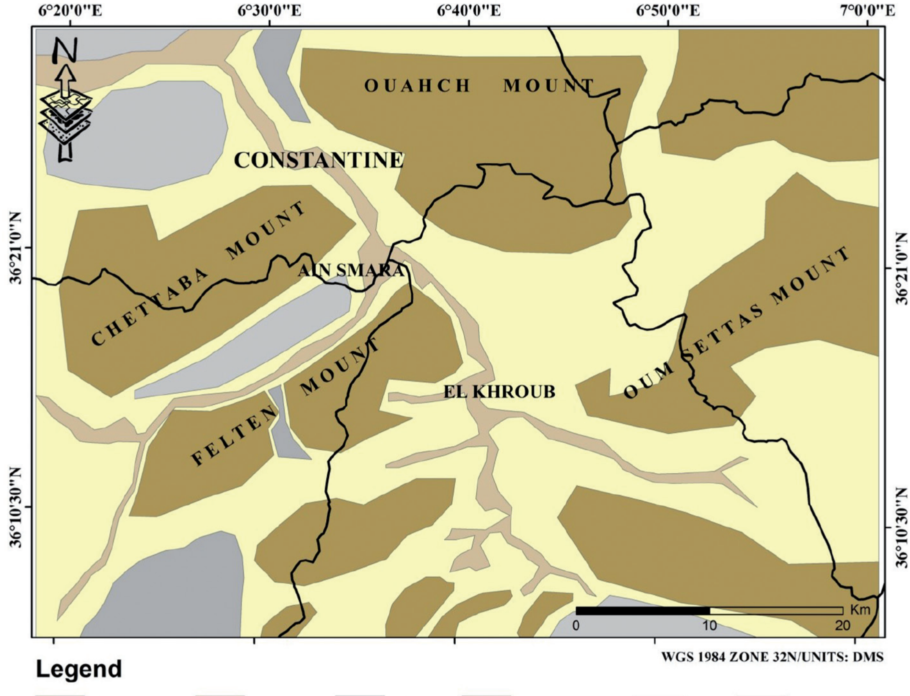

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Fig. 3. Geomorphological map of the study area

4.1.1. Alluvial plain

The alluvial plain in the study area is formed by alluvial deposits. It is originally followed the stream of Oued Rhumel. The position of the stream and its alluvial load varies in space and time. As a result, they occupied considerable surfaces.

4.1.2. Valley falls

These are areas occupied by non-detritic sediments and colluviums from mountainous terrain. The soil in this area has a fine to clay silt appearance with a fine texture, and os moderately well drained due to moderate humidity. The filling of these valleys is highly suitable for monoculture.

The study area is characterized by very good porosity and permeability, but sometimes the presence of clay acts as an impermeable layer.

4.1.3. Buried pavement (moderate)

The slope of the moderate buried pavement is gentle. Moderately deep clay soils with fine silts with a fine texture have been observed in the relief. Groundwater prospects are also moderate in this region.

4.1.4. Mudflat

Mudflats are present in a few localities of the study area where fine materials are deposited – they can store various associated substances. Mudflats are always located in areas of water availability, which is also characteristic of large estuaries.

4.1.5. Structural reliefs and hills

These are large rocky reliefs and vast rocky plateaus with perceptible elevation. A very shallow coarse calcareous and silty soil was observed. It is mainly covered with dense forests and plantations and is not suitable for agriculture or orchards. Structural hills act as high runoff areas due to hilly slopes, resulting in poor infiltration mainly due to moderately steep and very steep hillsides.

4.2. Fault density

The faults are obtained from the geological map of the Constantine region in addition to our field observations. Lineaments are extracted automatically using the main component (PC1). The extraction was done with the Geomatica software (PCI-LINE), then ArcGIS 10.2 (modification, division etc.). Statistical analysis of the data by the RockWorks 16 software allows us to create the rose diagram and to evaluate the difference in direction and density of the lineaments. The lineaments in this study are grouped into four orientations as follows: NE-SO, NO-SE, N-S. The predominant direction is the active fault direction of study area of Constantine, Ain Smara and Chettaba. The mean directions NE-SO and NO-SE indicate the neotectonic structures of the terrestrial atlas; in the end, the direction N-S is largely answered in the Area of Constantine (Fig. 4) .

4.3. Lithology

In the region of Constantine, the lithology of the lands is distributed in four types which are: clay, sandstone, limestone, river deposits (Fig. 5).

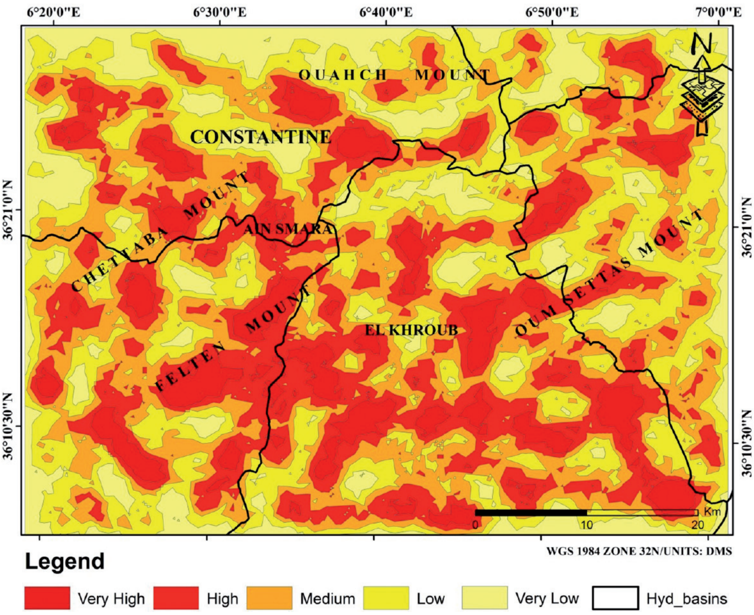

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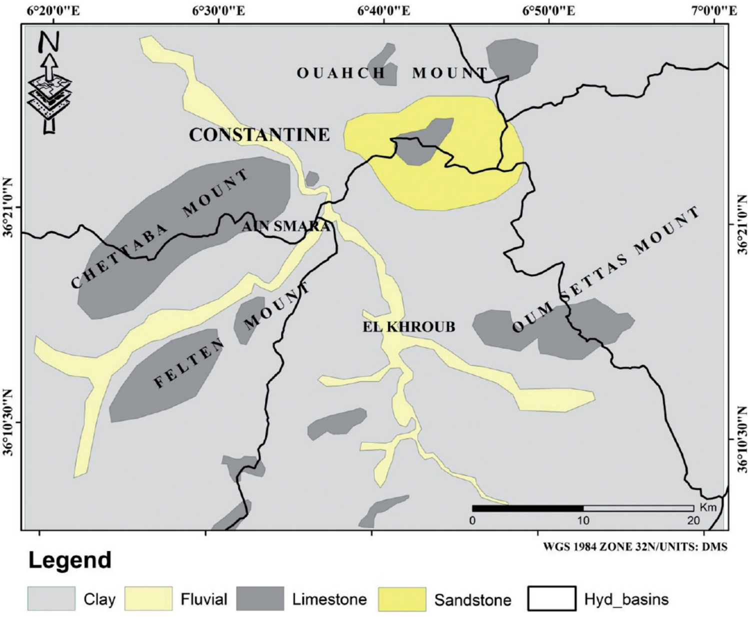
Fig. 4. Lineament density map of the study area



Source: Authors' own study

Fig. 5. Lithology map of the study area

4.4. Slope

Topographical contrasts such as steep slopes, ledges of terraces, isolated hills and mountainous reliefs have high slopes (Fig. 6). The analysis of the numerical terrain model and the distribution of slopes according to the average slopes, and of the lithology in the region of Constantine allows the following conclusions to be drawn:

- From < 10%, of slope, the lowest. Areas corresponding to this morphology of low inclination.
- From 10 to 20%, low-grade land is found in the northeast and southeast of the study area.
- From 20 to 30%, this category is occupied the southern part and a northern part of the study area.
- From 30 to 40%, this category is scattered throughout the study area.
- > 50, it occupies most of the study area. The steepest areas in the study area are at slopes greater than or equal to 50%.

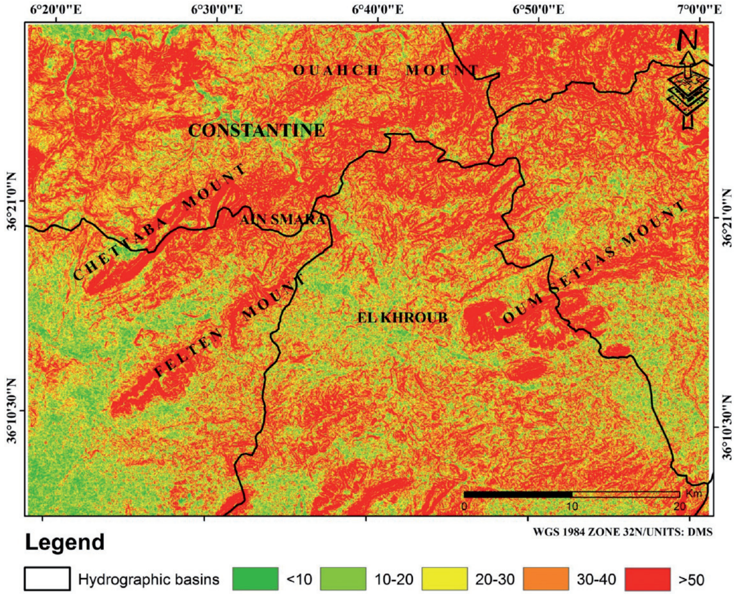


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Fig. 6. Slope map of the study area

4.5. Soils

Several soil types were encountered in the study area, including (Fig. 7):

- The podzolic soils in the eastern part at the level of the Djebel Ouahch on sandstone and Numidian clays.

- Unsaturated soils with a single horizon near Djebel Oum Settas, less permeable.
- Calcareous soils with halomorphic soils that occupy the northern part of the study area. In djebel Ouahch limestone and sandstone are located in high areas.
- The alluvial soils of Oued Rhumel and Oued Boumerzoug have a silty-sandy texture and are well drained.

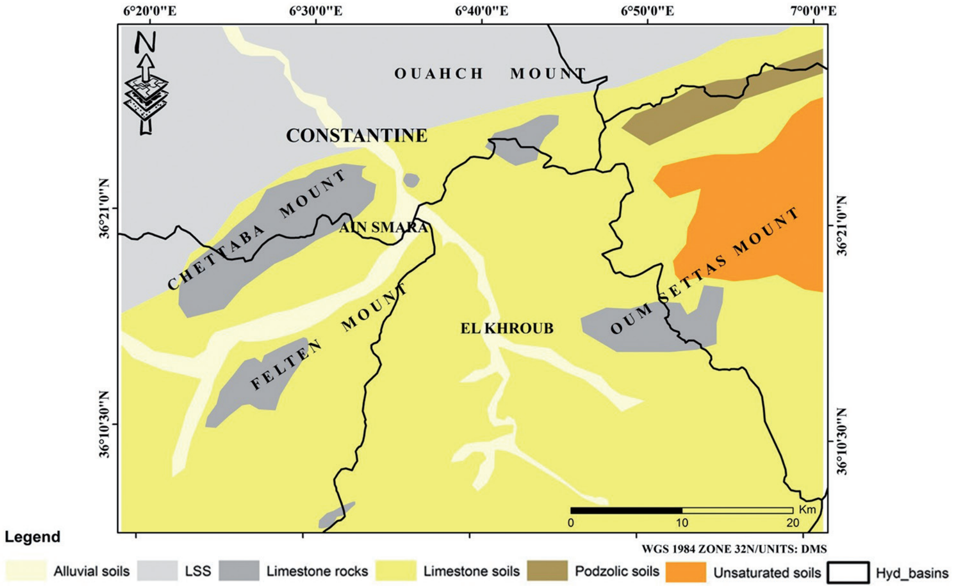

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Fig. 7. Soils map of the study area

4.6. Land use/land cover

Land use/land cover plays an important role in controlling groundwater resources. In forested and agricultural lands, runoff is generally lower and infiltration is greater, whereas in paved and inhabited areas, infiltration rates usually decrease. As a result, agricultural land with high vegetative cover has a high ranking, while pavement and stands have a lower ranking. Land use in the study area is as follows: fallow land, covering 1520.41 km^2 (53.05%), forests and vegetation 515.88 km^2 (18.80%), agricultural land 249.34 km^2 (8.70%), buildings 386.91 km^2 (13.50%) and streams 170.52 km^2 (5.95%) (Fig. 8).

4.7. Drainage density

In hydrogeology, drainage density expresses distance and proximity to different streams, as well as the physical properties of the surface. Determining the density and type

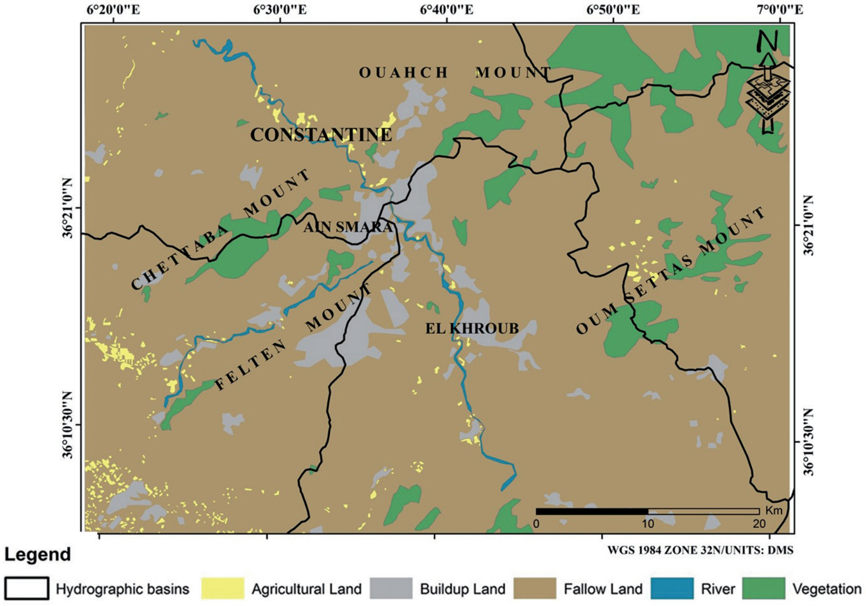

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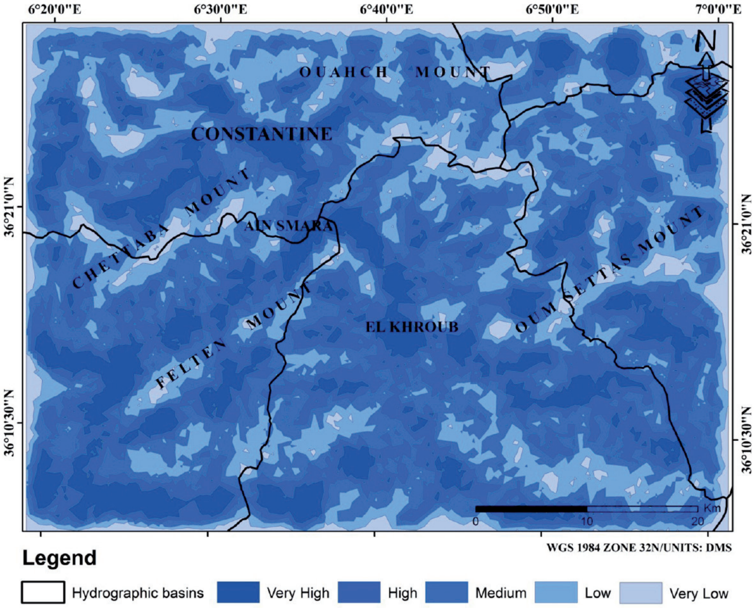
Fig. 8. Land use/Land cover map of the study area



Source: Authors' own study

Fig. 9. Drainage density map of the study area

of drainage provides information directly related to runoff, infiltration, and permeability. Each type of drainage gives information on the surface materials and the composition of the underlying soil, dendritic drainage refers mainly to homogeneous rocks. As for the grating, rectangular and parallel drainage patterns, they refer to structural and rock controls. The higher drainage density value results in higher surface runoff, resulting in the potential for groundwater depletion. Therefore, a high ranking is assigned to the area with low drainage density. In our study area the highest drainage density is located in the central, southern and western parts, where Oued Rhumel and Oued Boumerzoug are located (Fig. 9).

5. Discussion

5.1. Groundwater potential zones

The integration of seven thematic layers – geomorphology, lineament density, lithology, soils, slope, land use/land cover, and drainage density – into a geographic information system (GIS) facilitated the development of a comprehensive groundwater potential map [Fohrer et al. 2001, Weng 2012, Roy et al. 2020, Thakuriah 2023] (Fig. 10). The groundwater potential areas were classified into five distinct categories: 'Excellent,' 'Good,' 'Fair,' 'Poor,' and 'Very Poor,' which correspond to a scale from 1 to 5.

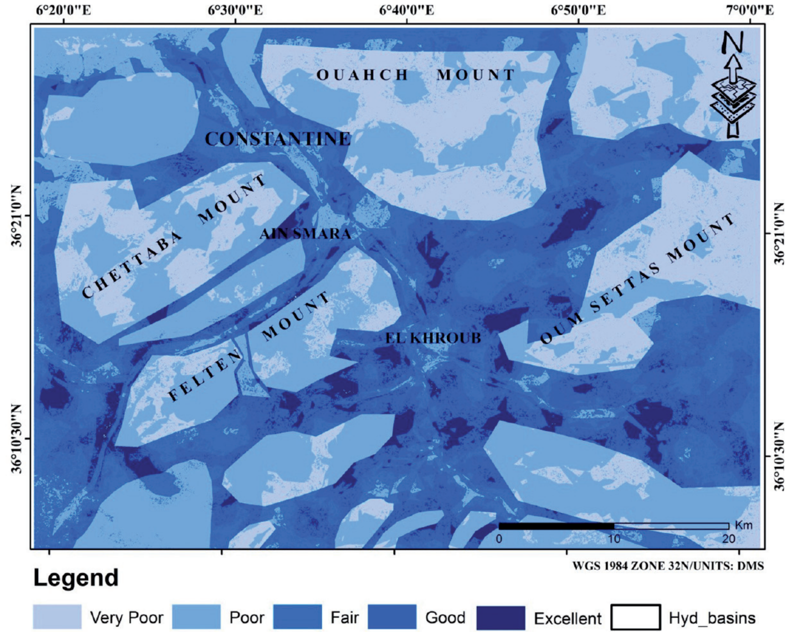
In the study area, the 'Very Poor' and 'Poor' zones are distributed randomly, covering 828 km² and 700 km², respectively, accounting for approximately 28.89% and 24.42% of the total area. This distribution likely correlates with steep slopes and unique geomorphological conditions. Conversely, the 'Fair' zones span roughly 415 km², representing 14.42% of the area. The 'Good' zone encompasses 627.5 km², or 21.87% of the total area, characterized by gentle slopes, low drainage density, high lineament density, and favorable geomorphological forms. Finally, the 'Excellent' zone, though limited to 295.5 km² (10.31%), indicates optimal groundwater conditions.

Recent studies have demonstrated that morphology, fault density, lithology, and soil characteristics are critical parameters for effectively identifying groundwater potential [Patra et al. 2018, Nsiah et al. 2018, Magesh et al. 2012, Singh et al. 2018, Ferozur et al. 2018, Fohrer et al. 2001, Weng 2012, Roy et al. 2020, Thakuriah 2023]. In our study, the use of seven thematic layers geomorphology, lineament density, lithology, soils, slope, land use, and drainage density aligns with these findings [Sener et al. 2005, Gumma and Pavelic 2013, Rahmati et al. 2015, Ferozur et al. 2018, Roy et al. 2020, Thakuriah 2023]. The GIS framework developed allowed for a comprehensive delineation of groundwater potential areas [Nag and Kundu 2016, Roy et al. 2020, Arabameri et al. 2021, Thakuriah 2023].

What sets our results apart from previous studies is twofold: first, the comprehensive array of parameters utilized for analysis, and second, the enhanced accuracy in assessing groundwater potential. This accuracy is substantiated by the validation of field data discussed in the subsequent section.

To address the reviewers' concerns regarding the statistical significance of our findings, we employed rigorous statistical analyses to evaluate the performance of our groundwater potential model. Specifically, we compared our results with benchmarks from similar studies, including [Das et al. 2022, Saha et al. 2024, Abdo et al. 2024, Bhakta et al. 2024]. This study investigates groundwater potential zones in relation to settlement and agriculture, providing additional context for our findings.

By comparing our results to these benchmarks, we can confirm that our assessment of groundwater potential is statistically significant and holds relevance within the broader context of existing research. These comparisons highlight the robustness of our approach and the reliability of our findings, contributing valuable insights into groundwater management in the Constantine region.



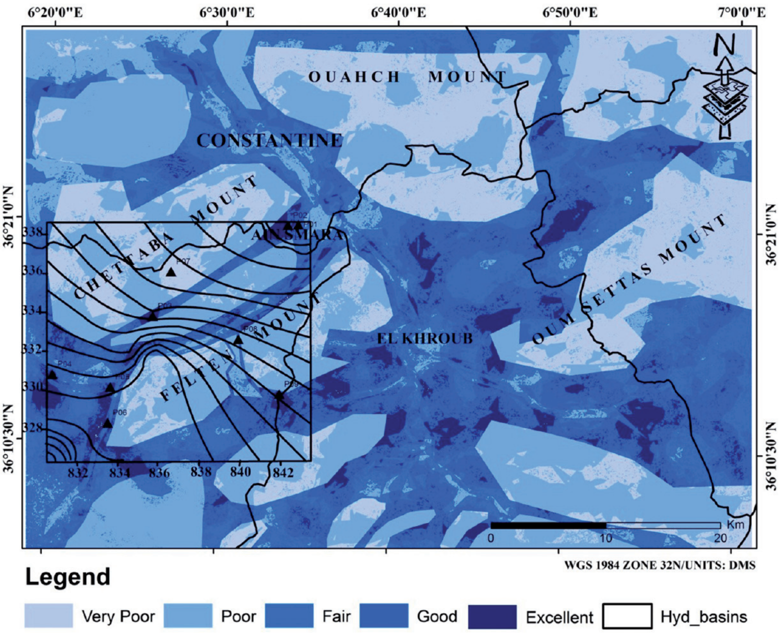
Source: Authors' own study

Fig. 10. Groundwater potential zones map of the study area

5.2. Validation of groundwater potential zones

According to the work of [Rabahi 2008], dug wells and boreholes confirm the availability of groundwater. The following piezometric map shows the potential of the water in each well and borehole, confirmed by the 9 pumping tests (Fig. 11).

The inventory and mapping of water points is the preliminary AHP of any regional groundwater research plan. On the inventory map we have materialized a set of boreholes, wells and sources [Rabahi 2008].



Source: Authors' own study

Fig. 11. Validation map of groundwater potential zones map

The 9 boreholes exploit deep aquifer levels. They are intended for the water supply of the Ain Smara SONACOME complex [Rabahi 2008].

A few sources have returned to our field of study, their flows remain low, some emerging in the Cretaceous massifs, and others in the plains. Most are captured and used for drinking water supply [Rabahi 2008].

There are 14 wells inventoried. They exploit the overlying aquifer (wells that rarely exceed 20 m depth). Most of these wells are located on the banks of the Oueds Seguin and Rhumel [Rabahi 2008].

5.3. Characteristics of the pumping test P9

Subsequent pumping tests were conducted for 296 hours, with the following results per step [Rabahi 2008]:

- 22.5 l/s for 61.0 hours,
- 29.5 l/s for 77.0 hours,
- 34.0 l/s for 92.0 hours,
- 35.0 l/s for 66.0 hours.

The water table level during the pumping tests with a flow rate of 35 l/s shows a tendency towards a gradual lowering. The process of lowering the water table level showed, during pumping at this level, fairly regular variations with an amplitude of 5 cm per day [Rabahi 2008].

The piezometry plot showed that the general groundwater flow is towards the north-east with an underground supply in general south-west – north-east direction and with a variable hydraulic gradient of up to 6.6% [Rabahi 2008].

The piezometric map shows that the overlying aquifer (Moi-Plio-Quaternary) is fed by the massifs surrounding especially the Cretaceous massifs of Djebel Felten, from tectonic accidents oriented NE–SW [Rabahi 2008].

The aquifer in the Karst (Middle Cretaceous, Maestrichtian) strata with its unstable hydrodynamic characteristics did not allow us to make a mathematical evaluation or a graphical resolution of the hydrodynamic parameters [Rabahi 2008].

6. Conclusions

The socio-economic development and long-term sustainability of agriculture is directly related to the integrated use of groundwater. In the region of Constantine and its surrounding areas, groundwater is widely used for the various needs of the population. The identification of potential groundwater areas will reduce the cost of research, especially by peasants. And also reducing research time, and here is the importance of this study. The primary importance of this study is to rely on groundwater in areas that are not provided with water coming from the Bani Harun Dam. This will improve the management of water resources in the Constantine region. This study will also benefit those interested in using it in other special dry and semi-dry areas. In Its agricultural land irrigation is based mainly on precipitation, water from dams, and dug wells. During the dry months, the groundwater is used in a way that is driven by irrational consumption. Our study is a contribution to the identification of potential groundwater reservoirs in the province of Constantine and its surrounding areas by the analytical hierarchical process method with the integration of ENVI and GIS. The objectivity of the resulting map has been confirmed by several previous studies in the region, such as the study of Rabahi [2008], as well as by most hydrogeological projects completed in the region. The map of potential groundwater areas can be used to identify places with a high concentration of water for the construction of wells, and so on, to avoid places with a weak concentration of water. The groundwater potential for the Constantine area and its surroundings has been classified into five following classes: Excellent, Good, Fair, Poor and Very Poor (whose groundwater potential areas are randomly distributed over the study area). Very Poor areas cover 28.89% of the total area, while Poor areas – 24.42%. Fair zones cover about 14.42. Good zones have a percentage of 21.87%, and the Excellent zones are 10.31%.

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