ECOLOGICAL ENGINEERING
& ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(8), 12–27
https://doi.org/10.12912/27197050/205342
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.04.20
Accepted: 2025.07.17
Published: 2025.08.01

Groundwater quality assessment using multivariate analysis, geostatistical modeling and water quality index: Case study – Laghouat city, Algeria

Samira Harrat[1], Oulad Naoui Noureddine[2*], Cherif El-Amine[1], Djehiche Abdelkader[3]

[1] Laboratory of Water Management and Treatment, University of Sciences and Technology of Oran, POBox 1505, Bir El Djir, 31000 Oran, Algeria
[2] Materials, Energy Systems Technology and Environment Laboratory, Department of Hydraulic and Civil Engineering, University Ghardaia, Algeria
[3] Department of Civil Engineering, Faculty of Civil Engineering and Architecture, Amar Telidji University, P. O. Box 37.G, 03000 Laghouat, Algeria
* Corresponding author's e-mail: ouladnaouinoureddine.pub@gmail.com

ABSTRACT

In Laghouat city, groundwater is the only resource responsible for meeting drinking water needs, and given a fairly significant population growth in the study area, the concerns about the change in quality and quantity of water in this region were raised. This scientific research aimed to determine the current state of groundwater quality in the Barremian, Mio-Plio-Quaternary located in Laghouat city. Samples from thirty-five groundwater drilling points located in this region were collected and analyzed during the low water period (August 2019) to identify the characteristics of the main physicochemical parameters, using the water quality index as an indicator to assess the groundwater quality of this study area. These parameters were integrated into the GIS software to create a spatial distribution map for each parameter. Statistical analysis of the data was performed using principal component analysis in XLSTAT 2014.5.03. The synthesis of the analyses obtained shows that these analyzed waters are very hard, The WQI calculation shows overall that 51.43% of the groundwater samples have poor quality, 48.57% of the groundwater samples have good quality. In Barremian area, both of composites Ca^{2+},Mg^{2+}, Na^{+}, Cl^{-} and SO_4^{2-} are intensely associated with TDS, EC and TH, whereas TDS and EC are strongly connected with Ca^{2+}, Na^{+}, K^{+} and Cl^{-} regarding Mio-plio-Quaternary. These values indicate that the mineralization is mainly related to sulfates and chlorides as well as other elements. The high hardness can be explained by the chemical nature of these waters and the contact with geological formations, and the intense evaporation that characterizes the arid climate of the region. The poor quality of the analyzed waters is probably due to the poor sealing of the sanitation network in this city, and the effect of wastewater discharged at the level of Oued M'zi, deserving good monitoring and sustainable management.

Keywords: groundwater, rock water, water quality index, Barremian, mio-plio-quaternary, Laghouat.

INTRODUCTION

In recent years, much research has focused on the quantity and quality of groundwater or surface water resources in semi-arid and arid areas (Khan et al., 2020 ; Azlaoui et al., 2021 ; Ait-Mohamed Amer et al., 2021). Thus, the study and knowledge of groundwater quality is essential, especially in arid regions (Hajji et al., 2018; Barkat et al., 2023; Chabour et al., 2021) like Laghouat city, whereas groundwater is the only water supply source. Moreover, population growth in this city (study area) requires excessive exploitation of this source which leads to quality degradation and insufficient water supply, whereas this valuable source is available to decision makers on water resources. In parallel, a sustainable management and continuous assessment of monitoring the quality and quantity of water in this city is recommended to ensure the protection of human health and environment. In addition, the knowledge of the factors (Brahmi et al., 2021; Kallel et al., 2018; Hammam et al., 2023) involved in the degradation of groundwater quality and presenting a risk to public health is essential. This study aimed to determine the geochemical characteristics of groundwater by analyzing the main physicochemical parameters in order to assess quality based on the water quality index (proposed by Brown et al., 1972) that provides useful information to managers of water resources (Pasha et al., 2023; Thabit et al., 2023) on the current state of groundwater quality, contaminated areas, causes of water quality degradation (Sekkoum et al., 2020).The aim of this work is to adapt preventive measures to protect and sustainably manage groundwater resources, so according to this research, several results were mentioned. Calculation of the quality index Water (Lekrine et al., 2023; Mohamadi et al., 2021; Derdour et al., 2023) shows that most groundwater samples have good quality located in the eastern part of the city of Laghouat. On the other hand, the rest of the groundwater samples are of poor quality located in the western part, this latter result due primarily to free discharges of wastewater into the water table (the existence of lost wells) the weak watertightness of the sewerage system in this city. It is a tool to adapt a spatial and temporal follow-up to mention other fields for capturing drinking water and to launch a control and continuous monitoring to protect the eastern part of the study area from any risk of contamination.

APPROACH AND METHODOLOGY

Study area

With 25,052 km^2 of covered surface, Laghouat is an Algerian province whereas Saharan Atlas range crosses this city. It is part of the central highlands group, composed of the three departments of Djelfa, M'Sila and Laghouat. It is bounded to the north by the mountain range and Boukhour city to the south, Bourdj Snouci to the east and El Kheneg to the west (Figure 1) meteorological data such as rainfall is less than 200 mm, and evaporation are very important. This means that the temperature can rise to 50 degrees Celsius in summer and drop slightly below 20 degrees Celsius in winter. Thus, it has an arid climate. It also has the largest natural gas field in Africa with a reserve estimated at several billion cubic meters.

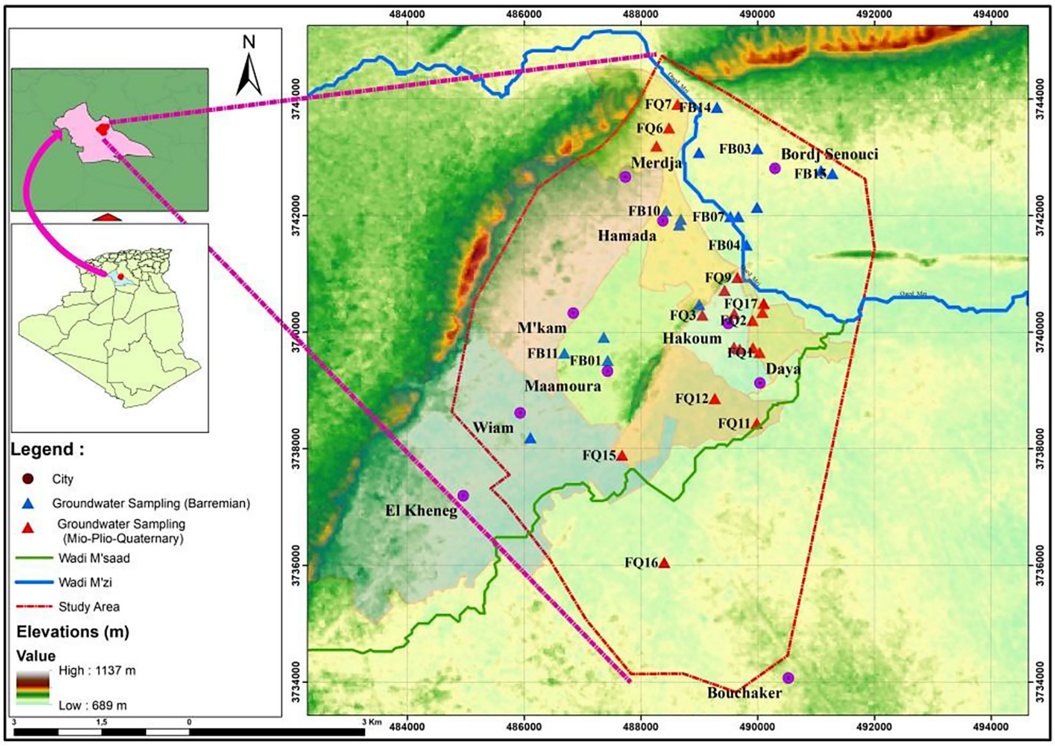


Figure 1. Location of study area

Geological settings

Laghouat territory extends over two clearly different geological areas, particularly in terms of structure and geological evolution, namely the Saharan Atlas to the north and the Saharan platform to the south. The department has a bedrock of sedimentary rocks dating from the secondary and tertiary, Quaternary and Cretaceous. The geological map at 1/20000 (Figure 2) shows that the predominant formations are essentially of secondary age. The tertiary and quaternary formations occupy the valley bottoms and depressions. The lithological succession observed in the Saharan Atlas is as follows, from bottom to top.

Sampling and analysis

In the town of Laghouat, a total of 35 samples of groundwater for human consumption were selected to ensure uniform distribution throughout the study area (Figure 1), the aim was to assess the quality of this resource which is the main source of drinking water supply. The sample is taken after a prolonged pumping (15 to 20 minutes), the samples are collected in sterile bottles rinsed with distilled water and then with water for analysis (Figure 3a). Physical parameters, such as temperature, pH and electrical conductivity (EC) were recorded instantly on site using a HANNA Instruments HI98127. Transport was carried out in a cooler which

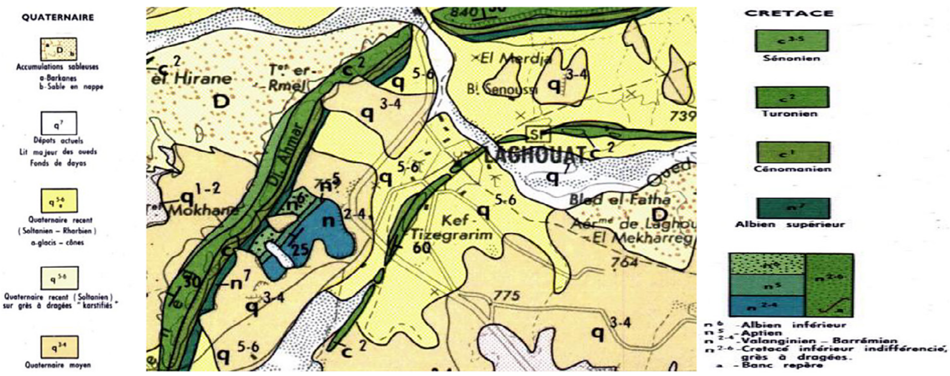


Figure 2. Geological map of the study area, (Extract from the geological map of Laghouat au 1/20000)

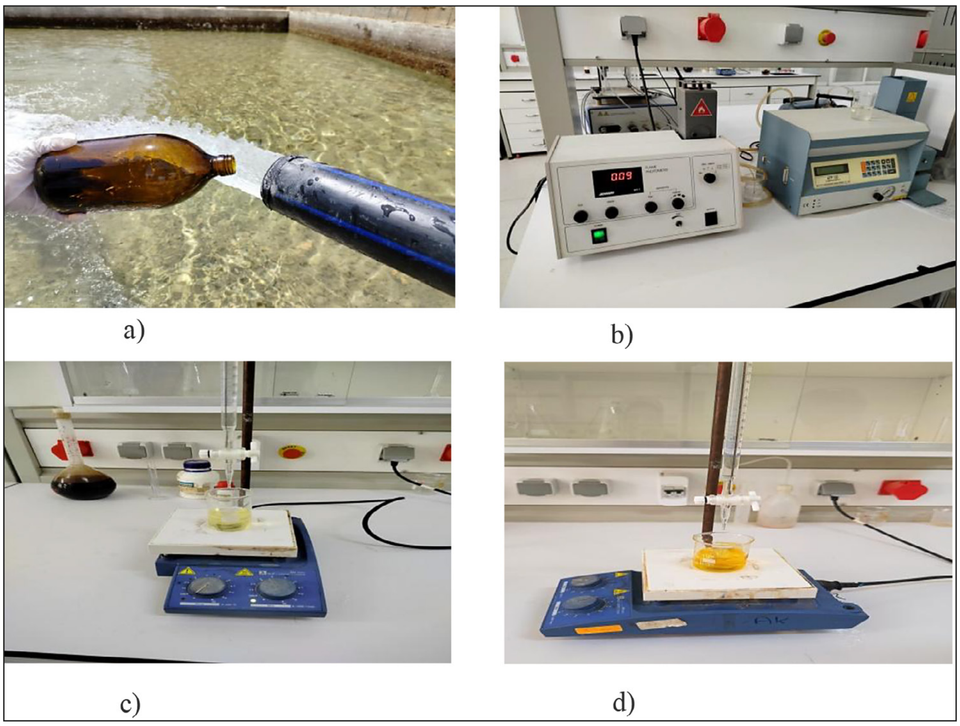


Figure 3. Experimental photo (a) sample collection, (b) sodium dosage, (c) chloride dosage, (d) bicarbonate dosage

ensures good preservation of the samples. The experimental stage was carried out in the laboratory of water analyses in the Algerian Waters Supply Service (AWSS) of Laghouat city. The methods of analysis used are taken from Rodier in 2009: major parameters such as total duration, calcium and magnesium were determined in the Algerian water laboratory (AWSS) by the complexometric method at EDTA, and sodium and potassium were analysed by the JENWAY PFP7 flame spectrophotometer (Figure 3b). The chlorides were measured (Figure 3c) by the Mohr method, bicarbonate by titrimetry with sulfuric acid (Figure 3d), and nitrate by spectrophotometry. The quality control of analytical data was performed by regularly analyzing blanks, duplicates and standards, and checking for ionic balances. The ion charge balance error was less than 5%. The interpretation of the results is based on Algerian standard quality standards (JORADP, 2011) and World Health Organization standards (WHO, 2011).

Water quality index

The quality index is one of the most effective tools for obtaining a complete picture of water quality, it is a mathematical instrument used to transform large quantities of water characterization data into a single number that expresses the overall water quality at a certain location and time (Tyagi et al., 2013; Singh et al., 2013; Tiwari et al., 2018). The quality index is calculated according to the following steps: relative weight wi is mathematically represented as follows

$$Wi = \frac{w_i}{\sum w_i} \quad (1)$$

where: W_i – the relative weight, w_i – the weight for each parameter, allocated according to its relative importance in the overall quality of water for consumption. The maximum weight of 5 was assigned to such parameters as nitrate, total dissolved solids, chloride, and sulfate because of their major importance in the assessment of water quality (Srinivasamoorthy et al., 2014).

Bicarbonate receive the minimum weight of 1 because they play an insignificant role in the assessment of water quality. Other parameters, such as calcium, magnesium, sodium and potassium were weighted between 1 and 4 depending on their importance in determining water quality (Table 1). In the second step, the water quality assessment scale is determined as follows:

$$q_i = \frac{C_i}{S_i} \times 100 \quad (2)$$

where: q_i – the water quality assessment scale, C_i – this is the concentration of each chemical parameter in each water sample in mg/l, S_i: this is the drinking water standard for each chemical parameter in mg/l according to World Health Organization guidelines (2011).

The *SI* is first determined for each parameter as follows:

$$SI_i = W_i \times q_i \quad (3)$$

The final step the calculation of the *WQI*:

$$WQI = \sum SI_i \quad (4)$$

The following Table 2 gives the quality index classification ranges.

Table 1. Weight and relative weight of each parameter for the study area

Parameter	WHO (2011)	Algerian standards (2011)	Weight (w_i)	Relative weight (W_i)
pH	6.5–8.5	6.9 < pH < 9.0	4	0.105
Conductivity (μS/cm)	1000	2800	4	0.105
TDS (mg/l)	500	No-Limit	5	0.132
Calcium (mg/l)	75	200	2	0.05
Magnesium (mg/l)	50	150	2	0.05
Sodium (mg/l)	200	200	3	0.08
Potassium (mg/l)	12	12	2	0.05
Chloride (mg/l)	250	500	5	0.132
Sulfates (mg/l)	250	400	5	0.132
Nitrates (mg/l)	50	50	5	0.132
Bicarbonates (mg/l)	120	No-Limit	1	0.03
			$\Sigma w_i = 38$	$\Sigma w_i = 1$

Table 2. Water quality classification ranges and types of water based on WQI values (Tiwari et al., 2018; Ibrahim., 2019; Azlaoui et al., 2021)

Range	Type of water
< 50	Excellent water
50–100	Good water
100–200	Poor water
200–300	Very poor water
> 300	Unfit for drinking

Geographic information system (GIS)

GIS (geographic information systems) software is one of important tools making decision on the spatial distribution of groundwater water quality. Therefore, all major physicochemical parameters of the study area were mapped using inverse distance weighted (IDW) interpolation techniques in ARC GIS.

RESULTS AND DISCUSSION

Characterization of groundwater samples

The physico-chemical parameters of the groundwater samples analyzed in this study, including minimum and maximum values, standard deviation and Average, are presented in the following Table 3.

The pH values are in the range of 6 to 8.5 in natural waters (Chapman et al., 1996). It decreases at high organic matter levels and increases during low water, when evaporation is significant (Meybeck et al., 1996; In: Derwich et al., 2010).

In all the waters sampled in the area of study, the pH values measured are homogeneous, they comply with the Algerian standards and the limits of the World Health Organization (WHO). The average pH in Barremian and the Mio-plio-quaternary are 7.4 and 7.54, respectively, which gives

Table 3. Descriptive statistics of chemical composition

Parameter	Unit	Barremian				Mio-plio-quaternary			
		Maximum	Minimum	Average	Standard deviation	Maximum	Minimum	Average	Standard deviation
pH		7.8	7.02	7.4	0.25	7.87	7.09	7.54	0.22
CE	μS/cm	3191	1406	2216.6	627	3090	1385	1717.2	422.66
TDS	mg/l	1596	503	1031.2	396.71	1540	481	835.31	285.78
TH	mg/l	1040	520	808.6	190.49	930	535	698.55	114.07
Ca^+	mg/l	268.6	123	202.6	51.7	200.5	104.26	151.2	23.26
Mg^+	mg/l	97.2	42.5	73	18.41	121.5	48.6	74.13	18.71
Na^+	mg/l	195.5	66.93	108.84	39.79	161	62.56	94.28	32.89
K^+	mg/l	17.5	3.51	7.98	3.51	11.7	3.51	6.44	3.28
Cl^-	mg/l	386.95	110.05	258.88	91.22	376	111.47	214.42	64.55
SO_4^-	mg/l	706.81	258	477.33	139.07	706.33	200	377.94	139.86
HCO_3^-	mg/l	292.8	132	179.05	45.87	317.2	157.99	227.93	2.28
NO_3^-	mg/l	62.48	3.72	27.28	18.84	64	3.72	19.86	20.09

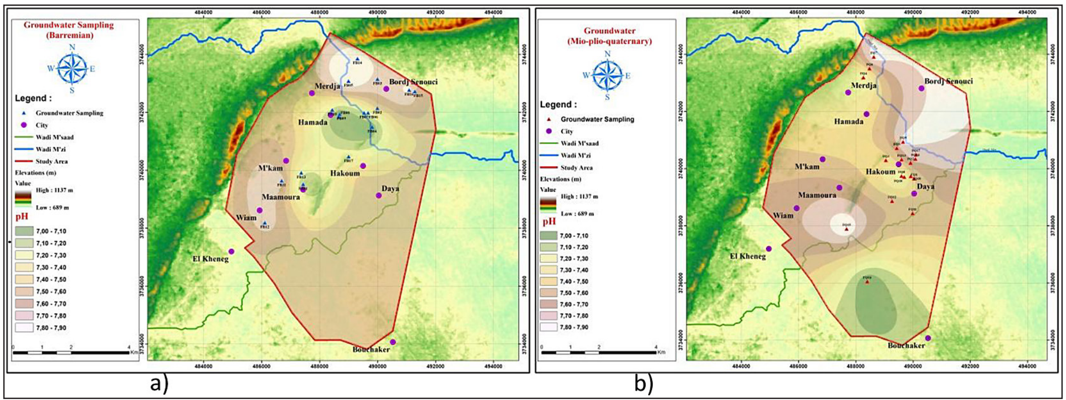


Figure 4. Spatial distribution map of the pH, (a) Barremian, (b) Mio- plio- quaternary

the waters a character close to neutrality. Figure 4 shows the spatial analysis of this parameter.

The TDS values in the Barremian and the Mio-plio-quaternary (Figure 5) are 1031.2 mg/l and 835.31 mg/l, respectively. in the Barremian all samples exceed the World Health Organization recommended 500 mg/L (WHO 2011) standard, while 16.6% of the samples in the other groundwater have a TDS within the required limit for these latter standards.

Variations in conductivity concentrations from one point to another indicate spatial distribution within the aquifer and good drainage (Raeisi, 1997). Note that in lithologically homogeneous terrain, the waters are charged as and when their path, the observation of the iso-conductivity map shows that this rule is not always verified in the sector, because of a part of the intense evaporation itself the depth of the surface water table, on the other hand, because of Quaternary and Barremian dilution by layer less calcareous loaded in Laghouat bridge.

The maximum value of electrical conductivity (Figure 6) is recorded at Hamada FB10 borehole, it is 3191 µS/cm. While the minimum value is recorded at Daya Rac FQ1 holes, it is 1385 µS/cm. In total, 70.5%, 94.4% of the samples in Barremian, Mio-plio-quaternary waters have conductivity within the required limit for Algerian standards of 2800 µS/cm [JORADP, 2011].

Calcium and magnesium – measurement of minerals dissolved in water – describe hardness. Groundwater in both aquifers, compared to the WHO, 2011 standards, is very hard water due to the nature of the calcareous ground which is rich in calcium and can be easily eroded by water. The average hardness value (Figure 7) in Barremian and Mio-plio-quaternary groundwater is 808.6 mg/l and 679.58 mg/l, respectively.

The maximum value of calcium is recorded at Hamada FB 08 borehole, it is 268.6 mg/l. while the minimum value is recorded at Daya FQ1 holes, it is 104.26 mg/l. In the Barremian, calcium (Figure 8) varies between 123 and 268.6 mg/l whereas the average value is 202.6 mg/l and a standard deviation is 51.7 mg/l. That is 94% of the Ca^{2+} concentrations in the Mio-plio-quaternary and 47% of the samples of the Barremian are within the

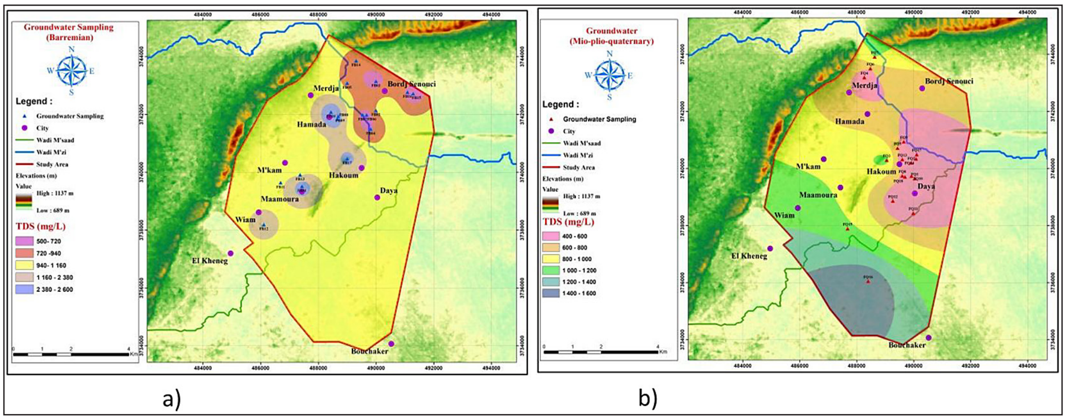


Figure 5. Spatial distribution map of total dissolved solids, (a) Barremian, (b) Mio- plio- quaternary

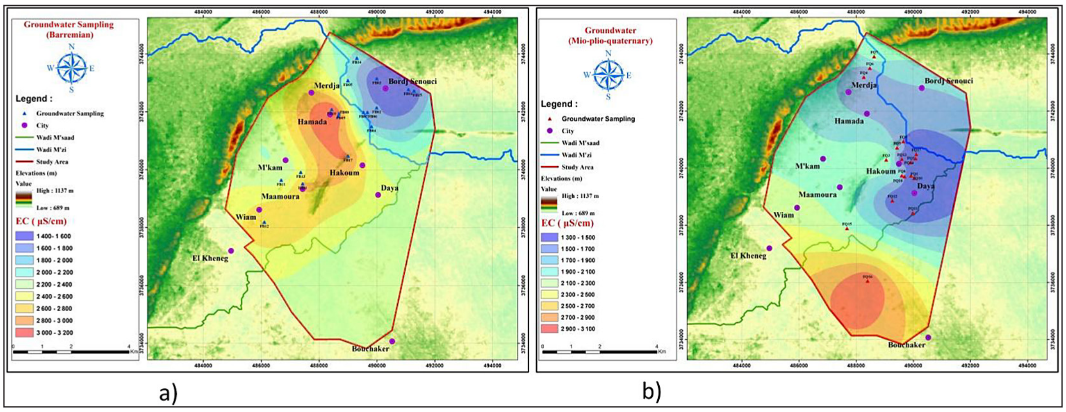


Figure 6. Spatial distribution map of electrical conductivity, (a) Barremian, (b) Mio- plio- quaternary

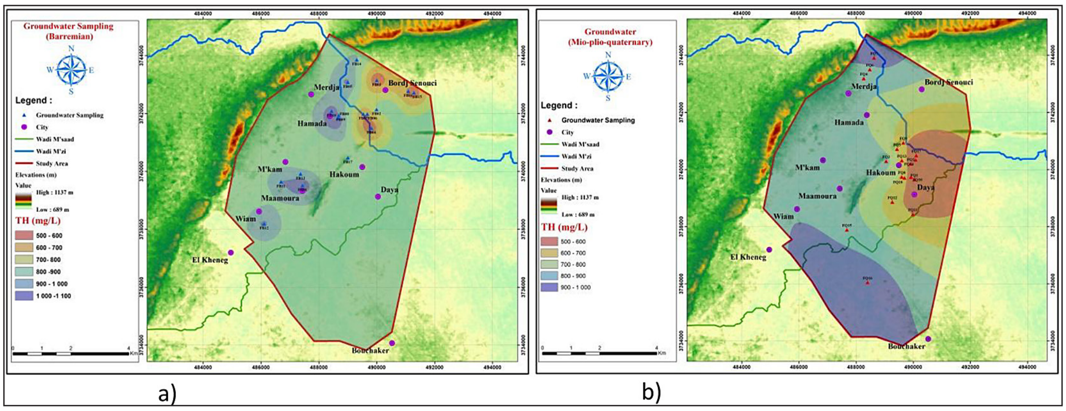


Figure 7. Spatial distribution map of hardness, (a) Barremian, (b) Mio- plio- quaternary

acceptable limits of the Algerian standards equal to 200 mg/L (JORADP, 2011). It was then noted that the high concentrations encountered in this region may be partly linked to the dissolution of the formations of the limestone constituting the substrate. The concentrations of Mg^{+2} ions in the Barremian (Figure 9) are lower than in the Mio-plio-quaternary layer; they are 73 mg/l. The high levels recorded may be related to the presence of clay zones in the various formations. In all waters sampled in both groundwater, the concentrations of Mg^{+2} do not exceed the limits of the Algerian standard [JORADP, 2011]. Although respectively 11.7% and 5% of the Mg^{+2} ion concentrations in the Barremian and Mio-plio-quaternary are below the 50 mg/l [WHO, 2011].

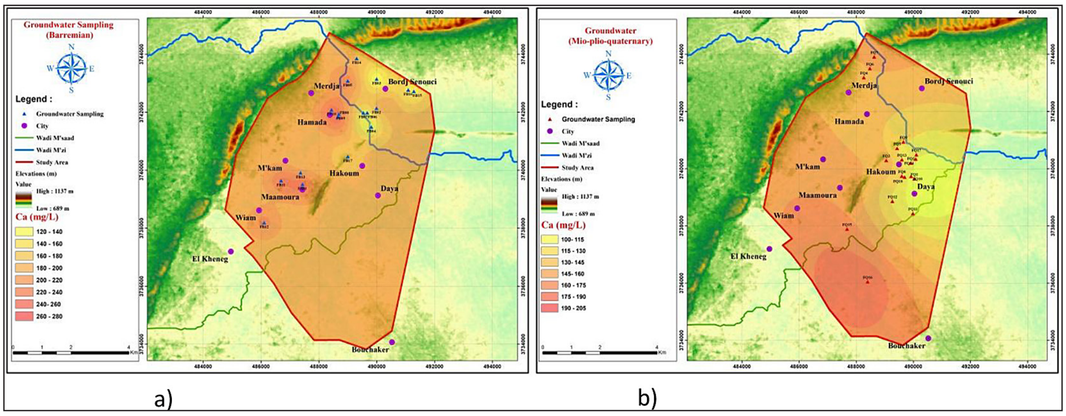


Figure 8. Spatial distribution map of calcium, (a) Barremian, (b) Mio- plio- quaternary

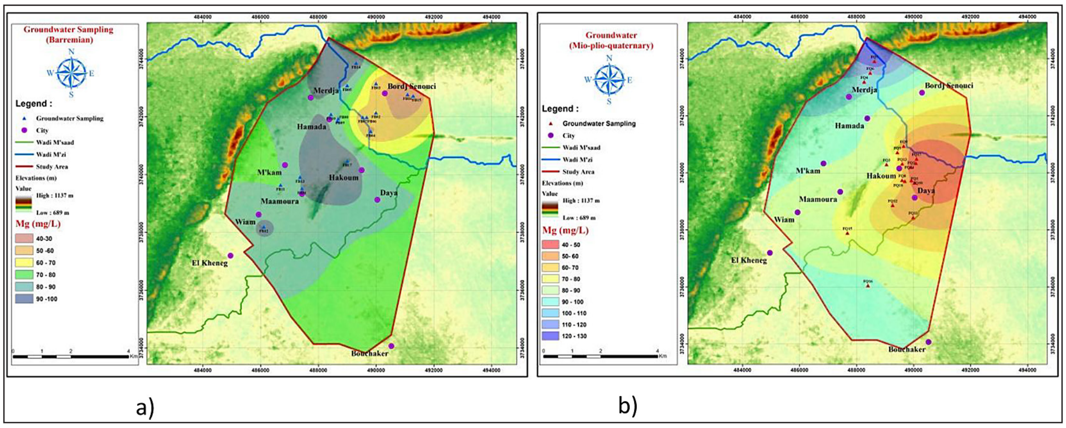


Figure 9. Spatial distribution map of magnesium, (a) Barremian, (b) Mio- plio- quaternary

The Na^+ concentrations in Barremian groundwater (Figure 10) ranged from 66.93 to 195.5 mg/l with an average of 108.84 mg/l and a standard deviation of 39.79 mg/l. the minimum value is recorded in mio-plio-quaternary at Daya FQ9 holes, it is 62.56 mg/l the presence of sodium in the study area is attributed to the decomposition of mineral salts such as the clays of the Mio-pliocene. All sodium concentrations values presented in Figure 10 respect World Health Organization normalization, WHO, 2011 and JORADP 2011(below of 200 mg/l).

The average concentrations of potassium in groundwater from the Barremian formation and the Mio-plio-quaternary (Figure 11) are 7.98 mg/l; 6.44 mg/l, respectively. The results recorded in Barremian show that 5.9% of concentrations exceed the Algerian standards [JORADP 2011].

Chloride ion is a conserved element. It does not participate in water-rock interactions and water salinity originates due to this ion, it is highly mobile (Fidelibus and Tulipano, 1996). It is a perfect tracer because of its anionic exclusion property (Rice et al., 1986; James and Rubin., 1986; Wieranga et al., 1989) caused by electrostatic repulsion phenomena in the vicinity of clay particles (negatively charged); thus, anions and in particular chloride (faster than neutral molecules) will circulate in the center of pores and conduits where the speed of water is faster (Porro et al., 1993; Schoen et al.,1999; Magesen et al., 2003). The obtained concentrations of chloride, amounting to 22.2% and 58.8% (Figure 12) concentrations, respectively in the Mio-plio-quaternary and Barremian aquifers, exceed the World Health Organization standards, 250 mg/L (WHO, 2011). The maximum value of chloride is recorded at Hamada FB 08 borehole, is 386.95 mg/l. while the minimum value is recorded at Bourdj FB3 holes, it is 110.05 mg/l. On the basis of Algerian standard, all the groundwater samples are below 500 mg/L (JORADP, 2011).

The values of 477.33 mg/L and 377.94 mg/L represent the average sulfate concentrations in Barremian and Mio-Pliocene-quaternary groundwater, respectively. Figure 13 shows that 35.3% and 61.1% of sulfate concentrations in these two

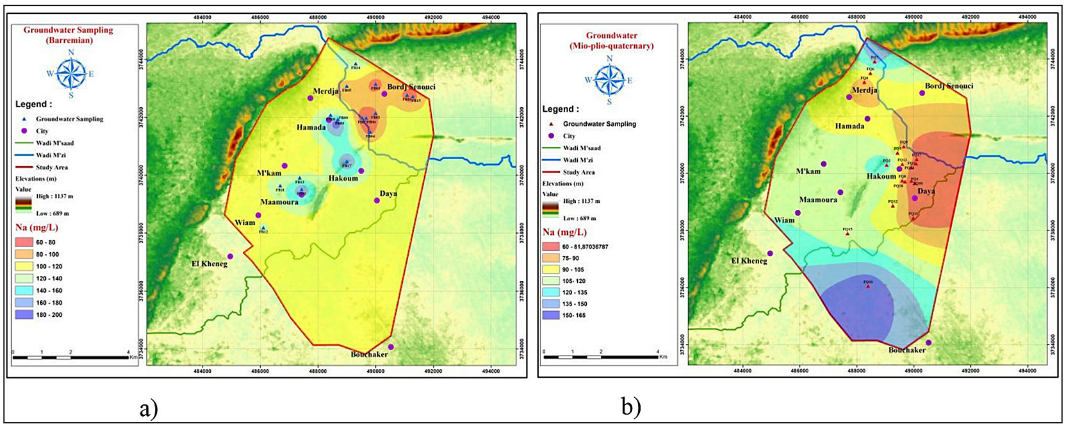


Figure 10. Spatial distribution map of sodium, (a) Barremian, (b) Mio- plio- quaternary

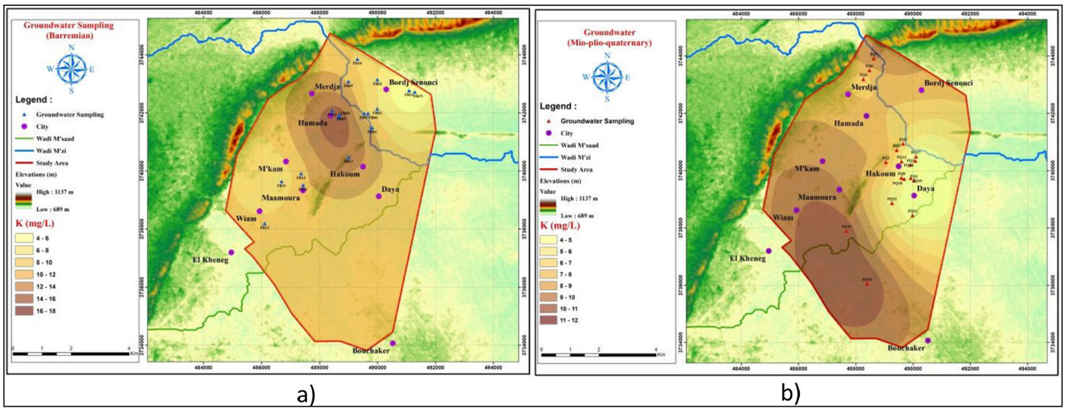


Figure 11. Spatial distribution map of potassium, (a) Barremian, (b) Mio- plio- quaternary

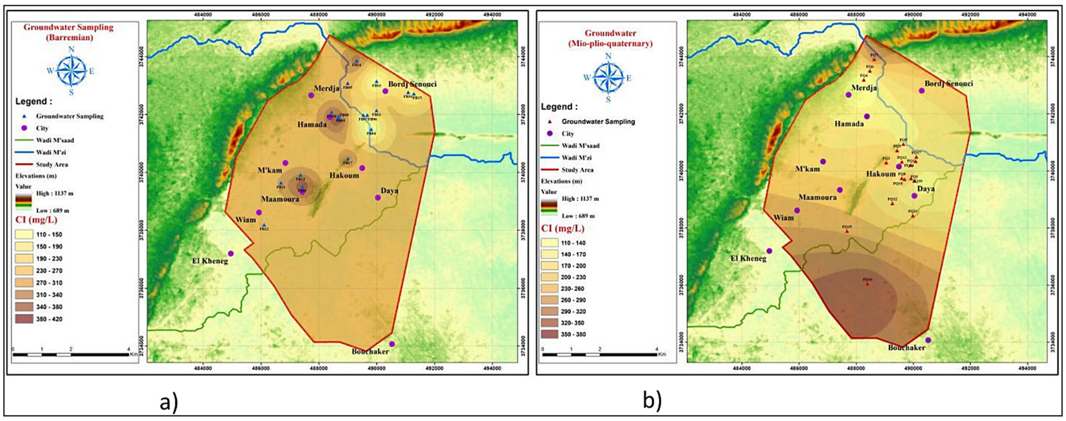


Figure 12. Spatial distribution map of chloride, (a) Barremian, (b) Mio- plio- quaternary

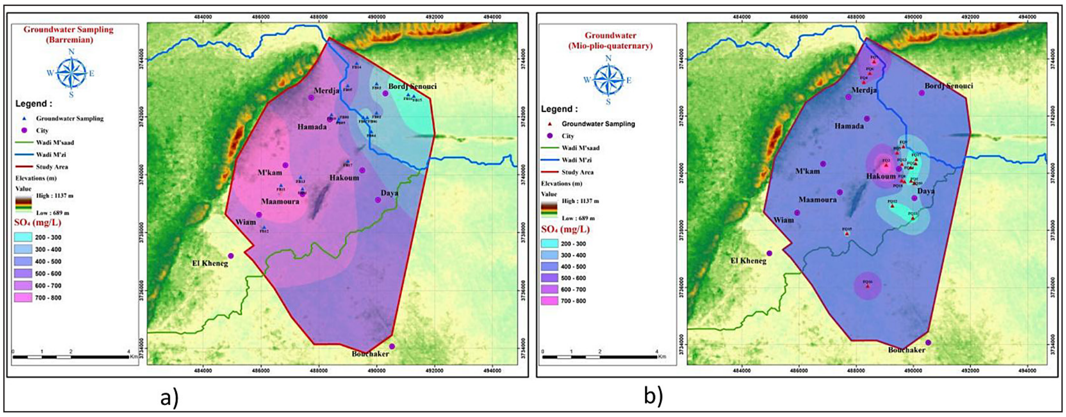
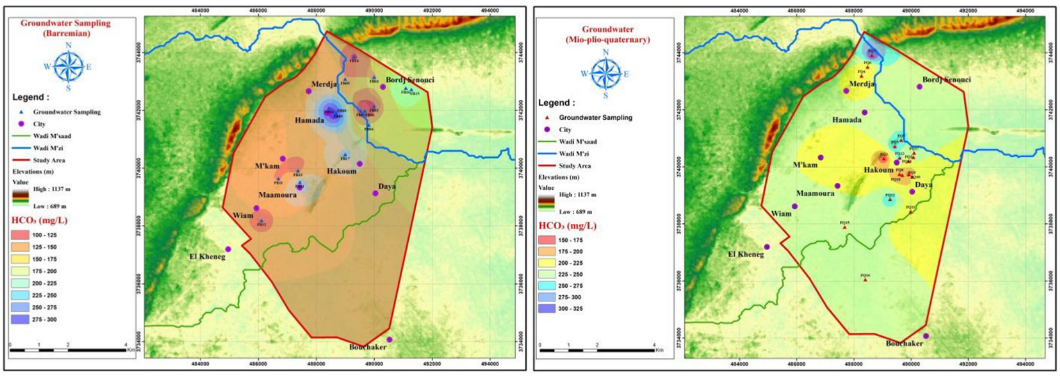


Figure 13. Spatial distribution map of sulfate, (a) Barremian, (b) Mio- plio- quaternary

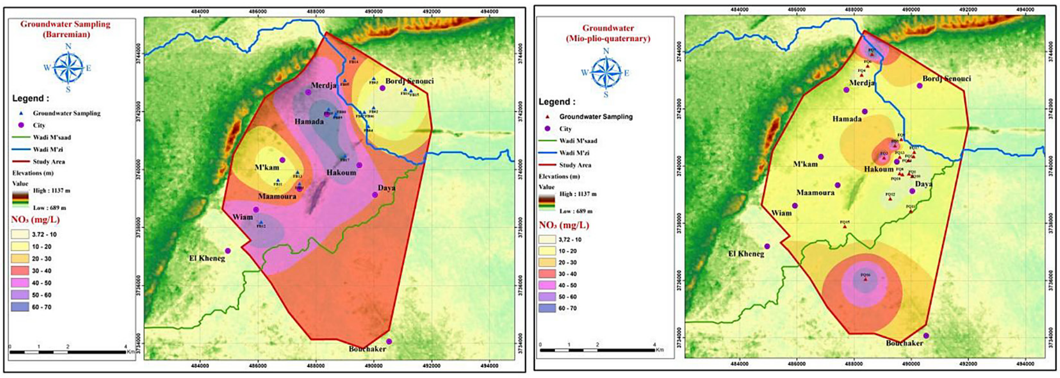
aquifers are below the Algerian standard limit of 400 mg/L (JORADP, 2011). The high sulfate content of the water is explained by the presence of gypsum in the Mio-Pliocene formations.

The HCO_3^- ions are formed from the dissolution of carbonate minerals by meteoric waters that become charged with CO_2 as they percolate through the soil. In carbonate aquifers. Bicarbonate levels are a few hundred mg/l. Certain mineral waters draining magmatic rocks have even higher contents (a few mg/l). Under the influence of CO_2 of deep origin or linked to the decomposition of the organic matter of fertilizers (Stitou et al., 1995; Hani., 2003). The bicarbonate levels in the groundwater of the Barremian aquifer (Figure 14) vary from 132 to 292.8 mg/L.



a) b)

Figure 14. Spatial distribution map of bicarbonate, (a) Barremian, (b) Mio- plio- quaternary



a) b)

Figure 15. Spatial distribution map of nitrate, (a) Barremian, (b) Mio- plio- quaternary

In the Mio-Plio-Quaternary aquifer, the average concentration is 227.93 mg/l. The results show that all the bicarbonate concentrations are above the limit of 120 mg/l set by the World Health Organization (WHO, 2011). These bicarbonate levels may be the result of limestone leaching in the formations. In the wild, the nitrate concentration rarely exceeds 0.45 mg/l and depends on the transfer time and the nature of the rock (Derradji et al., 2004). However, there are risks associated with these cultivation practices as excessive use of chemical and organic fertilizers can result in nitrate leaching to groundwater (Refsgaard et al., 1999). Worldwide observations (Ayraud, 2005; Primeau and Grimard, 1989; Bergström and Jarvis, 1991) and studies indicate a strong link between intensive agriculture and high nitrate concentrations in groundwater (Andrews et al., 1997; Lasserre et al., 1999; Benmarce, 2015). The average values for nitrate in the Barremian groundwater and the Mio-plio-quaternary (Figure 15) are 27.28 and 19.86 mg/L, respectively. The high values observed, due to the low tightness of the sewerage network over the whole region in question, directly affect groundwater quality.

WQI for drinking water assessment

Table 4 shows the calculated WQI values for groundwater in the city of Laghouat, maximum value is recorded at Hamada FB 08 borehole, it is 199.3, while the minimum value is recorded at Bourdj FB15 holes, it is 86.38 mg/l. The good quality was noticed in the city Daya (Figure 16) at the following boreholes: FQ1, FQ2, FQ9, FQ10, FQ11, FQ12, FQ14, FQ17, and FQ18. In Nourdj: FB3, FB4, FB15, and FB16.

Statistical analysis

In the study of source water chemistry, not a single (variable) parameter is observed, but often a large number of parameters at a time. The separate study of each of these variables is an important phase when analyzing the chemical behavior of sources, but it is often insufficient. Indeed, the separate study of each variable leaves aside the links that may exist between them and which are often a very important aspect. It is therefore necessary to analyze the data taking into account their multidimensional nature. Data structure exploring was carried out using a particularly powerful method, namely factor analysis (Hotelling., 1933; Nagabhsushan et al., 2007; Husson et al., 2010). The advantage of this technique lies in the fact that it makes it possible to reduce most of the variance expressed by the descriptors to a few factorial planes. The first F1 axis expresses the highest percentage of the total variance. The second F2 axis, independent of the first, expresses most of the residual variance and so on (Mudry and Blavoux, 1986). The Pearson correlation coefficient was determined to establish the relationship between the physicochemical parameters of the waters. A principal component analysis (PCA) was conducted using XLSTAT 2014.5.03.

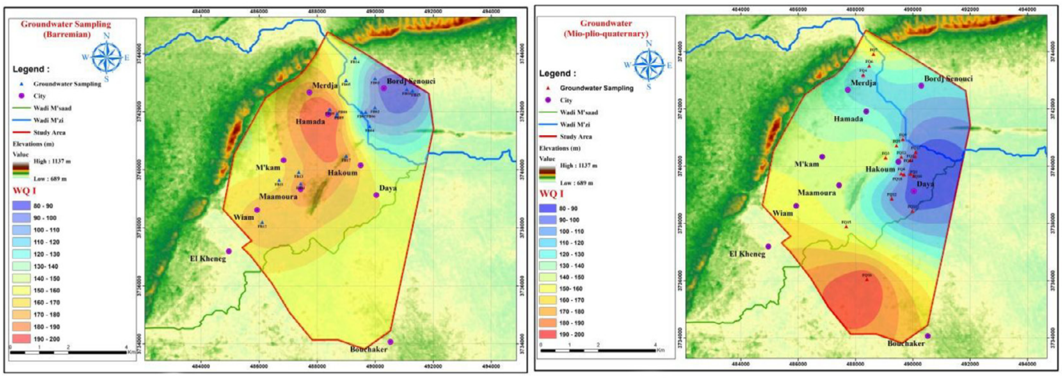
Principal component analysis of groundwater in the Barremian

The first two main components describe 84.97% of the initial variability (Figure 17) of data (F1 69.47% and F2 15.50%). EC(95.09%) is correlated strongly positive with F1 (69.47%) in the first axis. TDS (96.09%), TH (91.63%),

Table 4. Calculated WQI of each groundwater samples

Sample No.	Location name	Lambx	Lamby	WQI	Type of water
FB01	Maamoura	487434,4	3739517,7	191.49	Poor water
FB02	Bourdj 2	489993,9	3742144,6	126.21	Poor water
FB03	Bourdj 3	489995,23	3743150,17	94.23	Good water
FB04	Hakoum 4	489811	3741496	99.92	Good water
FB05	Bourdj 5	488997,17	3743083,56	139.77	Poor water
FB06	Hakoum 6	489671	3741986	95.27	Good water
FB07	Hakoum 7	489537	3741986	94.95	Good water
FB08	Hamada 8 f	488658,62	3741841,65	199.3	Poor water
FB09	Hamada 9 m	488688,38	3741937,23	174.29	Poor water
FB10	Hamada M 10	488436,92	3742085,43	184.02	Poor water
FB11	M'kam 600	486691,93	3739641,1	150.82	Poor water
FB12	Wiam 12	486108,18	3738191,62	169.28	Poor water
FB13	M'kam centre A	487366,46	3739914,81	141.82	Poor water
FB14	Bourdj 14 M	489306,61	3743859,59	136.49	Poor water
FB15	Bourdj 15 A	491283	3742723	86.38	Good water
FB16	Bourdj 16 A	491088,66	3742774,22	96.51	Good water
FB17	El garbia Atik 17	489001,37	3740474,92	177.98	Poor water
FQ1	Daya 1Rac	490038,82	3739651,57	89.91	Good water
FQ2	Daya2 Han	489915,93	3740204,7	93.28	Good water
FQ3	Past 3	489054,44	3740294,47	159.03	Poor water
FQ4	Merdja 4	488269	3743193	99.68	Good water
FQ5	Past Amri 5	489434,84	3740717,93	144.6	Poor water
FQ6	Merdja 6	488482,8	3743503,75	112.85	Poor water
FQ7	Merdja 7	488631	3743912	161.31	Poor water
FQ8	Daya 8 M	489599,3	3739744,88	114.47	Poor water
FQ9	Daya A 9	489655,98	3740940,8	94.34	Good water
FQ10	Daya 10	489923,2	3739736,32	86.51	Good water
FQ11	Daya 11 A	489989,35	3738438,19	91.21	Good water
FQ12	Daya 12	489271,46	3738865,68	92.95	Good water
FQ13	Hakoum 13	489602,41	3740320,16	93.22	Good water
FQ14	Daya 14	490084,859	3740342,58	91.19	Good water
FQ15	Abattoir 15	487681	3737894	134.1	Poor water
FQ16	Bouchakeur 16	488404,29	3736052,92	188.97	Poor water
FQ17	Daya 17 H M	490107,94	3740493,89	93.37	Good water
FQ18	Daya 18	489695,52	3739710,66	94.61	Good water

Ca^{+}(87.23%), Mg^{+}(84.89%), Na^{+} (92.73%), Cl^{-} (92.24%), and SO_4^{2-} (84.63%), NO_3^{-} (81.50%), and a moderate positive correlation with K^{+} (74.47%), HCO_3^{-}, (65.04%), and a negative correlation with pH (-34.44%). In addition, the F2 axis (15.50%) exhibits a positive correlation with EC (10.45%), TDS (4.51%), Na^{+} (8.84%), K^{+}(51.71%), HCO_3^{-} (54.56%), and NO_3^{-} (33.70%) and a negative correlation with pH (-74.46%), TH (-36.10%), Ca^{+} (-31.04%), Mg^{+}(-38.94%), Cl^{-} (-22.33%), and SO_4^{2-}(-42.23%). As it is shown in Table 5, total dissolved solids (TDS), electrical conductivity (CE) and hardness are strongly correlated to the Ca^{2+}, Mg^{2+} and Na+ cations and to the Cl-, SO_4^{2-} anions. These results indicate that groundwater mineralization is mainly related to sulfates and chlorides, as well as other elements. Evaporitic minerals dissolution such as halite (NaCl) and gypsum ($CaSO_4$. $2H_2O$) acquire this mineralization. The presence of evaporites is supported by the high correlation between sodium and chloride



a) b)

Figure 16. Spatial distribution of water quality index (WQI) in Laghouat, **(**a) Barremian, (b) Mio- plio- quaternary

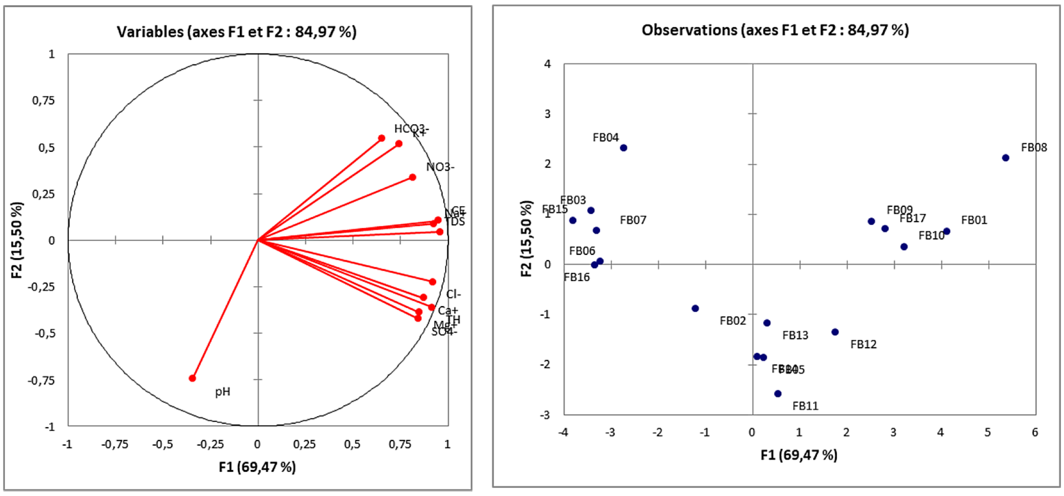


Figure 17. Projection of groundwater variables and individuals (Barremian)

Table 5. Correlation matrix for groundwater samples in Barremian

Variables	pH	CE	TDS	TH	Ca+	Mg+	Na+	K+	Cl-	SO4-	HCO3-	NO3-
pH	1											
CE	-0.430	1										
TDS	-0.406	0.988	1									
TH	-0.082	0.822	0.857	1								
Ca^{+}	-0.133	0.787	0.830	0.966	1							
Mg^{+}	0.036	0.749	0.767	0.889	0.749	1						
Na^{+}	-0.348	0.852	0.856	0.779	0.700	0.794	1					
K^{+}	-0.588	0.681	0.663	0.501	0.455	0.507	0.747	1				
Cl^{-}	-0.204	0.838	0.861	0.933	0.888	0.862	0.870	0.511	1			
SO_4^{-}	-0.041	0.749	0.800	0.924	0.878	0.861	0.748	0.454	0.816	1		
HCO_3^{-}	-0.442	0.654	0.642	0.398	0.447	0.270	0.666	0.701	0.498	0.269	1	
NO_3^{-}	-0.358	0.821	0.772	0.602	0.543	0.621	0.764	0.838	0.620	0.498	0.694	1

(r = 0.870), sulfate (r = 0.748) and between calcium and sodium (r = 0.700), chloride (r = 0.888), sulfate (r = 0.878) ions. The good correlation between magnesium and sulfates on the one hand (r = 0.861) and chlorides on the one hand (r = 0.862) also certifies the presence of a base exchange between ions in aquifers and its influence on water chemistry.

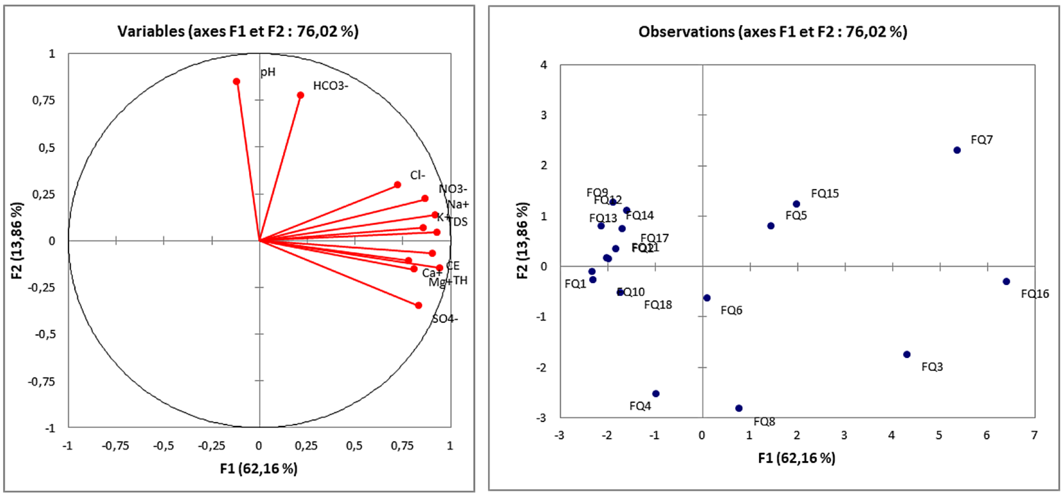


Figure 18. Projection of groundwater variables and individuals (Mio-plio-quaternary)

Table 6. Correlation matrix for groundwater samples in Mio-plio-quaternary

Variables	pH	CE	TDS	TH	Ca^+	Mg^+	Na^+	K^+	Cl^-	SO_4^-	HCO_3^-	NO_3^-
pH	1											
CE	-0.226	1										
TDS	-0.079	0.977	1									
TH	-0.198	0.788	0.806	1								
Ca^+	-0.042	0.821	0.827	0.775	1							
Mg^+	-0.249	0.549	0.565	0.896	0.430	1						
Na^+	-0.040	0.777	0.814	0.829	0.623	0.754	1					
K^+	0.033	0.765	0.811	0.760	0.593	0.685	0.720	1				
Cl^-	0.131	0.747	0.791	0.592	0.624	0.385	0.709	0.503	1			
SO_4^-	-0.314	0.658	0.664	0.872	0.626	0.846	0.752	0.767	0.273	1		
HCO_3^-	0.421	0.112	0.158	0.131	-0.034	0.199	0.322	0.217	0.173	-0.019	1	
NO_3^-	0.031	0.691	0.733	0.772	0.444	0.792	0.890	0.746	0.643	0.697	0.382	1

Principal component analysis of groundwater in the Mio-plio-quaternary

The first two main components describe 76.02% of the initial variability (Figure 18) of the data (F1 62.16% and F2 13.86%). The first axis, F1 (62.16%), has a strong positive correlation with the EC (90.60%), TDS (92.96%), TH (94.31%), Mg^+ (81.08%), Na^+ (92.09%), K^+ (85.83%), NO_3^- (86.90%), and SO_4^- (83.95%). and a correlation with the EC moderate positive with Ca^+ (77.95%). Cl^- (72.25%). HCO_3^- (21.41 and a negative correlation pH (-11.77%). In addition, the F2 axis (13.86%) exhibits a positive correlation with pH (84.85%), TDS (4.34%), Na^+ (13.64%), K^+ (6.92%), HCO_3^-(77.39%), Cl^- (29.59%), and NO_3^-(22.18%), and a negative correlation with EC (-31.16%), TH (-14.59%), Ca^+(-10.65%), Mg^+(-15.33%) and SO_4^-(-34.82%). According to Table 6, TDS, CE and hardness are strongly correlated with the Ca^{2+}, Na^+ and K^+ cations and the Cl^- anions and NO^{3-} ; These results indicate that the mineralization of groundwater is mainly related to chlorides as well as other elements.

CONCLUSIONS

This current topic is the first scientific research that was addressed in the city of Laghouat (study area), it is a survey on the quality of groundwater intended for human consumption between two aquifers (Barremian, Mio-plio-quaternary). It was concluded that the quality of groundwater, of the city Daya is good, overall, The current results show that 48.57% of the samples in the study area are classified as being of good quality, 61.1% and 35.3% of the samples examined were found to be potable by the WQI index (category «good»), respectively in the Mio-plio-quaternary and Barremian aquifers, their concentrations conform to Algerian standards (JORADP, 2011). In turn, the poor quality mentioned in this area (51.43%) was due to domestic and industrial waste water discharges and the climate change effect that characterizes the arid climate of the region. This requires control, continuous monitoring and treatment prior to use to protect human health in the city of Laghouat. The study of the correlations between the different dissolved elements, as well as the examination of their spatial distribution, showed that water/rock interactions are at the origin of the evolution of water mineralization. The main phenomenon occurring in the aquifer system is the dissolution of evaporites, mainly gypsum and halite, associated with an exchange of bases, which are manifested primarily by ion substitution (Ca-Mg and Na-K). For better understanding, future research should be carried out, including such perspectives as adding microbiological parameters and trace elements (heavy metals), to integrate the spatial and temporal variability of groundwater quality and quantity in the region, as well as to study the impact of climate change on groundwater resources. Integrating sustainable management of groundwater resources through the installation of drinking water treatment plants, ensuring the waterproofing of sewage networks, and rehabilitation of all stations (filling stations, purification plants...) are essential recommendations to ensure the protection of groundwater resources.

REFERENCES

1. Andrews, R.J., Lloyd, J.W., et Lerner, D.N. (1997). Modelling of nitrate leaching from arable land into unsaturated soil and chalk1. Development of a management model for applications of sewage sludge and fertilizer. *Journal of Hydrology, 1*(4), 179–197. https://doi.org/10.1016/s0022-1694(97)00009-7
2. Ait-Mohamed Amer, R., Baahmed, D., Cherif, E.A., Iddou, A. (2021). Trend detection of hydroclimatic parameters in central coastal basin of Oran in Algeria: is there any impact on water resources. *Arabian Journal of Geosciences, 14*(15), 1442. https://doi.org/10.1007/s12517-021-07816-7
3. Ayraud, V. (2005). *Détermination du temps de résidence des eaux souterraines: Application au transfert de l'azote dans les aquifères fracturés hétérogènes.* Thèse doctorat. université de Rennes1, 312. https://theses.hal.science/tel-00088100v1
4. Azlaoui, M., Zeddouri, A., Haied, N., Nezli, I.E., Foufou, A. (2021). Assessment and mapping of groundwater quality for irrigation and drinking in a Semi-Arid Area in Algeria. *Journal of Ecological Engineering, 22*(8), 19–32. https://doi.org/10.12911/22998993/140369
5. Barkat, A., Bouaicha, F., Ziad, S., Mester, T., Sajtos, Z., Balla, D., Makhloufi, I., Szabó, G. (2023). The integrated use of heavy-metal pollution indices and the assessment of metallic health risks in the phre atic groundwater Aquifer-case of the Oued Souf Valley in Algeria. *Hydrology 10*: 201. https://doi.org/ 10. 3390/ hydro logy1 0100201
6. Benmarce, K. (2015). *Caractérisation physico-chimique des eaux souterraines dans la région de Guelma. Nord-Est Algérien.* Thèse Doctorat en géologie, Spécialité Hydrogéologie, Université Badji Mokhtar, Annaba. https://dspace.univ-annaba.dz//handle/123456789/3206
7. Brahmi, S., Baali, F., Hadji, R., Brahmi, S., Hamad, A., Rahal, O., Zerrouki, H., Saadali, B., Hamed, Y. (2021). Assessment of groundwater and soil pollution by leachate using electrical resistivity and induced polarization imaging survey, case of Tebessa municipal land fill. *NE Algeria Arab J Geosciences, 14*: 265. https://doi.org/10. 1007/ s12517-021-06571-z
8. Bergström, L., Jarvis, N.J. (1991). Prediction of nitrate leaching losses from arable land under different fertilization intensities using the SOIL-SOILN models. *Soil USE Manage, 7*(2), 79–84. https:// doi.org/ 10.1111/ j.1475-2743.1991.tb00854.x
9. Brown, R.M., McClelland, N.l., Deininger, R.A., O'Connor, M.F. (1972). *A water quality index-crashing the psychological barrier. In Indicators of environ mental quality.* Springer, Boston, MA, 173–182. https://doi.org/ 10.1007/ 978-1-4684-2856-8_15.
10. Chabour, N., Dib, H., Bouaicha, F., Bechkit, M.A., Messaoud Nacer, N. (2021). A conceptual framework of groundwater flowpath and recharge in Ziban aquifer: south of Algeria. *Sustain Water Resources Management 7*(1). https://doi.org/ 10.1007/s 40899-020-00483-8
11. Chapman, D., Kimstach, V. (1996). *Selection of water quality variables. Water quality assessments : a guide to the use of biota. sediments and water in environment monitoring*. Chapman edition. 2nd ed. E & FN Spon. London. 59–126. https://doi.org/ 10.1201/9781003062103
12. Derdour, A., Abdo, H.G., Almohamad, H., Alodah, A., Al Dughairi, A.A., Ghoneim, S.S., Ali, E.

(2023). Prediction of groundwater water qual ity index using classification techniques in arid environments. *Sustainability,15*(12), 9687. https://doi.org/10.3390/su15129687

13. Derradji, F., Khérici, N., Roméo, M., Caruba, R. (2004). Aptitude des eaux de la vallée de la Seybouse à l'irrigation (Nord-Est algérien). *Sécheresse, 15*: 353–360.
14. Derwich, E.E., Benaabidate, L., Zian, A., Sadki, O., Belghity, D. (2010). Caractérisation physico-chimique des eaux de la Nappe alluviale du haut Sebou en aval de sa Confluence avec oued fes. *Larhyss Journal,* 101–112. https:// api.semanticscholar.org/ Corpus ID: 131294052
15. DPAT. (2023). Monographie de la Wilaya de Laghouat. Direction de la Planification et de l'Aménagement du Territoire.
16. Fidelibus, M.D., Tulipano, L. (1996). Regional flow of intrusing sea water in thecarbonate aquifers of Apulia (Southern Italy). Proceedings 14th Salt Water Intrusion Meeting. *Rapporter och meddelandennr 87*. 230–241.
17. Ibrahim, M.N. (2019). Assessing groundwater quality for drinking purpose in Jordan: application of water quality index. *Journal of Ecological Engineering, 20*(3), 101–111. https://doi.org/10.12911/22998993/99740
18. Hajji, S., Ayed, B., Riahi, I., Allouche, N., Boughariou, E., Bouri, S. (2018). Assessment and mapping groundwater quality using hybrid PCA-WQI model: case of the Middle Miocene aquifer of Hajeb Layoun-Jelma basin (Central Tunisia). *Arabian Journal of Geosciences, 11*: 620. https://doi.org/10.1007/s12517-018-3924-5
19. Hamma,B.,Alodah,A.,Bouaicha,F.,Bekkouche,M., Barkat,A., Hussein,A. (2024). Hydro chemical assessment of groundwater using multivariate statistical methods and water quality indices (WQIs). *Applied Water Science, 14*, 33. https://doi.org/10.1007/s13201-023-02084-0.
20. Hani, A. (2003). *Analyse méthodologique de la structure et des processus anthropiques : Application aux ressources en eau d'un bassin côtier méditerranéen*. Thèse doctorat. D'état en géologie. Spécialité Hydrogéologie. Université Badji Mokhtar. Annaba.
21. Hotelling. (1933). Analysis of a complex of statistical variables into principal components. *J.Educ. Psy.24*. 417–441, 498–520.
22. Husson, F., Josse, J., Pagès, J. (2010). Principal component methods-hierarchical clustering- Partitional clustering: Why would we need to choose for visualizing data? *Technical report-Agrocampus*, 17.
23. James, R.V., Rubin, J. (1986). Transport of chloride ion in a water-unsaturated soil exhibiting anion exclusion. *Soil Science Society of America Journal, 50*(5), 1142–1149. https://doi.org/10.2136/sssaj1986.03615995005000050010x
24. JORADP. (2011). Executive Decree No. 11–125 of March 23, 2011 on the quality of water for human consumption in Algeria. *Official J of People's Democratic Republic of Algeria, 18*, 6–9. https ://www. jorad p.dz/FTP/jo-francais/2011/F2011 018.pdf
25. Kallel, A., Ksibi, M., Ben Dhia, H., Khélifi, N. (2018). *Recent Advances in Environmental Science from the Euro-Mediterranean and Sur rounding Regions.* Springer International Publishing, Cham Kelley WP (1963) Use of saline irrigation water. Soil Sci 95: 385–391.
26. Khan, M.Y.A., El Kashouty, M., Bob, M. (2020). Impact of rapid urbanization and tourism on the ground water quality in Al Madinah city. Saudi Arabia: a monitoring and modeling approach. *Arabian Journal of Geosciences, 13*(18), 922. https://doi.org/10.1007/s12517-020-05906-6
27. Lasserre, F., Razack, M., Banton, O. (1999). A GISlinked model for the assessment of nitrate contamination in groundwater. *Journal of Hydrology*, 3–4, 81–90. http://dx.doi.org/10.1016/S0022-1694(99)00130-4
28. Lekrine, Y., Demdoum, A., Bouaicha, F. (2023). The integration of geo chemical and isotopic approaches for thermo-mineral water char acterization: the case of Tebessa (North Eastern Algeria). As *ITJGW, 12*, 77–90. https://doi.org/10.7343/as-2023-667
29. Magesan, G.N., Vogeler, I., Clothier, B.E., Green, S.R., Lee, R. (2003). Solute movement through an allophanic soil. *Journal of Environmental Quality. 32*(6): 2325–2333.
30. Meybeck, M., Friedrich, G., Thomas, R., Chapman, D. (1996). *Rivers Water quality assessments: a guide to the use of biota. sediments and water in environment monitoring*. Chapman edition. 2nd ed. E & FN Spon. London. 59–126.
31. Mohamadi, A., Demdoum,A., Bouaicha, F., Menani, M.R. (2021). Evaluation of the quality of groundwater for its appropriateness for irrigation purposes using Water Quality Index (WQI), Mchira-Teleghma aquifer case study, northeastern Algeria. *Sustain Water Resour Manag 7*, 155. https://doi.org/10.1007/s40899-021-00571-3
32. Mudry, Blavoux. (1986). Utilisation de l'analyse en composantes principales (sur variables centrées réduites) pour le fonctionnement hydrocinématique de trois aquifères karstiques du Sud-Est de la France. 53–59.
33. Nagabhsushan, P., Kumar,P. (2007). *Principal Component Analysis of histogram Data*. Springer-Verglag Berlin Heidelb erg. EdsISNN Part I I LNCS 4492. 1012–1021.
34. Pasha, G.A., Ghumman, A.R., Almuhaylan, M.R., Shafiquzzaman, M., Al Salamah, I.S., Haider, H.

(2023). *Groundwater modelling of the Saq Aquifer using Artificial Intelligence and Hydraulic Simulations.* In: Artificial Intelligence and Machine Learning Techniques for Civil Engineering, IGI Global, 181–215. https://doi.org/10.4018/978-1-6684-5643-9.ch008

35. Porro, I., Wierenga, P.J., Hills, R.G. (1993). Solute transport through large uniform and layered soil columns. *Water Resources Research*, 29–4, 1321–1330. https://doi.org/10.1029/92WR02528
36. Primeau, S., Grimard, Y. (1989). *Rivière Yamaska 1975–1988. vol. 2 : Résultats complémentaires sur la qualité des eaux. Ministère de l'Environnement du Québec.* Direction de la qualité des cours d'eau. Sainte-Foy. Québec.
37. Rice, R.C., Bowman, R.S., Jaynes, D.B. (1986). Percolation of water below an irrigated field. *Soil Science Society of America Journal. 50*(4): 855–859.
38. Raeisi, K. (1997). Hydrochemographs of Bergham karst sprin as indicators of aquifers characteristics. *Journal of Cave and Karst Studies. 59*(3). 112–118. https:// www.researchgate.net/ publication/ 237829613
39. Refsgaard, J.C., Thorsen,M., Jensen, J.B., Kleeschulte, S., Hansen, S. (1999). Large scale modelling of groundwater contamination from nitrate leaching. *Journal of Hydrology*, 3–4, 30, 117–140. https://doi.org/10.1016/S0022-1694(99)00081-5
40. Rodier, J. (2009). *L'analyse de l'eau; eaux naturelles. eaux résiduelles. eaux de mer. Chimie. physico chimie. microbiologie. biologie.* Interprétation des résultats. 8ème édition Dunod. Paris. 1383 pages.
41. Schoen, R., Gaudet, J.P., Bariac, T. (1999). Preferential flow and solute transport in a large lysimeter, under controlled boundary conditions. *Journal of Hydrology, 215*, 1–4, 70–81. https://doi. org/ 10.1016 / S0022-1694(98)00262-5
42. Sekkoum, M., Aissa, S., Stamboul, M. (2020). Groundwater hydrochemistry of Aflou syncline. Central Saharan Atlas of Algeria. *Desalination and Water Treatment, 190*, 424–439. https://doi. org /10.5004/dwt.2020.25649
43. Singh, P., Thakur, J.K., Singh, U.C. (2013). Morphometric analysis of Morar River Basin, Madhya Pradesh,India,using remote sensing and GIS techniques. *En vironmental Earth Sciences, 68*(7), 1967–1977. https://doi.org/10.1007/s12665-012-1884-8
44. Srinivasamoorthy, K., Gopinath, M., Chidambaram, S., Vasanthavigar, M., Sarma, V.S. (2014). Hydrochemical characterization and quality appraisal of ground water from Pungar sub basin. Tamilnadu. India. *Journal of King Saud University-Science, 26*(1), 37–52. https://doi.org/10.1016/j.jksus2013.08.001
45. Stitou, J., Pulido-Bosch, A. (1995). Impacts anthropiques sur l'aquifère alluvial de Smir (Tetouan. Maroc)., *Hydrogéologie*. n° 3, 39–46.
46. Thabit, H., Haider, H., Ghumman, A.R., Alattyih, W., Alodah, A., Hu,G., Shafiquzzaman, M. (2023). Fuzzy-based human health risk assessment for shallow groundwater well users in Arid Regions. *Sustainability 15*(22): 15792. https://doi.org/10.3390/su152215792
47. Tyagi, S., Sharma, B., Singh, P., Dobhal, R. (2013). Water quality assessment in terms of water quality index. *American Journal of water resources, 1*(3), 34–38. https://doi.org/10.12691/ajwr-1-3-3
48. Tiwari, A.K., Singh, A.K., Mahato, M.K. (2018). Assessment of groundwater quality of Pratapgarh district in India for suitability of drinking purpose using water quality index (WQI) and GIS technique. *Sustainable Water Resources Management, 4*(3), 601–616. https://doi.org/10.1007/s40899-017-0144-1
49. WHO. (2011). *Guidelines for drinking-water quality world health organization.* 4th edn. Geneva. Switzerland.
50. Wierenga, P.J., Van Genuchten, M.T. (1989). Solute transport through small and large unsaturated soil columns. *Ground Water. 27*(1): 35–42.