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Research Article

Assessment of groundwater quality and its suitability for drinking in the ouargla region northeastern Algerian Sahara

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Abstract:

This study focused on the determination of the different physicochemical characteristics of groundwater from 59 boreholes distributed over the three main aquifers of the Ouargla region (South-East of Algeria). The quality of the water was also assessed in order to evaluate their amenities and the international standards of drinking water quality of the World Health Organization (WHO) and the water quality index (WQI). The physicochemical parameters selected for this study, namely pH, total dissolved solids, electrical conductivity, total hardness, alkalinity, calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulfate, and Temperature, were determined by following the procedures prescribed by international standards. were determined by following the procedures prescribed by international standards. In groundwater quality studies, statistical analysis techniques such as correlation analysis, principal component analysis (PCA) and analysis of variance (ANOVA) were used to assess the main factors and mechanisms governing spatial variations in the Ouargla basin region. The results obtained showed that the facies characterizing the study area were a mixed combination of Ca–Mg–Cl, Ca-Cl and Na-Cl, with the dominant ions being most often chlorides and sulfates, as well as calcium and magnesium. The WQI values calculated for the Ouargla basin region ranged from 174.69 to 312.71. The geospatial distribution of the water quality index shows that the water of the Albian aquifer is poor, while the majority of the water of the Miopliocene and Senonian aquifers is very poor. However, the results of this study indicate that most of the water is not potable and requires additional pre-treatment before consumption.

1. Introduction

Water is one of the essential resources for the sustenance of all living beings. The demand for water for various purposes is increasing rapidly due to the continual rise in population, rapid urbanization with changing lifestyles, and growing industrialization [1]. In the Algerian northern Sahara, most of the water resources are groundwater. This groundwater, contained in the continental formations of the Intercalary Continental (IC) and the Terminal Complex (CT), constitutes one of the largest hydraulic reservoirs in the world [2,3]. With a better understanding of the importance of drinking water quality to human health, there is a significant need to assess groundwater quality [4]. Moreover, there is a need for studies on how groundwater will be managed.

For efficient management, the assessment of groundwater resources requires an understanding of the hydrogeochemical and hydrogeological features of the aquifer [5,6]. To achieve this, the examination of groundwater quality is essential, considering both the physical and biological characteristics that must be compatible with international or local standards, along with its implications for human health and various application domains. It is also important to know the rate of groundwater renewal, the role of precipitation in layer recharging, and the time water remains on the surface before penetrating the subterranean layers [7]. The Water Quality Index (WQI) is a mathematical method and composite factor that provides information based on the variables (elements) that the water contains. These variables are converted into a single result that describes the quality of the studied water [8, 9]. The Ouargla Basin, the subject of this study, is one of the basins north of the Algerian Sahara. Over the past decades, this basin has witnessed significant exploitation, leading to qualitative and quantitative degradation of this resource. However, the main objective of this study is to evaluate and map the groundwater quality status of the Ouargla Basin using the Water Quality Index and Geographic Information System.

2. Materials and Methods

2.1 Description of the Study Area

The Our study area is located in the city of Ouargla, one of the main oases of the Algerian Sahara. It is situated in the southeast of Algeria, approximately 750 km from the capital. The Ouargla basin is occupies an area of 95000 hectares, measuring 30 km long and 12 to 18 km wide. Its height is between 103 and 150 meters above sea level, it is bordered to the West by a plateau of 200 to 230 m altitude and to the East by a plateau less than 160 meters above sea level. altitude, linked to the sands of the great oriental erg. On the east it is bordered by Eurg Touil and Arifdji; on the west by the valley of Me Zab; On the north by Sebkhet Safioune and on the south by the dunes of Sedrata. The geographical coordinates of the study area are longitudes 5°23' and 5°49' East and latitudes 31°89' and 32°28' North [10]. Figure 01 presents the study area location and Wells locations.The climate of the Ouargla region is of the Saharan type, characterized by a hot, dry summer and a mild winter. Over the course of the year, the temperature typically varies from 5°C to 42°C and is rarely below 2°C or above 46°C. The annual average rainfall is about 40.44 mm.

2.2 Geological and Hydrogeological Settings

In study area, the Miopliocenelands outcrop, they are covered by a small thickness of Quaternary deposit (ergs, dunes). The basin is dug into the continental formations of the MioPliocene. These are red sands and soft sandstones with cross-stratification, with limestone nodules, interspersed with limestone or gypsum levels that can be seen outcropping on its eastern and western edges. The description of the sedimentary formations was established by interpreting water and oil drilling logs [11,12]. The stratigraphic series of the Ouargla basin is represented from bottom to top by the following formation (Figure 2):The Quaternary consisting of alluvial or eolian sands with the surface layer, located at a depth of 2 meters on average, sometimes gypsum and reworking products of the MioPliocene terrains, The Miopliocene formed by sands and sandstones and sometimes limestones and clays; the thickness of this formation is of the order of 85 meters on average. The Eocene is characterized by marls, anhydrite and sometimes sand at the top; it constitutes a lithological continuity with carbonated senonian. The Senonian is divided into three different lithological units. Namely, the carbonate Senonian at the top, constituted by limestone with dolomitic marl layers its average thickness is around 150 meters, and the Anhydritic Senonian at the base, constituted by an irregular alternation of anhydrite, dolomite, clay, and salt banks, and by a more or less uniform composition its average thickness is around 250 meters. At the base there is the Salty Senonian is known for its massive salt; we sometimes find clays, limestones, and anhydrite. The thickness of this formation is of the order of 200 meters on average. The Turonian appears in the form of carbonacious clays and limestone banks with a thickness not exceeding 100 meters in most cases. The Cenomanian is characterized mainly by interbedded clay and dolostones; we sometimes find limestone, anhydrite, and rarely salts, its thickness varies around 200 meters. The Albian is characterized by a great thickness (>400 m) in almost all the boreholes; it is marked mainly by sandstone, sand, sometimes clay and marl, and very rarely limestone.The North Sahara Aquifer System (SASS), shared by Algeria, Tunisia, and Libya, extends over an area of more than one million km^2, about 70% of which lies within Algeria [13 ,14]. The SASS consists of two main superimposed aquifers: The Continental Intercalary (CI) aquifer, which is the deepest, and the Complex TerminalCT) aquifer. The subsoil of the Ouargla region contains the following aquifer systems (Figure 2) [15 ,16]:-The phreatic aquifer has a thickness ranging from 1 to 8 meters. Its reservoir, of heterogeneous composition, is made up of detrital materials such as blocks, pebbles, gravel, and sand. The bedrock consists of a thick clay formation, which sometimes appears as sand lenses in discordance with the clay layers. The aquifer is mainly recharged by precipitation, infiltration from valleys, and irrigation return flows. However, it is not exploited due to the high salinity of its water.

-The Complex Terminal (CT) aquifer is composed of two distinct aquifer horizons. The first is the Mioplioceneaquifer, which is about 100 meters thick and consists of sands, clays, and evaporitic materials, occurring at depths between 20 and 100 meters. The second is the Senonian–Eocene (Upper Cretaceous) aquifer, composed mainly of limestone, with a thickness of approximately 300 meters and located at a depth of around 200 meters.

- The Continental Intercalary (CI) aquifer consists of sandy and sandstone formations interbedded with clay and dolomitic sandstone layers. It dates from the Albian to Barremian age and has a total thickness of approximately 550 meters. The top of the aquifer lies at depths between 850 and 1200 meters. The CI aquifer is artesian and gushing, with wellhead pressures of about 15 bar and flow rates exceeding 160 l/s. The water temperature is relatively high, ranging from 50 °C to 60 °C, due to the considerable depth of the aquifer.

2.3 Sampling and analysis

The study area was spanned by five water sampling campaigns that covered 59 wells, which included six wells from the Albian aquifer (ALB), 38 wells from the Senonian aquifer (SEN) and 15 wells from the Miopliocene aquifer (MP) (Figure 01: C). The samples were collected in 1.5 L plastic bottles, which were cleaned with tap water and then distilled water. During field preparation, the bottles were rinsed with the sample water itself before sampling. After collecting the water samples, each vial was properly labeled for identification, packed in a special box, and transported to the Laboratory of the ADE (Algérienne Des Eaux), Ouargla unit.The physicochemical parameters (pH, temperature, and electrical conductivity) were measured in situ immediately after sample collection using the Multi-parameter SL 1000. Chloride ions were determined by Mohr's method. Concentrations of Bicarbonate were determined by titration using 0.1 N HCl. Sodium and potassium ions were determined by flame atomic absorption spectrometry using the JENWAY PFP7 Flame Photometer. Sulfates were determined by the spectrophotometricmethod using a Hach Lange DR 6000 spectrophotometer. Calcium concentrations were measured by complexometry (EDTA), and magnesium concentrations were derived from total hardness. The accuracy of the chemical analysis was verified bycalculating ion balance errors using Eq. (1), which is based on the principle that the sum of major anions and the sum of major cations should be equivalent (concentrations expressed as meq L^{-1}). The error in % is given by Eq. (1).

$$\mathrm{IB} = \left(\frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}}\right) \times 100 \qquad (1)$$

A chemical analysis of the water is considered representative and acceptable only when the ionic balance error is equal to or less than 10% [17] .

2.3 Estimation of the Water Quality Index

The Water Quality Index (WQI) is used because it provides a single number (a grade) that expresses overall water quality at a certain location based on several water quality parameters (WHO standards) [18]. It is calculated from different water parameters to evaluate the water quality in the area and its potential for drinking purposes [19, 20].Four steps are followed to estimate the WQI. In the first step, a weight (wi) is assigned to each element between 1 and 5 according to its importance and influence on drinking water and human health [18, 19]. The highest weight, 5, was assigned to sulfate (SO_4^{2-}), chloride (Cl^-), and total dissolved solids (TDS), as these often most significantly influence groundwater quality. A weight of 4 was assigned to pH, while a weight of 3 was assigned to calcium (Ca^{2+}), magnesium (Mg^{2+}), and total hardness (TH). A weight of 2 was assigned to potassium (K^+) and sodium (Na^+). The minimum weight, 1, was assigned to bicarbonate (HCO_3^-), which rarely plays a significant role in groundwater quality [21]. In the second step, the relative weight (Wi) is computed using Eq. (2) with the weighted arithmetic index method, as detailed below [22, 23], and the following steps [24, 25].

$$\mathrm{Wi} = \frac{\mathrm{wi}}{\sum_{i}^{n} \mathrm{wi}} \qquad (2)$$

Where:

Wi is the relative weight

wi is the weight parameter

n is the number of parameters

In the 3 step, the quality rating scale (qi) for any parameter was determined using Eq. (3).

$$\mathrm{qi} = \left(\frac{\mathrm{Ci}}{\mathrm{Si}}\right) \times 100 \qquad (3)$$

Where:

qi is the quality rating.

Ci is the chemical concentration/water sample (mg/L).
Si is the WHO drinking water quality standard (mg/L).
Assign weights, relative weights and the limits required by WHO are shown in Table 2.

In the final step, the SI_i is first determined for each chemical parameter Eq. (4),

$$SI_i = q_i \times W_i \qquad (4)$$

then used SIi to calculate the WQI as per the following Eq. (5):

$$WQI = \sum SI_i \qquad (5)$$

Table 1. *The assigned weights and relative weightof physicochemical parameters*

Parameter	WHOs	Wight	Relative Wight
		wi	Wi
pH	6.5-8.5	4	0.1212
TDS	1500 mgL^{-1}	5	0.1515
Ca^{2+}	200 mgL^{-1}	3	0.0909
Mg^{2+}	150 mgL^{-1}	3	0.0909
K^+	30 mgL^{-1}	2	0.0606
Na^+	200 mgL^{-1}	2	0.0606
Cl^-	250 mgL^{-1}	5	0.1515
HCO_3^-	380 mgL^{-1}	1	0.0303
SO_4^{2-}	400 mgL^{-1}	5	0.1515
TH	500 mgL^{-1}	3	0,0909
EC	1500 µS/cm	-	-
Total		33	1

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In the final step, the SI_i is first determined for each chemical parameter Eq. (4),

$$SI_i = q_i \times W_i \qquad (4)$$

then used SIi to calculate the WQI as per the following Eq. (5):

$$WQI = \sum SI_i \qquad (5)$$

2.4 GIS analysis

Generating spatial distribution maps of various water quality parameters involves integrating attribute and spatial data. Interpolation, a process for estimating unknown values that fall between known values, can address this challenge [26]. Therefore, the inverse distance weighted (IDW) interpolation technique in ArcGIS 10.2 has been used to prepare spatial distribution maps for all physicochemical parameters. This interpolation method assumes that each point has a local influence that decreases with distance. Many researchers have used IDW interpolation to create water quality index maps [27, 28]. Maps of the spatial distribution of pH, EC, TDS, TH, anions and cations, and WQI for the study area have been created to support water resources management and decision-making.

2.5 Multivariate statistical analysis

The major groundwater quality factors were examined using multivariate statistical methods. The IBM SPSS version 21 software was used to process the analytical data. Basic statistics, including Principal component analysis (PCA) and analysis of variance.

2.5.1 Principal component analysis PCA

Principal Component Analysis (PCA) studies and visualizes correlations between variables to potentially reduce the number of variables to be measured subsequently. It provides crucial information for the entire data set while preserving the relationships in the original data. PCA mainly involves the following steps: First, the correlation matrix of the original data is calculated. Then, the eigenvalues and eigenvectors are computed, and a set of mutually perpendicular principal component (PC) axes are established. Finally, a new group of variables is extracted by rotating the axes defined by PCA [29–30]. The varimax method rotates the variables such that the loadings of all variables on each factor are close to 1, 0, or -1. Loadings close to 1 reflect a strong correlation with the main factor, while loadings close to 0 indicate no significant correlation with the variables [31–32]. Variables with rotated loadings greater than 0.5 are considered significant [30].

2.5.2 Analysis of variance

The Kruskal–Wallis test is a statistical test used to compare two or more groups for a continuous or discrete variable. It is a non-parametric test, meaning that it assumes no specific distribution of the data and is analogous to one-way analysis of variance (ANOVA). For each water quality parameter, the Kruskal– Wallis test was used to investigate differences among the three aquifers (Miopliocene, Senonian, and Albian). The Kruskal–Wallis test was applied to test the following

hypotheses:
• H0: There are no differences among the three aquifers.
• H1: There is at least one difference among the three aquifers [33, 34].

3.Results and discussion

3.1. Water Quality for Drinking Purpose

Thephysicochemical characteristics of thegroundwater samples were statistically evaluated, with results including minimum, maximum, average, and standard deviation parameters presented in Table 2. Groundwater quality is crucial for evaluating its suitability for drinking purposes.The spatial variation of water quality parameters, such as EC, TDS, TH, pH, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-, is assessed based on WHO standards. These parameters arecategorized as desirable, permissible, and not permissible.Temperature (T) is an important abiotic factor as it affects the solubility of gases, the dissociation of dissolved salts, and pH. It depends on the geological nature and depth of the aquifer relative to the Earth'ssurface. Temperature increases gradually with a geothermal gradient of about 1 °C per 30 meters. The aquifers in the study area extend to depths between 50 and 1600 meters [35, 36].The temperature of the Miopliocenеaquifer ranges from 20.2°C to 27.75°C, while the temperature of the Senonian aquifer ranges from 23.5°C to 29°C. Both levels are thermally homogeneous, with a slight increase in temperature for the Senonian aquifer, which is expected as temperature increases with depth. The Albian aquifer is characterized by very high temperatures, ranging between 52°C and 54°C, which exceed the WHO recommended norm of 18°C to 25°C.The pH depends on the origin of the water, the geological nature of the substrate, and the watershed crossed [37, 38]. The pH of all water samples ranged from 7.00 to 7.99, indicating that the groundwater in the Ouargla Basin is generally slightly alkaline. TDS values ranged from 1075 to 2955mgL^{-1}, with average values of 1864.12, 1793.16, and 1361.67mgL^{-1} for the Miopliocene, Senonian, and Albian aquifers, respectively. TDS values decreased with increasing aquifer depth, with the Senonian aquifer having the highest TDS value (2955 mgL^{-1}). The TDS map (Figure 3: D, E, and F) shows that water in the Miopliocene aquifer is generally above the permitted limit (1500 mgL^{-1}), especially in the southwest part of the region. In the SEN aquifer, TDS values are below the permissible limit in the center of Ouargla city towards the west, while the rest of the area exceeds the permissible limit. This indicates that water-rock interactions increase with aquifer depth, likely due to excessive use in shallower aquifers. Conductivity indicates the quantity of ionic matter dissolved in water and depends on soil characteristics. According to WHO [18], the minimum conductivity for all samples collected exceeds the potable standards (>1500 µS/cm). The spatial distribution of EC (Figure 4: a,b,and c) shows that 100% of water samples are not permissible for drinking. Total hardness of water is influenced by the concentration of ions such as Ca^{2+} and Mg^{2+}. It is usually expressed as the equivalent quantity of $CaCO_3$ (WHO). Total hardness (TH) ranged from 710 to 1500 mgL^{-1}, with average values of 992.35, 1010.53, and 804.50 mgL^{-1} for the Miopliocene, Senonian, and Albian aquifers, respectively. According to water quality standards established by the WHO (Table 1), all samples exceed the minimum hydrotimetric titre of 500 mgL^{-1} $CaCO_3$, indicating very hard water in the region. However, the TH map (Figure 4: d, e, and f) shows that the Albian layer is less hard compared to the Senonian and Miopliocene layersThe concentrations of Sodium vary from 150 to 750 mgL-1. Based on WHO standards, 86.67%, 92.1%, and 66.67% of the samples exceeded the permissible limits for the Miopliocene, Senonian, and Albian aquifers, respectively. High sodium levels are harmful and cause cardiac, renal, and circulatory diseases [39].The Calcium values in the groundwater layers of the study area ranged between 148.29 and 344.68 mgL^{-1}. The percentage of samples exceeding the permissible limit according to WHO standards was 86.67%, 68.41%, and 16.67% for Miopliocene, Senonian, and Albian aquifers, respectively. High concentrations of calcium lead to the development of kidney or bladder stones in humans [40].The range of magnesium concentrations vary from 51.04 to 170.13 mgL^{-1}. All samples from the Miopliocene and Albian aquifers are below the permissible limits, except for the Senonian aquifer, where 13.36% of magnesium concentrations exceeded the permissible limits. A high concentration of magnesium causes scouring diseases in livestock [39].The concentration of potassium in the area was between 12 and 65 mgL^{-1}. According to WHO standards, the majority of samples from all aquifers were under the permissible limit. However, some samples were found to exceed the permitted limit by varying percentages:20%,5.26%, and 16.67% in Miopliocene, Senonian, and Albian aquifers, respectively.The concentrations of chloride in the area ranged from 399.9 to 1359.69 mgL^{-1}. All samples were within the not permissible limits set by WHO standards for all aquifers. High levels may be injurious to health and affect the heart and kidneys. Taste, indigestion, corrosion, and palatability are also affected[41].

3.2. Groundwater Type

Overall characterization of the hydrogeochemical data is possible if the hydrogeochemical types of water are known, generally referred to as water types, and expressed using various plots, such as Durov, trilinear Piper [42].Representation on the Piper diagrams allowed a rapid approach to analytical results to characterize the waters and to classify the anions and major cations for the aquifers. The chemical facies and order of major cations and anions in each aquifer are shown in Figure 4 as follows:In the Miopliocene water, we encounter three types of water: Calcium chloride (Ca-Cl) type (40%), Sodium chloride (Na-Cl) type (40%), and Calcium chloride and magnesium (Ca-Mg-Cl) type (20%). The dominant cations are calcium (Ca^{2+} >Na^{+} >Mg^{2+}), changing with the direction of flow to become (Na^{+}> Ca^{2+} >Mg^{2+}). The dominant anions are chlorides (Cl^{-} >SO_4^{2-} >HCO_3^{-}).The waters of Senonian are of the Calcium chloride and magnesium type (57.9%) and Calcium chloride type (31.6%), with a tendency to become Sodium chloride type(10.5%). The dominant cations are calcium and magnesium. The dominant anions are chlorides (Cl^{-} >SO_4^{2-} >HCO_3^{-}), with a trend downstream towards the sulfate pole.The type of Albian water is a mixture of Calcium chloride and magnesium type (50%) and Calcium chloride type (50%). The dominant cations are calcium (Ca^{2+} > Mg^{2+} > Na^{+}). The dominant anions are chlorides (Cl^{-} > SO_4^{2-} > HCO_3^{-}).

3.3. Water quality index for domestic suitability

The quality of water is very significant to human health because it has a direct link with human well-being. The WQI results based on groundwater quality categories are presented in Table 3.The WQI values for the Miopliocene aquifer show that 6 samples (40%) are considered poor, 8 samples (53.33%) were estimated as very poor, and 1 sample (6.67%) was estimated as water unsuitable for drinking. In the Senonian aquifer, 14samples (36.84%) are considered poor, 21 samples (55.26%) were estimated as very poor, and 3 samples (7.9%) were estimated as water unsuitable for drinking. For the Albian aquifer, 5 samples (83.33%) were classified as poor, whereas 1 sample (16.67%) was classified as very poor. The WQI values calculated for the Ouargla Basin range from 174.69 to 312.71.The maps in Figure 6 show that the majority of the water is in poor or very poor condition.

4.Multivariate statistical analysis

4.1. Principal Component Analysis Results

The correlation matrix is used to find the correlation between the physicochemical properties of groundwater. It reveals the sources of solutes and the processes that produce the observed water composition [43]. A high correlation coefficient (close to 1 or -1) indicates a strong positive relationship between two variables, while a value around zero indicates no significant relationship at a significance level of $P<0.05$. Specifically, parameters with $r > 0.7$ are strongly correlated, while an r value between 0.5 and 0.7 represents a moderate correlation [44]. In our study, data including 11 parameters were analyzed. To better understand the correlation within this large dataset, a heat map of correlation coefficients and Principal Component Analysis (PCA) were used to monitor the relationship between the WQI and the other variables. The results are shown in Figures 7–9.Figure 7.shows that WQI indicates a low positive correlation with all elements except for pH and Mg, which have low and negative correlations, and two principal components explained a total of 67.22% of the dataset, with PC1 representing 50.52% and PC2 representing 16.7%. The first group consists of TDS, Na^{+}, $SO4^{2-}$, and Cl^{-}. These parameters are highly correlated ($r > 0.9$), indicating that the Miopliocene water acquires its chemical properties primarily from these minerals. The second group consists of pH and $HCO3^{-}$, which explain the alkalinity of the water.According to Figure 8 the WQI is highly correlated with Cl^{-}, TDS, TH, $SO4^{2-}$, Na^{+}, Ca^{2+}, and Mg^{2+} ($r > 0.71$), and weakly correlated with $HCO3^{-}$, pH, and K^{+}. The positions of the variables in the rotated 2D space explain 72.58% of the Senonian aquifer data.It was demonstrated that the PC1 factor represents 50.52% and forms a homogeneous set of observations composed of variables that are WQI is strongly positively correlated with Mg^{2+} and TH ($r > 0.75$), while the relationship with SO_4^{2-} is moderate ($r > 0.63$). The other parameters have a low correlation with the WQI (see Figure9), with some showing low and negative correlations. exhibits similar observationsindicating that the water quality of the Albian aquifer is linked to the concentrations of Mg^{2+}, SO_4^{2-}, and TH.

4.2. The Kruskal–Wallis test

For each of the twelve water quality parameters, the Kruskal–Wallis test was used to investigate differences between the three aquifers (Miopliocene, Senonian, and Albian). The significance of the results is assessed based on the p-value. When p is greater than 0.05, there is no significant variation in the parameter under study. Otherwise ($p<0.05$), a significant difference is inferred, and the analysis continues with the Mann-Whitney test to locate this difference. Table 4 shows the statistical treatments based on the Kruskal-Wallis test. For parameters such as pH, TH, Ca^{2+}, Mg^{2+}, K^{+}, SO_4^{2-}, and Cl^{-}, with $p > 0.05$, there is no significant difference in the values of these parameters between the different aquifers. On the other hand, for parameters such as TDS, EC, Na^{+}, $HCO3^{-}$, and temperature, there is a significant variation ($p < 0.05$) in the values between the different aquifers. The Mann- Whitney test conducted on these parameters yields the following results:There is no difference between the concentrations of all parameters in the Miopliocene and Senonian aquifers. This may indicate an exchange between them, which could be due to their excessive and indiscriminate exploitation in the study area [21- 43].

4. Results of the Kruskal–Wallis test for the three
Table studied aquifers. The significance level is 0.05.On the other hand, for TDS, EC, Ca^{2+}, and Na^{+}, we observe significant variation in the values of these parameters between the Albian aquifer and the other aquifers (Miopliocene, Senonian). This variation is attributed to the diverse soil composition and the great depth of the Albian aquifer.

There is also a difference in the values of temperature (T) and bicarbonate (HCO_3^{-}) concentrations for the

Albian aquifer compared to the Miopliocene andSenonian aquifers. The Albian aquifer's water temperature can reach 56°C due to its great depth. The concentration of bicarbonates in this aquifer is higher because of the water coming into contact with carbonate rocks and the evaporation of carbon dioxide.

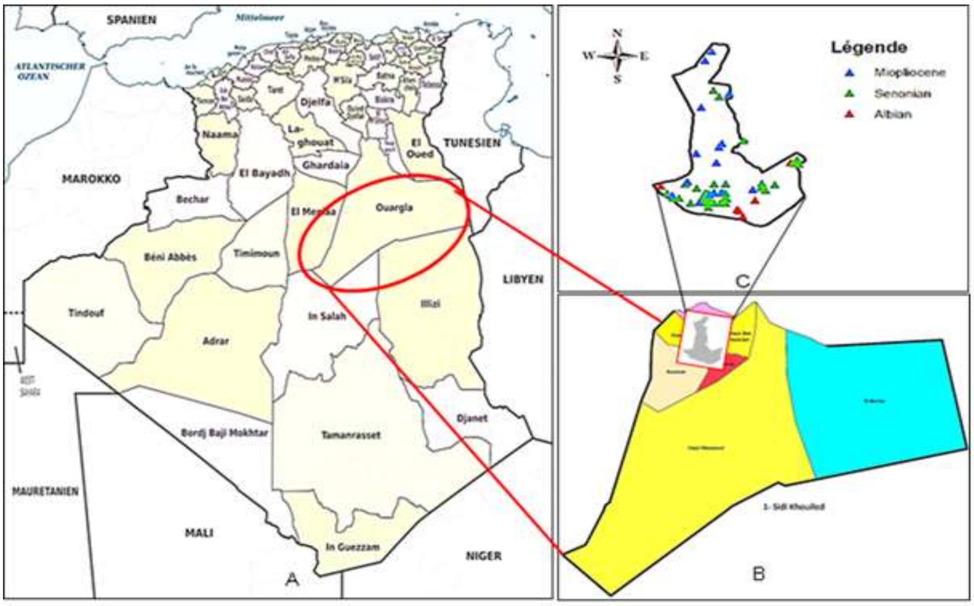

Figure 1 (A – C): *Ouargla county location, Ouargla basin location, and sampling locations*

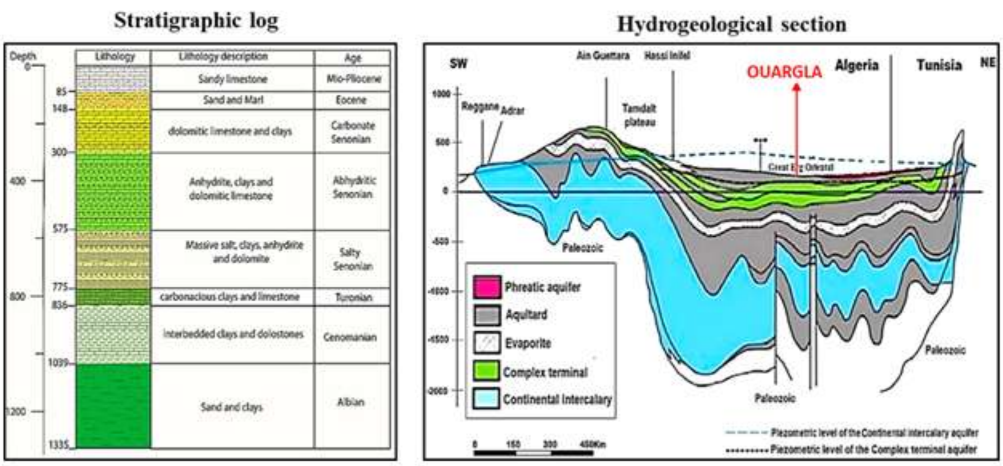

Figure 2: *Stratigraphic log of Elhdeb 1 drilling and Hydrogeological section of the Northern Sahara aquifers [11].*

Table 2. *Physicochemical parameters of groundwater samples of study areas*

Wells ID	PH	T	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	TH	TAC	TDS	EC
Miopliocene water													
MP1	7.0	24.0	320.6	85.1	500	42	117.9	999.8	780.0	1150	96.7	2325	4650
MP2	7.1	26.5	252.5	82.6	500	31	134.2	939.8	600.0	1040	110.0	2000	4000
MP3	7.5	23.9	216.4	104.5	450	14	138.3	879.8	600.0	970	113.3	2005	4010
MP4	7.5	22.0	216.4	94.8	500	19	113.9	834.1	680.0	930	93.3	2050	4100
MP5	7.5	20.2	192.4	82.6	350	21	105.7	647.9	540.0	820	86.7	1620	3240
MP6	7.8	27.8	244.5	89.9	400	36	174.7	832.5	550.0	980	155.8	1900	3800
MP7	7.2	22.9	216.4	104.5	450	14	116.7	915.9	600.0	970	95.5	2005	4010
MP8	7.7	22.6	240.5	92.3	200	14	143.2	618.0	420.0	980	117.4	1425	2850
MP9	7.5	27.0	292.6	82.6	400	21	122.0	819.8	512.0	1070	100.0	1800	3600
MP10	7.4	27.0	200.4	97.2	300	15	85.4	647.9	580.0	790	70.0	1585	3170
MP11	7.5	22.6	260.5	51.0	250	17	148.8	579.9	444.0	860	121.7	1425	2850
MP12	7.6	24.0	212.4	92.4	300	23	134.2	624.6	520.0	910	110.0	1515	3030
MP13	7.2	22.9	216.4	104.5	450	14	116.7	915.9	600.0	970	95.5	2005	4010
MP14	7.9	25.9	340.7	133.7	500	25	134.2	1239.7	800.0	1400	110.0	2680	5360
MP15	7.4	24.7	180.4	94.8	200	14	149.0	539.0	436.0	840	122.1	1335	2670
Min	7.0	20.2	180.4	51.0	200	14	85.4	539.0	420.0	790	70.0	1335	2670
Max	7.9	27.8	340.7	133.7	500	42	174.7	1239.7	800.0	1400	155.8	2680	5360
Mean	7.5	24.2	242.6	92.8	379.4	22.1	129.1	812.5	581.3	992.4	107.3	1864	3728.2
SD	0.3	2.2	46.6	17.4	109.7	8.8	21.4	191.9	112.0	151.3	19.6	369.9	739.8
% of watre above PL	0	0	86.7	0	86. 7	20	0	100	100	100	0	80	100
Senonian water													
SEN1	7.1	24.6	224.4	82.6	250	17	130.1	608.9	495	900	106.7	1405	2810
SEN2	7.1	27.9	328.7	55.9	400	32	117.9	799.8	680	1050	96.7	2090	4180
SEN3	7.1	25.0	220.4	72.9	250	16	126.1	571.9	441	850	103.3	1395	2790
SEN4	7.2	27.0	148.3	85.1	300	29	105.7	639.9	456	720	86.7	1420	2840
SEN5	7.2	24.0	252.5	72.9	350	12	130.1	756.2	500	930	106.7	1950	3900
SEN6	7.2	27.7	288.6	82.8	300	13	134.2	783.8	500	1060	110.0	1735	1735
SEN7	7.3	29.0	280.6	170.1	300	17	146.4	799.8	700	1300	120.0	1765	3530
SEN8	7.4	23.5	176.4	87.5	250	19	117.9	599.9	416	800	96.7	1395	2790
SEN9	7.2	27.0	240.5	158.0	500	22	126.9	1079.8	844	1300	103.3	2430	4860
SEN10	7.1	24.0	268.5	72.9	750	65	146.4	1119.7	950	970	120.0	2725	5450
SEN11	7.3	28.5	196.3	70.5	250	17	105.7	554.4	480	780	85.7	1335	2670
SEN12	7.5	26.0	300.6	133.7	600	30	105.7	1359.7	852	1300	86.7	2790	5580
SEN13	7.4	25.0	320.6	170.1	600	29	101.7	1299.7	788	1500	83.3	2955	5910
SEN14	7.9	28.4	240.5	162.8	400	23	184.9	998.0	720	1270	151.6	2300	4600
SEN15	7.4	27.0	196.4	68.0	300	27	22.4	659.9	464	770	18.3	1440	2880
SEN16	7.4	23.9	184.4	99.7	300	12	109.8	599.9	504	870	90.0	1445	2890
SEN17	7.2	24.0	180.4	75.3	350	25	125.5	676.0	520	760	102.9	1550	3100
SEN18	7.2	23.8	240.5	116.7	400	18	146.4	899.8	510	1080	120.0	1980	3970
SEN19	7.3	24.0	180.4	60.8	250	15	105.7	510.4	450	990	86.7	1250	2500
SEN20	7.4	25.5	220.4	111.8	450	24	122.0	743.8	680	1010	100.0	1745	3490
SEN21	7.3	25.0	220.4	157.4	500	30	122.0	1059.8	800	1200	100.0	2360	4720
SEN22	7.3	24.3	304.6	102,1	450	30	150,5	963,6	780	1440	123,3	2165	4330
SEN23	7.4	26.0	256.5	148.3	480	30	138.3	936.6	720	1250	113.3	2180	4360
SEN24	7.3	24.9	176.4	70.5	300	15	126.1	579.9	410	730	103.3	1380	2760

SEN25	7.1	25.8	228.5	85.1	200	42	172.0	618.0	436	920	141.0	1535	3070
SEN26	7.5	26.0	216.4	99.7	350	22	109.8	655.1	520	950	90.0	1555	3110

Table 2. Cont.

Wells ID	PH	T	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	TH	TAC	TDS	EC
Senonian water													
SEN27	7.3	26.1	216.4	99.7	300	22	95.5	623.9	520	950	78.3	1550	3100
SEN28	7.5	25.0	212.4	109.4	350	27	143.2	859.8	480	980	117.4	1790	3580
SEN29	7.4	23.9	200.4	109.4	350	21	122.0	719.8	550	950	100.0	1740	3480
SEN30	7.3	25.0	160.3	109.4	300	26	200.3	719.8	744	850	164.2	1400	2800
SEN31	7.3	24.8	344.7	94.8	400	23	127.3	945.2	664	1250	104.3	1870	4300
SEN32	8.0	25.8	180.4	89.9	200	15	110.9	423.2	496	820	90.9	1075	2150
SEN33	7.5	26.2	164.3	94.8	200	18	102.0	549.6	405	800	83.6	1200	2400
SEN34	7.4	25.8	240.5	55.9	300	15	127.3	679.8	480	830	104.3	1550	3100
SEN35	7.4	26.4	160.3	97.2	400	25	143.8	841.5	520	800	117.9	1305	3610
SEN36	7.3	25.3	312.6	136.1	600	30	96.2	1083.1	960	1340	76.4	2720	5440
SEN37	7.1	24.6	272.5	109.3	250	16	137.9	799.8	450	1020	109.3	1575	3170
SEN38	7.3	26.3	244.5	121.5	400	17	134.2	979.8	550	1110	110.0	2090	4180
Min	7.1	23.5	148.3	55.9	200	12	22.4	423.2	405.0	720.0	18.3	1075	1735
Max	8.0	29.0	344.7	170.1	750	65	200.3	1359.7	960.0	1500.0	164.2	2955	5910
Mean	7.3	25.6	231.6	102.6	365.3	23	125.5	792.1	590.4	1010.5	102.7	1793.2	3582.5
SD	0.2	1.4	51.9	32.3	125.8	10	28.6	219.7	158.8	212.6	23.5	485.8	1011.6
% of water above PL	0	0	68.4	13.2	92.1	5.3	0	100	100	100	0	65.8	100
Albian water													
ALB01	7.1	51	180.4	94.8	300	24	134.2	510.4	585	852	143.2	1500	3000
ALB02	7.1	52	196.4	87.5	200	30	164.4	570.3	450	850	134.7	1450	2900
ALB03	8.0	52	178.8	97.2	150	35	162.3	399.9	480	830	133.3	1195	2390
ALB04	7.0	53	180.4	63.2	300	18	126.1	830.3	232	710	103.3	1210	2420
ALB05	7.3	53	160.3	109.4	300	26	200.3	719.8	744	850	164.2	1400	2800
ALB06	7.4	53	244.5	106.9	200	46	184.3	573.8	480	849	69.1	1415	2830
Min	7.0	51	160.3	63.2	150	18	126.1	399.9	232	710	69.1	1195	2390
Max	8.0	53	244.5	109.4	300	46	200.3	830.3	744	852	164.2	1500	3000
Mean	7.3	52.3	190.1	93.2	241.7	29.8	161.9	600.7	495.2	823.5	124.6	1361.7	2723.3
SD	0.4	0.8	29.0	16.7	66.5	9.8	28.4	153.0	168.4	56.2	33.5	128.1	256.2
% of water above PL	0	100	16.7	0	66.7	16.7	0	100	83.3	100	0	16.7	100

Table 3. *Water Quality Classification based on WQI*

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

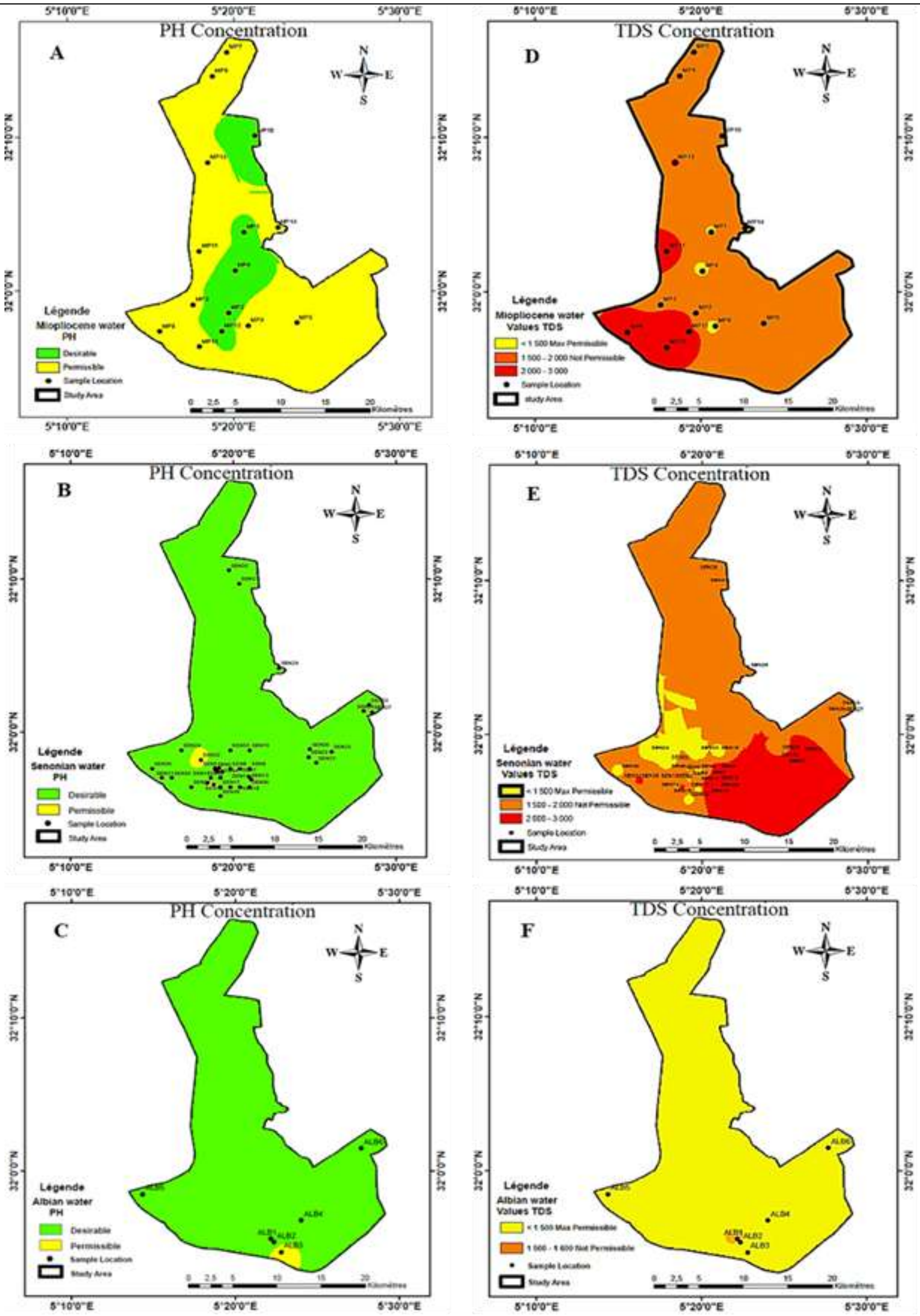

Figure 3 (A – F): *Spatial variation maps of PH, and TDS for aquifers Miopliocene, Senonian, and Albian.*

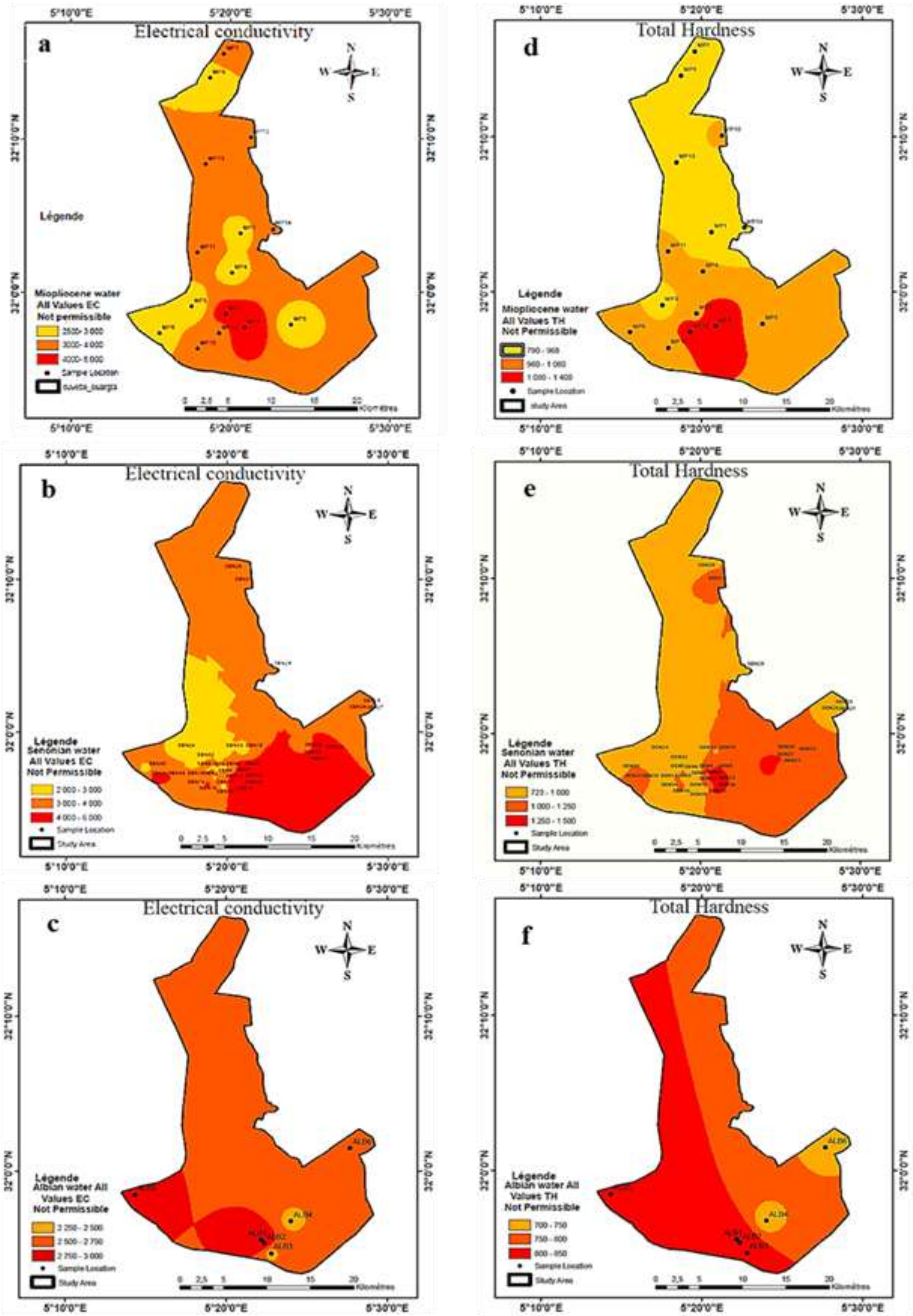

Figure 4 (a – f): *Spatial variation maps of EC, and TH for aquifers Miopliocene, Senonian, and Albian.*

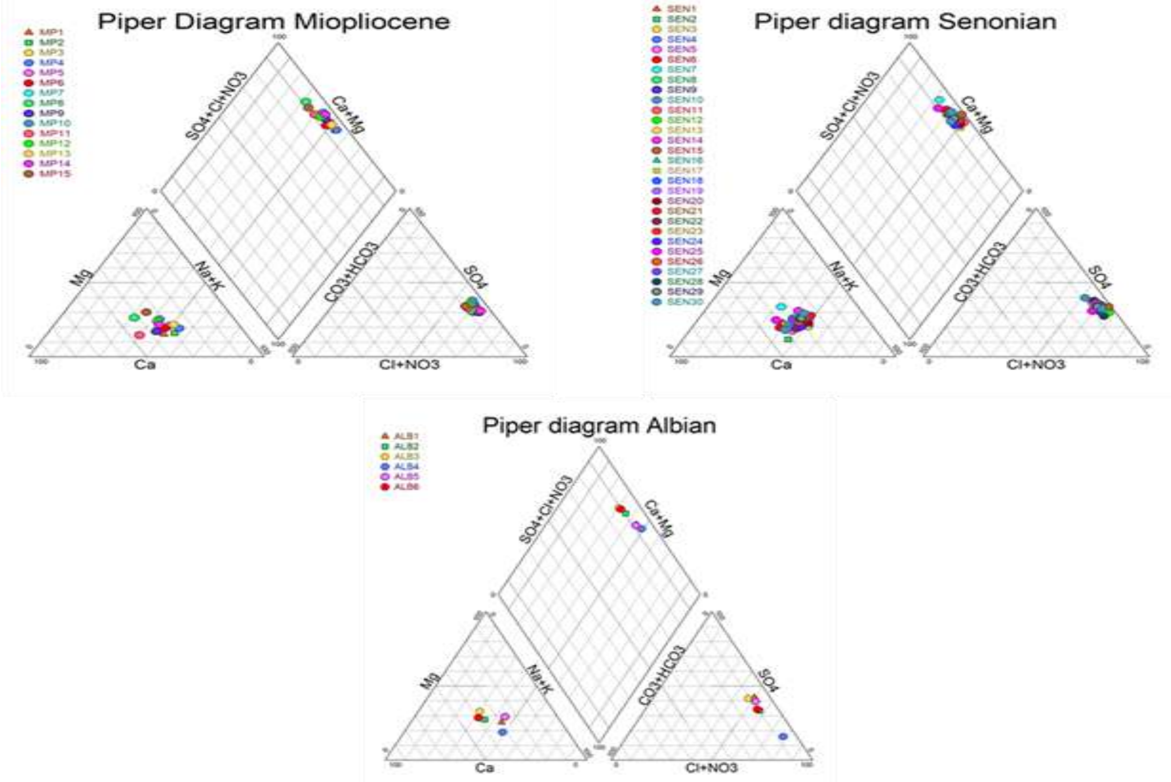

Figure 5:*Piper diagrams for for aquifers Miopliocene, Senonian, and Albian*.

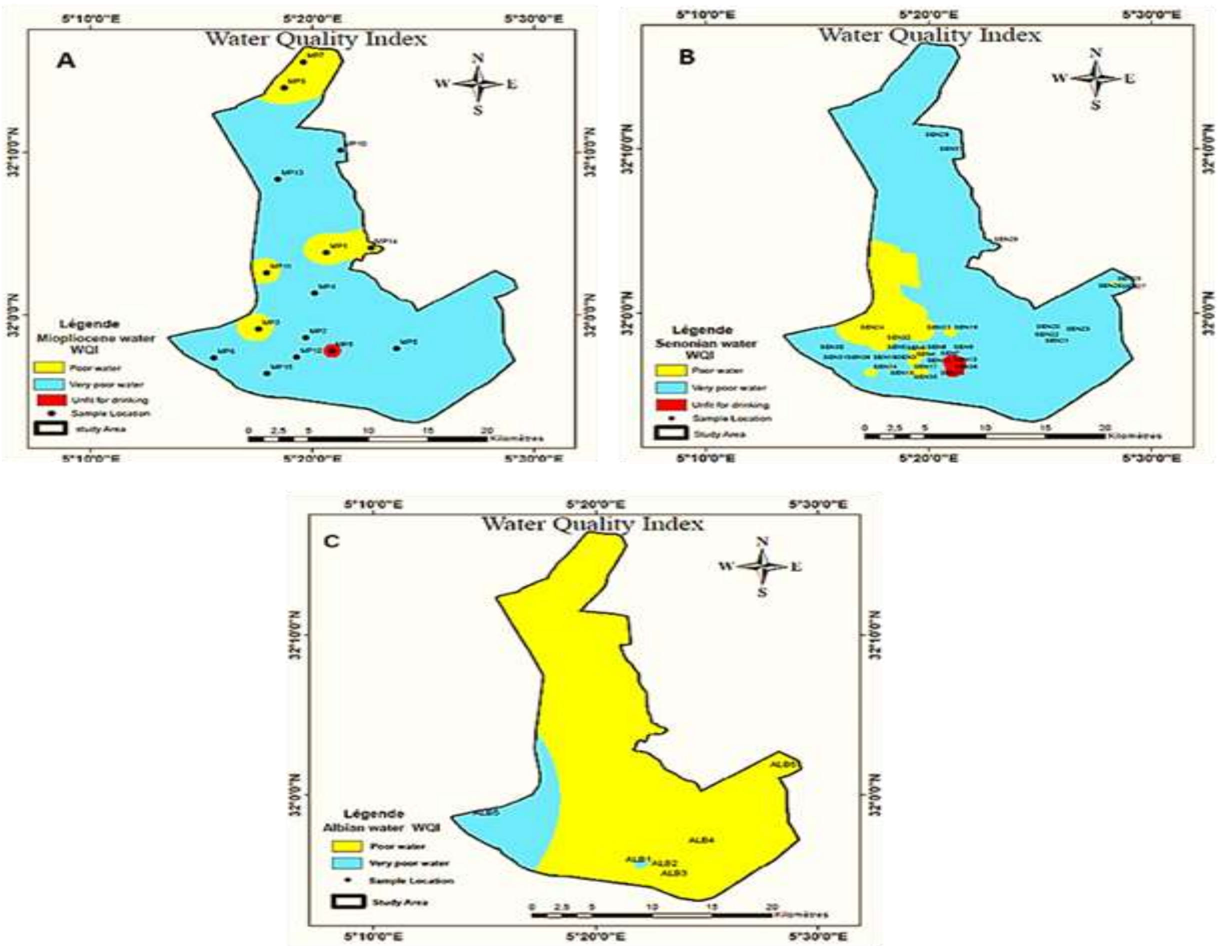

Figure 6 (A – C): *Spatial variation maps for Water quality index (WQI) of Drinking Purpose for three aquifers*

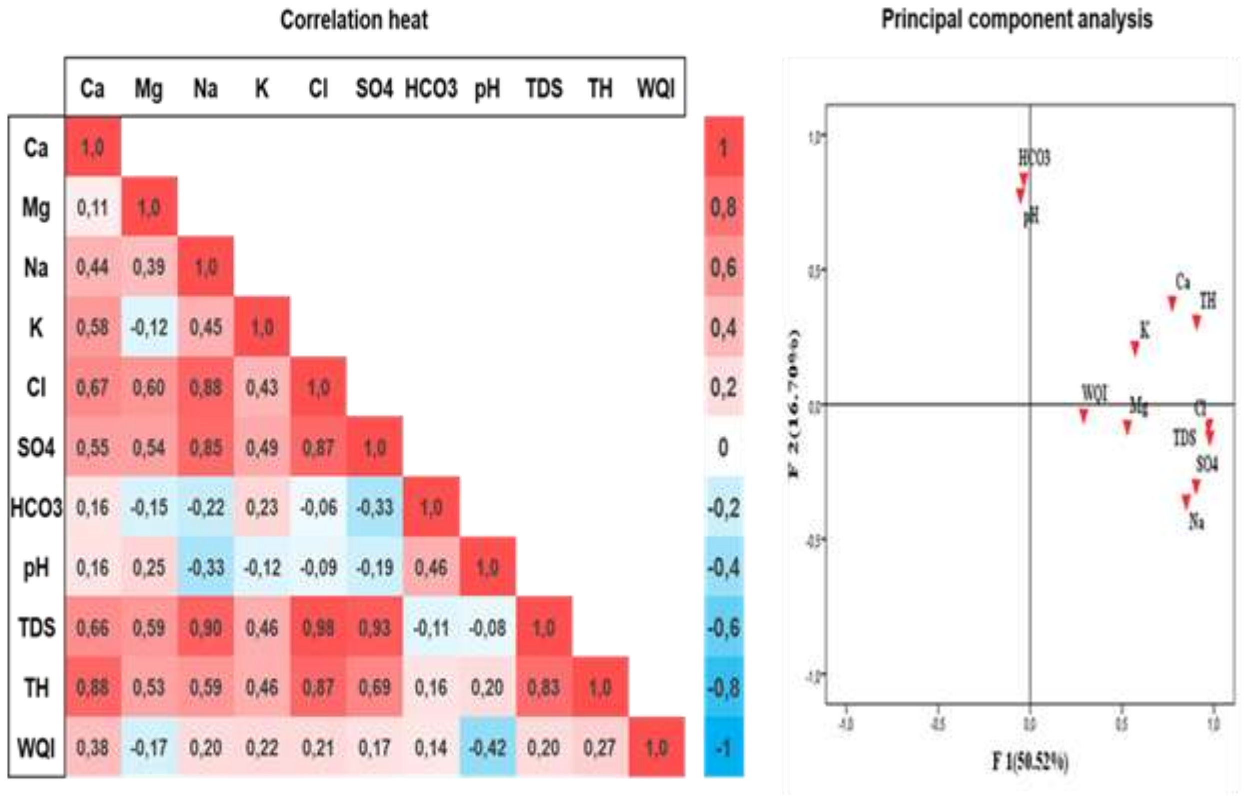

Figure 7:*Correlation heat plot and Principal component analysis biplot (2PC) for the Miopliocene aquifer*

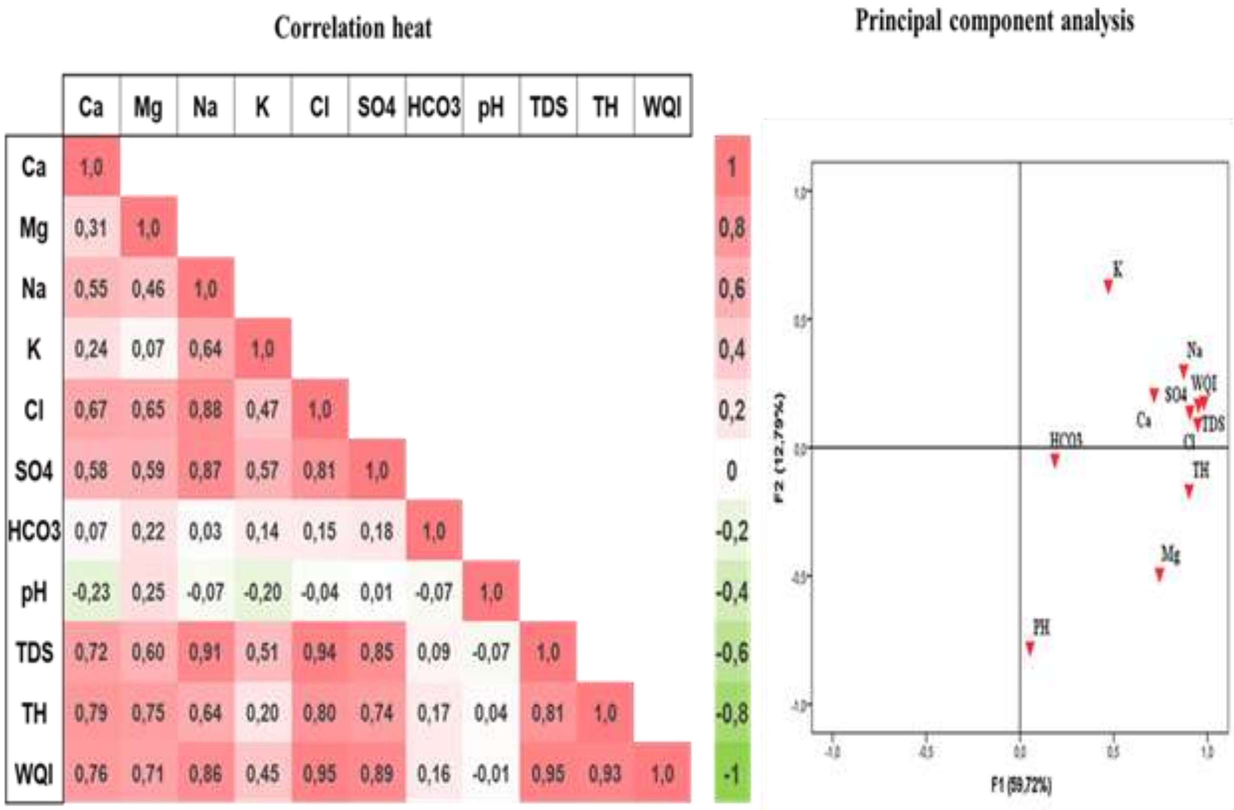

Figure 8: *Correlation heat plot and Principal component analysis biplot (2PC) for the Senonianaquifer*

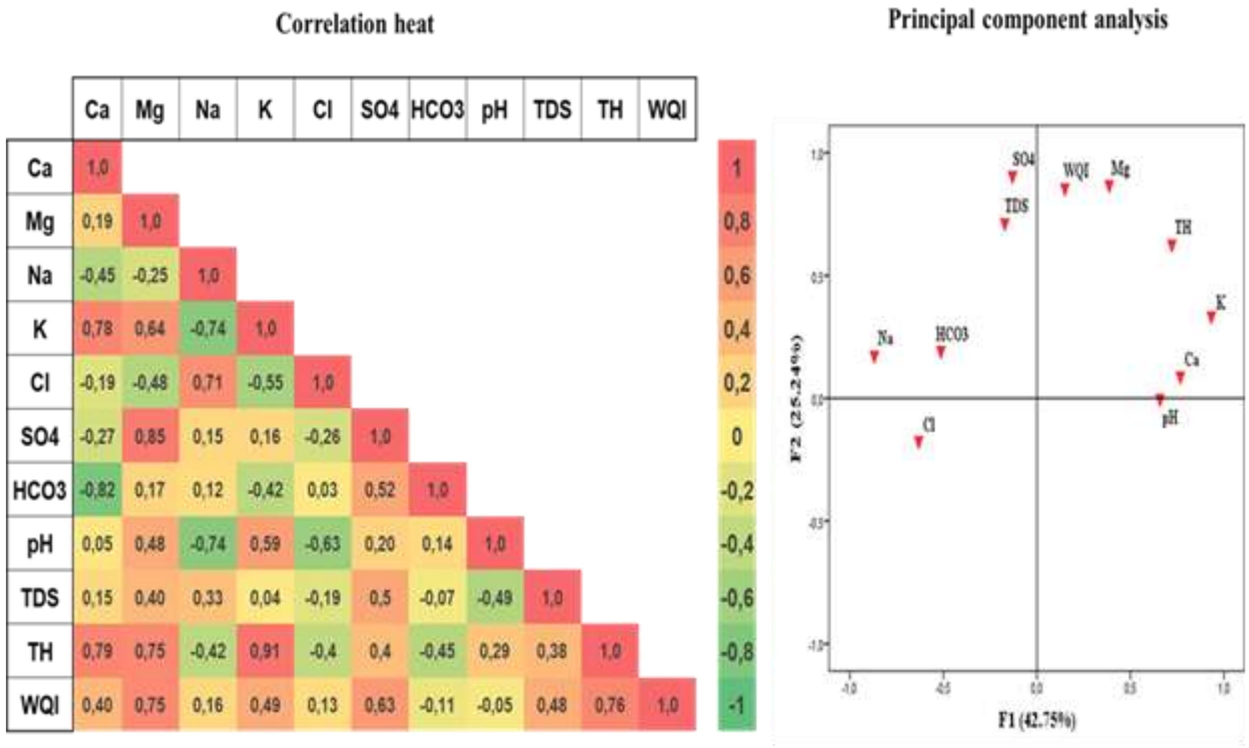

Figure 9: Correlation heat plot and Principal component analysis biplot (2PC) for the Albian aquifer

5. Conclusions

In this study, groundwater quality and its suitability for drinking purposes were evaluated across different aquifers in the Ouargla region. The assessment utilized a hydrochemical approach, the Water Quality Index (WQI), and Geographic Information System (GIS) tools. The key findings of the study are as follows:

• The groundwater system across the study area is weakly alkaline. TDS values indicate that the water in the Miopliocene and Senonian aquifers often exceeds the limits established by the World Health Organization (2011), while the water in the Albian aquifer is generally slightly below the permissible limit. All aquifers exceed the permitted limits for electrical conductivity and total hardness, reflecting very high conductivity and hard to very hard groundwater in the study area.

GIS-based spatial analysis using spline interpolation techniques represented the spatial variation of pH, EC, TDS, and TH. Higher concentrations are predominantly found in the southern portion of the study area and decrease with the depth of the aquifer from the Mioplioceneto the Albian aquifer.

• The study of chemical facies shows that the groundwater in the study area is of the mixed Ca-Mg-Cl, Ca-Cl, and Na-Cl types, with dominant ions being chlorides and sulfates, as well as calcium and magnesium. This is attributed to water-rock interactions.

• The WQI was used to evaluate groundwater quality and its suitability for drinking purposes. The WQI values for the Ouargla basin range from 174.69 to 312.71. The majority of the water falls into poor or very poor quality categories. The WQI has a strong positive or weak positive correlation with most elements, except for pH and HCO_3^-, which have negative or very weak correlations.

• Two factors are related to the formation of groundwater quality in the study area. Factor 1 characterizes the natural hydrogeochemical characteristics through water-rock interactions, described by the dissolution of minerals in rocks. Factor 2 reflects the weathering and dissolution of carbonate minerals from the soil.

•There were no significant differences in the hydrochemical properties of the Miopliocene and Senonian aquifers, likely due to their interconnection. However, the Albian aquifer differs due to its diverse soil composition and significant depth.

• In general, the water in the study area is excessively saline, with concentrations of major elements exceeding WHO potability standards. This confirms the poor quality of these waters for human consumption, indicating that demineralization is necessary before use.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of 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

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- **Author contributions:** Conceptualization, MERKhOUFI Abdelmalek; Formal analysis, MERKhOUFI Abdelmalek; Investigation, MERKhOUFI Abdelmalek; Methodology, MERKhOUFI Abdelmalek and KATEB Samir; Project administration, KATEB Samir; Software, MERKhOUFI Abdelmalek; Supervision, KATEB Samir and BAOUIA Kis; Validation,KATEBSamirandBAOUIAKis;Writing–original draft, MERKhOUFI Abdelmalek; Review & editing, KATEB Samir and BAOUIA Kis.

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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