


Hydrochemical characteristics of aquifers and their predicted impact on soil properties in Biskra region, Algeria

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ABSTRACT

Biskra has seen an intensification of agricultural activities in the last few years, and groundwater is widely exploited for irrigation. An investigation has been carried out where water samples are taken according to the standard protocol from 32 boreholes and artisanal wells, thus affecting the three main aquifers (Quaternary, Mio-Pliocene and Senono-Lower Eocene). The study methods are based on the application of Diagrams (Piper, Riverside, Wilcox) and Phreeqc (saturation index). Electrical Conductivity (EC), Percent of Sodium Ions (% Na⁺), Residual Sodium Carbonate (RSC), Sodium Adsorption Ratio (SAR), Kelly's Index (KI) and Permeability Index (PI) are used to characterize potential impacts on soil properties. The analytical results obtained show that the groundwater of the 3 aquifers is neutral and highly mineralized (EC reach of 5 dS/m). The chemical facies are Na-Cl, Ca-Cl and Na-SO₄. In relation to the geological conditions, the dominant cations and anions in the ion procession are Na⁺, Ca²⁺ and SO₄²⁻, Cl⁻ respectively. Carbonate minerals (dolomite, calcite, and aragonite) are found in water in saturated to over-saturated states. Evaporite minerals (anhydrite, gypsum, and halite) evolve from a state close to equilibrium to a sub-saturated level. The Riverside (SAR and EC) and Wilcox (% Na⁺ and EC) diagrams was applied to the 3 reservoirs reveal excessively mineralized water and are of poor to low quality. RSC index values show a low risk of soil sodization and PI values indicate good quality water for agricultural use. However, the results of the KIs indicate water of poor quality is recommended for irrigation.

Keywords: Aquifer, Soil, Hydrochemical status, Algeria

INTRODUCTION

In less than fifty years the world population has doubled, world food supplies have decreased and energy, land, biological and water resources have become under great pressure (Dal Ferro, 2009). In North Africa, the cultivation of new agricultural areas has become necessary to supply the growing population's food needs (Semar *et al.*, 2019). However, most of these lands are located in dry areas where the soil and water quality are poor and in some cases have inefficient drainage systems and high water table positions (Hassine, 2005; Hatira *et al.*, 2007; Askri and Bouhlila, 2010). In arid environments, no agricultural activity can be developed and prosper without the use of water for irrigation (Smadhi *et al.*, 2017). The environment of these regions is harsh (Amirouche *et al.*, 2021), marked by high temperatures accompanied by strong evaporation (Bouhlila, 2010; Oumata *et al.*, 2020). Precipitations are rare and random (Bachir *et al.*, 2021). Soils are often sandy, poor in clays and organic and salty matter (Hassine, 2005; Hatira *et al.*, 2007). As a result, no agricultural project can be envisaged without the use of groundwater. Due to the presence of significant water reserves in the aquifers of the continental intercalary and terminal North Sahara (Algeria, Tunisia), estimated at 60 000 billion cubic meters (Margat 1990). The Algerian state has encouraged the development of Saharan agriculture which is mostly and dependent on groundwater resources pumped from the complex terminal aquifer (Kuper *et al.*, 2016). This later is intended to reduce unemployment on the one hand and to guarantee food security (Dubost, 1991; Bessaoud, 2006). The Saharan agricultural systems are drastically threatened by the encroachment of sand dunes (Boulghobra *et al.*, 2015), the rapid decline in groundwater resources and the salinization of soil and water due to poor management (Brooks *et al.*, 2003). As a result, no agricultural project can be envisaged without the use of groundwater. In addition, groundwater is poorly renewable (Margat *et al.*, 2006, Al-Gamal, 2011) and mineralized (Daoud and Halitim, 1994; Dubost and Moguedet, 2002; Semar *et al.*, 2013) and their use requires precautions. Irrigation from poor quality water is a problem for crop development and yields (Richards, 1954; Wilcox, 1955; Ayers and Westcot, 1994; Oster, 1994).

Several studies on water quality in the irrigation field have been carried out and have all underlined the importance of considering preliminary studies before undertaking irrigation-based agricultural projects (Alicia *et al.*, 2009; Li *et al.*, 2013; Wanda *et al.*, 2013; Nagaraju *et al.*, 2014; Ravikumar *et al.*, 2015; Das and Nag, 2015). In Algeria, there is, in general, a lack of knowledge of links established between hydrochemical processes and the quality of groundwater and thus the quality of irrigation water and its effect on soil. Some ad hoc work (Fehdi *et al.*, 2009; Belkhiri and Mouni., 2012; Hamamouche *et al.*, 2017; Abdennour *et al.*, 2020) are carried out in particular in arid and semi-arid zones. In this study, the assessment of the geochemical status of groundwater from captured aquifers (Quaternary, Mio-Pliocene and Senono-

Lower Eocene) is conducted in the Biskra region, where agricultural activity based on irrigation practice dominates. This study also proposes the evaluation of groundwater suitability for irrigation. Several methods of quality analysis of irrigation water are proposed in the literature. In this research, the parameters raised relate to the electrical conductivity (EC), the sodium absorption Ratio (SAR), the percentage of sodium (% Na), the residual sodium carbonate (RSC), the permeability index (PI), Kelly's index or Kelly ratio (KI).

The preliminary results serve as a basis for generalizing this approach at the scale of large agricultural areas on the one hand and the different hydrogeological reservoirs exploited in this region.

Study area description:

Biskra is located about 400 km south-east of Algiers, the capital of Algeria (Figure 1). It corresponds to the geological and geomorphological, or even climatic, transition zone between the Tellian domain to the north and the Sahara to the south. The district of Biskra is a vast area with an average altitude of 100 m delimited by the Aurès reliefs to the north and north-east, while it opens out to the south with the Sahara. The study zone is delimited between 33.4° and 35.2° north latitude and 4.2° and 6.8° longitude covering an area of 21671 square kilometres.

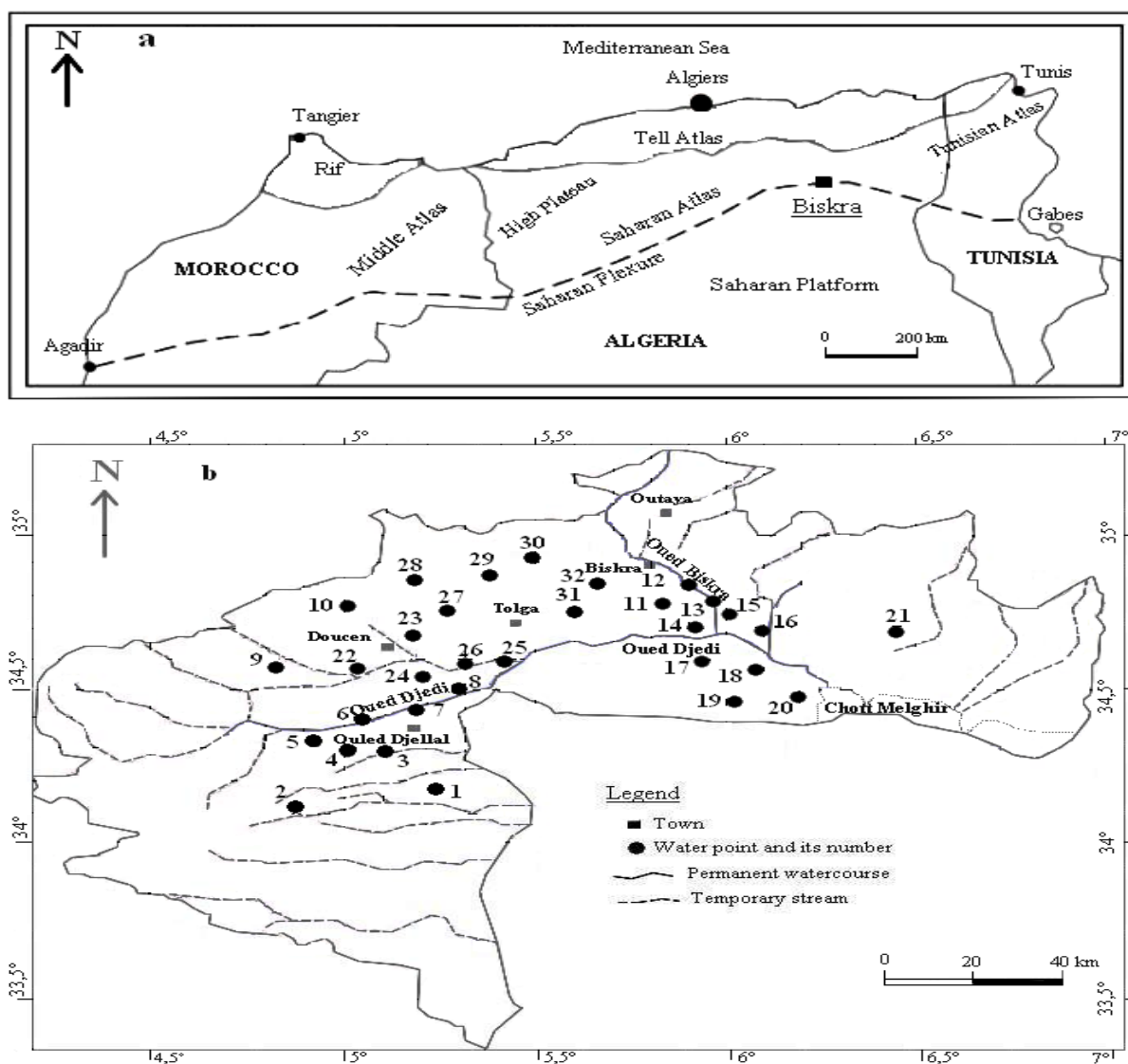


Figure 1: Presentation of the study area: a. Scheme of structural units of North Africa (modified after Durand Delga and Fontboté, 1960), b. Positioning of the points in Biskra.

Biskra is known for its arid climate with low and erratic rainfall, while temperatures are particularly high during the summer period (Figure 2). Soils in arid regions have a number of almost constant characteristics: slow evolution, weakly defined structure with often calcareous, gypsum or saline crusts (Aubert, 1960), for this purpose, it describes arid regions as the privileged domain of salt pedogenesis with the following consequences: soils that are generally not very fertile, shallow, and too calcareous or too gypsky, salty, poor in organic matter, unfavourably basic pH and a neutral salinity pathway and sensitivity to degradation and desertification (Halitim and Robert, 1992; Hamdi-Aissa et al., 2004). The region of Biskra is known as agricultural regions with main crops cultivated are date palm, vegetable crops under greenhouse, fruit trees, industrial crops and tobacco.

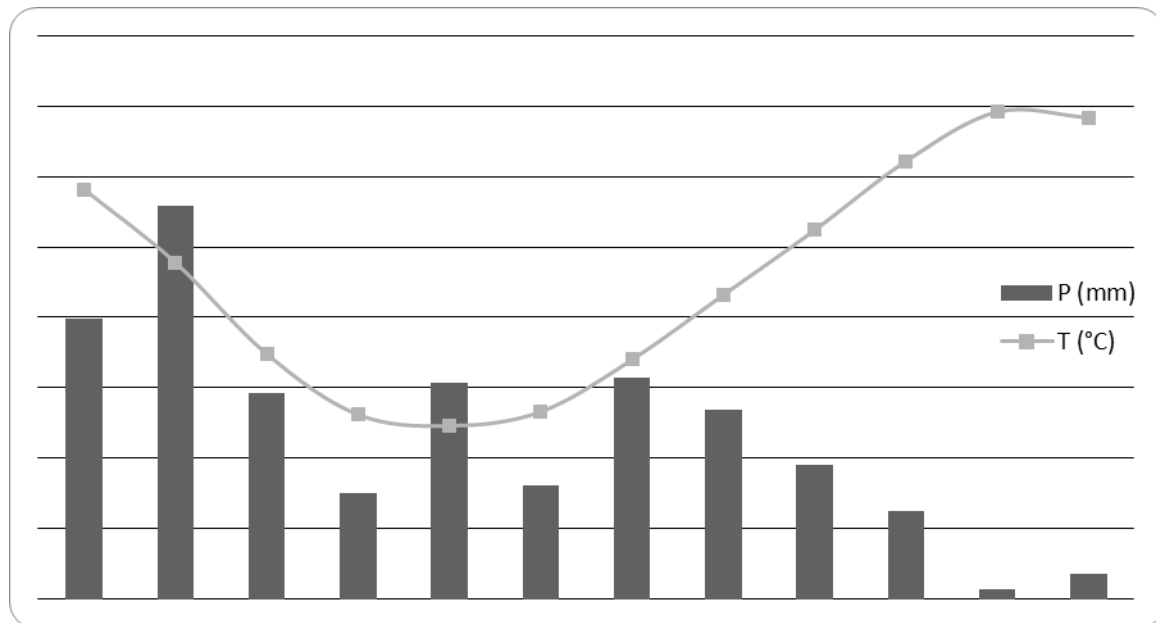


Figure 2: Monthly precipitation and temperature distribution at the Biskra Airport Station (2006-2015 period)

Hydrogeological framework:

Geologically, the region of Biskra is complex because it corresponds to the transition between the atlastic, mountainous and folded area and the Saharan area, flat and desert. This zone is marked by the southern atlastic accident, which is manifested by a set of folds, and tectonic accidents. This continuous accident extends over 2000 km, from Agadir in Morocco to Gabès in Tunisia. Many authors (Busson, 1972; Fabre, 1976; Guiraud, 1975; Chebbah, 2007) have studied lithology, tectonics and palaeogeography regions. Various hydrogeological studies are carried out (Nesson, 1978; Sy, 2007; Chabour, 2006) in particular by numerical modelling (Cavazza, 1968; OS et sahel, 2008). The latter have defined two major aquifer units at the Sahara scale: the Complex Terminal (CT) and the Continental Intercalaire (CI). The CT in the strict sense includes Senonian, Eocene, Miocene, and Plio-Quaternary, while the CT in the broad sense also includes Turonian. The CI corresponds to the horizons of Barremian, Aptian and Albian (Table 1). In the Ziban region the Lower Senonian is a lagoon and thus becomes the wall of the Terminal Complex. The Turonian is a limestone formation and its permeability depends on the degree of fracturing that affects it. These modelling studies are aimed at quantifying water resources and proposing transboundary exploitation schemes (Algeria, Libya and Tunisia). The aquifer formations are all of sedimentary origin resulting, during its geological history, long alternating marine and continental sedimentation phases that have resulted in a variety of lithological facies.

Table 1: Hydrogeological formations of the study area

Geological eras	Lithology	hydrogeological units	aquifer complex	
Quaternary	Alluvions, sands, clays, conglomerates	Permeable	quaternary groundwater	
Mio-pliocene	Alternating clays and sands, conglomerates	Permeable	Sandy groundwater	
Middle Eocene	gypsum clay	semi-permeable		
Lower Eocene	Limestones and clays	Permeable	Limestones groundwater	
Upper Senonian	Limestones	Permeable		
Maestrichtien Campanian				
Lower Senonian	Clay, gypsum, salts	Impermeable		
Turonian	Dolomitic limestones, dolomy	permeable (cracking function)	Turonian groundwater	
Cenomanian	Clay, marls and limstones, gypsum	Impermeable		
Albian	Limestone, marls, sandstone	Permeable	Continental Intercalaire	CI
Aptian	sandstone, dolomies			
Barremian – Lias	sandstone			

Quaternary water table:

At the level of the study area, the work carried out made it possible to describe the main aquifers as follow:

This sheet is generally located in the plains and wadis beds. It consists of sands, gravels, pebbles and sometimes clays. The aquifer is fed mainly by precipitation water, floods of wadis and returns of irrigation water. The water tables are shallow, between 2 and 50 m, the most important of which are Ouled Djellal, Sidi Khaled, Doucen, Tolga, Biskra wadi and especially Djedi wadi where they are widely exploited in irrigation. Palm groves. The flows converge on the Chott Melghir. The substratum of the aquifer rests, generally, on impervious clay formations of the Pliocene or in discordance on the Middle Eocene lagoon, when the Mio-Pliocene is absent, as it is the case at the level of Ouled Djellal and Sidi Khaled.

The Mio-Pliocene sands table:

The Mio-Pliocene sand sheet contains several aquifer levels of heterogeneous composition where gravel and sand are found in a clay matrix. In-depth, the formation becomes predominantly sandy-clay and rests on an impermeable formation composed of gypsum marl and Middle Eocene anhydrite. The sheet of sand is covered with a quaternary alluvial deposit more or less thick. The Mio-Pliocene sheet outcrops in places, bringing the aquifer into direct contact with the surface, thus ensuring its supply from surface water. To the east of the District of Biskra, this aquifer is subdivided into two aquifers separated by a thick layer of clay and sandy clay, the deep one designated by the name of the Pontian and the other moderately deep which is the tablecloth of the Mio-Pliocene. The main flow direction of the sand table is from the northwest to the southeast to Melrhir Chott. At the level of the plain of Outaya, this tablecloth is constituted by an alternation of clays, sands, gravels puddings and conglomerates with past gypseous. Geophysics has shown that it is in the eastern part that we observe the greatest extension of the Pliocene puddings that form the bulk of the aquifer system. These conglomeratic formations can reach thicknesses of 200m in the valley of the Biskra wadi. The average porosity of the Mio-Pliocene sheet is estimated at 30%. The transmissivity is very heterogeneous, it varies from 4 to $7.10^{-3} \text{ m}^2 / \text{s}$ and the storage coefficient oscillates between 10 and 50%. The general flow is from north to south.

Senono-Lower Eocene limestones water table

In the Ziban region, the most important aquifer of the CT is the Upper Senonian and Lower Eocene limestone nappe. The Senonian is individualized in two facies: at the base, the Eocene is formed mainly by dolomites and dolomitic limestones with some intercalations of marl, clay and even anhydrite, rock salt; facies considered very poorly permeable

and above the upper Senonian or Senonian carbonated permeable carbonaceous nature. The power of the lower Eocene formation varies between 100 and 500 m.

The carbonate Senonian, largely affected by cracking, is very productive and the water quality is good. The limestones of the Senono-Eocene complex, exposed in the southern part of the Saharan Atlas, contribute to the recharge of the Sahara aquifers. The reservoir of the limestone nappe is formed in the Tolga region by Lower Eocene limestones and is in communication with the upper Senonian formation of the same facies and can also be with the Turonian formations, despite the semi-permeable screen of the lower Senonian. Their thickness is estimated at 150 m to 250 m. The water table is in charge over a large part but the overexploitation has affected the water table. The flow of groundwater is generally from west to east. Test pumping in the Tolga area revealed transmissivities for the lower Eocene that ranged between 10⁻¹ and 10⁻² m² / s.

Turonian water table:

At Biskra the Turonian is composed of crystalline limestones, marly limestones and dolomitic limestones. Its power varies between 300 and 400 m. It is very homogeneous on both sides of the Atlas flexure. On the other hand, some aquifers of the complex terminal and especially the karstic complex of formations ranging from Turonian to Middle Eocene will be considered as a regional (sometimes multilayered) aquifer system spanning several sectors. On the other hand, the Cenomano-Turonian, marly and clay forming the substratum of the CT in the Sahara, is formed by carbonate formations at the level of the Saharan Atlas and Aurès.

Continental Intercalaire:

The Continental Intercalaire (CI) covers an area of 600 000 square kilometres and covers almost the entire northern Algerian Sahara. This aquifer consists of a clay-sandstone-sandstone formation of continental origin with important sedimentary layers of marine or lagoon origins, in particular, that of the Aptian. The percentage of clays can be very important in the eastern basin, basin generally artesian. At the level of the study area, this sheet is about 500 m thick and the depth of the roof is about 2000m. The roof of the CI corresponds to the Cenomanian clay and evaporite formations whose thickness can reach several hundred meters in the central part of the Algerian basin. The wall is ill-defined. The exploitation of this sheet is very expensive because of its depth, the temperature of the water being able to exceed 60°C. The direction of flow seems to be from North West to South East. The waters converge towards the Tunisian outlet by the Mednine fault.

MATERIALS and METHODS

Sampling waters and analyzes:

Water sampling included the quaternary aquifer (10 samples), Mio-Pliocene (11 samples) and the Senono-Lower Eocene (11 samples). These reservoirs are widely used for irrigation of different crops. In contrast, in the infill, the groundwater of these aquifers is relatively more mineralized. The groundwater sampling campaign took place from April 24 to May 9, 2016, where 32 samples were collected through boreholes and artisanal wells. Sampling procedures are performed according to standardized methods (ALPHA, 2005). A sample of water (one liter) is collected in pre-cleaned polyethylene bottles and rinsed with water. The samples were acidified with HNO₃ at pH = 2. All the samples were analyzed by major ions according to standard methods. Field measurements (pH, T and EC) are made by multi 340i portable multifunction device. Calcium and magnesium are determined by the complexometric titration method compared to the standard EDTA solution while sodium and potassium are evaluated by flame photometry. The chloride concentrations are determined by titrimetry according to the standard solution of AgNO₃. The contents of nitrates and sulphates are determined spectrophotometrically. The quality of the hydrochemical data is evaluated by the ionic balance establishing the relationship between all the cations (Ca²⁺, Mg²⁺, Na⁺, K⁺) and the total anions (Cl⁻, SO₄²⁻, HCO₃⁻ and NO₃⁻) for each complete analysis. In the reliability of the results, a threshold of 10% is retained.

Hydrochemistry:

From the chemical classification point of view, groundwater is classified according to the cation and the dominant anion. The chemical facies of groundwater is illustrated by Piper diagrams using the Diagram program (Simler, 2009). This diagram is composed of two triangles, one on the cationic facies and the second on the anionic facies. The projections of these two cationic and anionic facies define, in a diamond, the chemical facies of the considered water. The calculation of aqueous speciation at the field temperature and the thermodynamic equilibrium conditions of the water with respect to the principal phases present in the aquifer is based on geochemical modelling using the code Phreeqc v2.16 (Parkhurst and Appelo, 1999). The saturation index (SI) is calculated based on the logarithm of the ratio between the ionic activity product (IAP) and the equilibrium constant (K). The saturation index is used to define whether groundwater is saturated, under-saturated or over-saturated with respect to certain minerals (calcite, dolomite, aragonite, gypsum, anhydrite, gypsum, halite). The saturation state (SS) of a solution relative to a solid is defined as follows:

$$ES = IAP / K \quad (1)$$

If ES = 1, ie IAP = K, there is equilibrium, if ES > 1, IAP > K in this case, there is supersaturation and if ES < 1, IAP < K, there is under saturation.

The transition from the saturation state (ES) to the saturation index (SI) is done by the formula (2):

$$SI = \log ES = \log (IAP / K) \quad (2)$$

According to Drever (1982); Hem (1985); Appelo and Postma (2005), if a saturation index is zero ($SI = 0$), indicates that the analyzed water is saturated for the mineral and establishes a balance with the solids. A positive saturation index ($SI > 0$) means that the water sampled is over-saturated with respect to the mineral considered and therefore precipitation and deposition occur. A negative saturation index ($SI < 0$) explains that the water is undersaturated with respect to the mineral and consequently a dissolution occurs. Base exchanges are evaluated by the Chloro Alkaline Index (CAI) approach according to Schoeller's concept (1965, 1977). The latter suggests two Chloro Alkaline Index (CAI) indices to interpret the ions exchanged between the groundwater and the solid matrix. The indices of Schoeller are calculated by relations 3 and 4:

$$CAI-1 = [Cl^- - (Na^+ + K^+) / Cl^-] \quad (3)$$

$$CAI-2 = [Cl^- - (Na^+ + K^+) / SO_4^{2-} + HCO_3^- + CO_2 + NO_3^-] \quad (4)$$

The Cl^- , Na^+ , K^+ , SO_4^{2-} , HCO_3^- , CO_2 , NO_3^- ions are expressed in meq / l. According to the CAI sign, three situations arise:

- If the index is positive, the Na^+ and K^+ cations of the groundwater are exchanged for the Ca^{2+} and Mg^{2+} ions of the solid matrix,
- If the index is negative, there is an exchange of Ca^{2+} and Mg^{2+} ions of the groundwater with the Na and K ions of the surrounding formations,
- If the index is zero, in this case, there is a balance between the chemical composition of the groundwater and that of the surrounding land. There is no exchange.

Suitability of water for irrigation:

The suitability of water for irrigation is a key factor in the development and growth of certain crops. The water of poor quality can affect soil, agricultural production and the environment in general. The widely used parameters in the literature (Sumner, 1993; Ayers and Westcott, 1994; Al Bassam and Al Rumikhani, 2003; Ravikumar and Somashekar, 2011; Etteieb *et al.*, 2017) for assessing the suitability of water for irrigation are electrical conductivity (EC), the sodium absorption ratio (SAR), the percent of ion sodium (% Na), the residual sodium carbonate (RSC), the permeability index (PI), the Kelly index (KI).

The SAR is calculated by the formula 5 where the ions are expressed in meq / l. The % Na is quantified by equation 6 which involves the major cations present in the water. The cations are expressed in meq / l.

$$SAR = Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+}) / 2]} \quad (5)$$

$$\% Na = [(Na^+ + K^+) / (Ca^{2+} + Mg^{2+} + Na^+ + K^+)] 100 \quad (6)$$

The Riverside diagram constructed based on SAR and EC hazards as well as the Wilcox plot of the %Na and EC is used to characterize groundwater suitability for irrigation.

Residual sodium carbonate index (RSC) is calculated to assess the adequacy of groundwater relative to bicarbonate and carbonate contents using Equation 7, where the ions are expressed in meq/l. Furthermore, in the case of chlorinated chemical facies, SAR frequently minimizes the risk of sodization and alkalization of the water. For this reason, residual sodium carbonate index (RSC) has been adopted as another means of assessing irrigation water quality.

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (7)$$

A positive RSC indicates a risk of sodization. If the index is negative, the inclusion of sulphate ions in equation (8) is recommended.

$$RSC' = (HCO_3^- + CO_3^{2-} + SO_4^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (8)$$

Soil permeability can be affected, in the long term, by irrigation water which is rich in Na^+ , Ca^{2+} , Mg^{2+} , and HCO_3^- . The permeability index (PI) is calculated according to equation 9 and it is used to assess the influence of irrigation water on the physical properties of soils. Where the ions are expressed in meq/l.

$$PI = [(Na^+ + \sqrt{HCO_3^-}) / (Ca^{2+} + Mg^{2+} + Na^+)] 100 \quad (9)$$

Kelly's index is calculated to assess the suitability of water for irrigation according to equation 10 where the cations are expressed

$$KI = Na^+ / (Ca^{2+} + Mg^{2+}) \quad (10)$$

According to Marlet and Job (2006), we distinguish waters at risk of sodication ($RSC' > 0$) described as "chloride-dominant neutral saline route" from those that do not carry this risk ($RSC' < 0$) and described as "sulphate-dominant neutral saline route".

RESULTS

Geochemistry:

The analytical results of the chemical and statistical analyses of the groundwater parameters of the three aquifers studied are included in Table 2.

Table 2: Statistical description of the physical and chemical groundwater parameters of the three aquifers

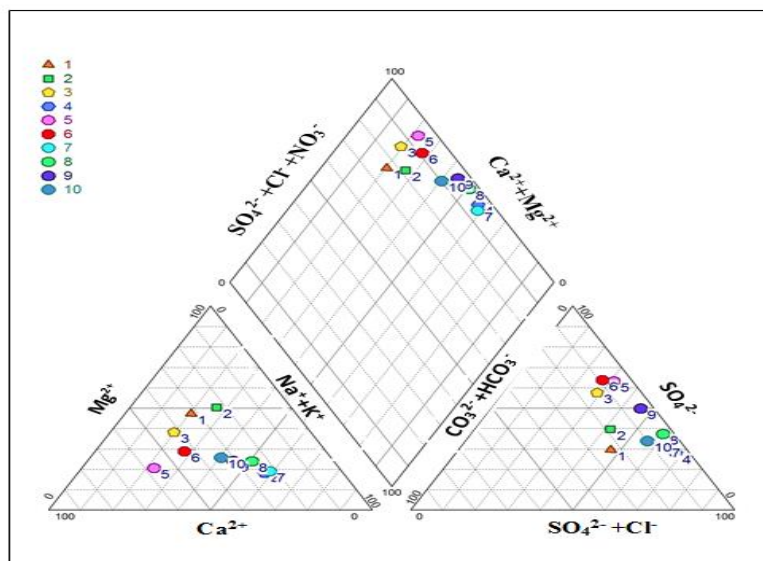
Paramètres	Quaternary water table (10 samples)			Mio-Pliocene water table (11 samples)			Senono-Lower Eocene (11samples)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
pH	7	7,29	7,16	6,76	7,51	7,02	6,92	7,46	7,21
EC ($\mu\text{S}/\text{cm}$)	1536	11 210	5 450,6	2 880	7 990	5 446,36	1924	8 890	4 221,27
TDS (mg/l)	1455	7508	4071,7	2713	7371	4416,27	2775	6274	3733,91
Ca ²⁺ (mg/l)	124	632	447,2	216	528	362,18	296	624	396,36
Mg ²⁺ (mg/l)	139,2	352,8	220,56	64,8	429,6	199,42	53,4	254,4	158,4
Na ⁺ (mg/l)	131,23	1737,26	722,42	275,89	1685,07	930,15	223,7	1371,92	728,2
K ⁺ (mg/l)	6,29	58,90	27,33	5,3	33,8	18,12	7,30	38,9	16,5
Cl ⁻ (mg/l)	284	2485	1153,75	355	2165,5	1307,05	461,5	1526,5	881,05
SO ₄ ²⁻ (mg/l)	366,31	1786,46	1201,26	505,26	2616,54	1343,54	848,1	2165,4	1301,9
HCO ₃ ⁻ (mg/l)	158,6	424,56	274,99	141,52	322,08	233,35	202,5	292,80	234,7
NO ₃ ⁻ (mg/l)	5,73	65,97	24,09	0	120	22,03	0	45	16,8
CAI-1	-0,24	0,50	0,07	-0,94	0,26	-0,18	-1,15	0,44	-0,31
CAI-2	-0,18	0,43	0,06	-0,27	0,73	-0,07	-0,57	0,29	-0,21

The results reported in [table 2](#) show that the pH varies between a minimum value of 6.76 for the Mio-Pliocene aquifer and a maximum value of 7.51 for the same reservoir. The average pH values are 7.16; 7.02 and 7.21 respectively for the Quaternary, Mio-Pliocene and Senono-Lower Eocene aquifers. Groundwater is neutral to slightly alkaline. The EC of groundwater oscillates between the minimum value of 1536 $\mu\text{S}/\text{cm}$ in the quaternary aquifer and the maximum of 11210 $\mu\text{S}/\text{cm}$ in the same hydrogeological reservoir. We observe a relatively high average in the Mio-Pliocene aquifer compared to other hydrogeological reservoirs. TDS equivalents also vary between 1455 mg / l and 7508 mg / l in the Quaternary aquifer. All water points have a TDS greater than 1455mg / l. Mean TDS values are greater than 3500 mg / l and suggest very mineralized waters (TDS > 1000mg/l) according to the Fetter ([2018](#)) classification. The groundwater of the 3 layers has excessive mineralization. The aquifers formed of an evaporitic lithology probably confer this excessive mineralization.

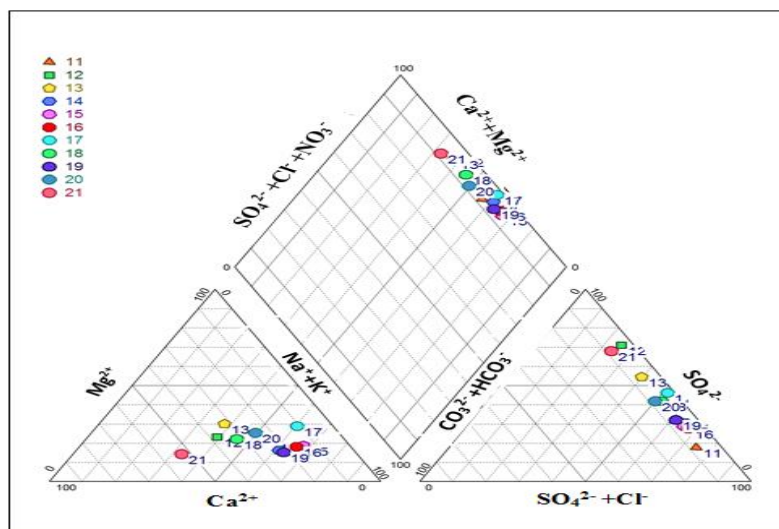
Among the cationic procession of the waters analyzed the maximum concentrations of Na⁺ are 1737.26 mg / l and 1685.07 mg / l found respectively in the Quaternary and Mio-Pliocene aquifers. The Senono-Lower Eocene aquifer, with a content of about 1372 mg / l, is relatively the least important. The minimum Na⁺ levels are 131.23 mg / l and 275.89 mg / l respectively observed in the Quaternary and Mio-Pliocene reservoirs. The Senono-Lower Eocene aquifer has a value of 223.7 mg / l. In terms of mean Na⁺ concentrations, the Mio-Pliocene sheet dominates with a value of 930.15 mg / l while the Senono-Lower Eocene and Quaternary reservoirs respectively have 728.2 mg / l and 722.4 mg / l. The high Na⁺ concentrations are likely to be related to basic exchanges and to the geological formations present in the region, such as those in the Outaya region exploited as a salt ore of the sodium chloride (halite) type. The Ca²⁺ contents follow those of Na⁺, in order of predominance, their values range from 362.18 mg / l for the Mio-Pliocene layer to 447.2 mg / l for the Quaternary layer. The Senono-Lower Eocene aquifer has an average of 396 mg / l. The high concentrations, found at a few points of water catching the Senono-Lower Eocene aquifer, are related to the predominance of calcareous soils. Mg²⁺ levels are rather low compared to those of Ca²⁺. The results vary between 158.4 mg / l for the Senono-Lower Eocene aquifer lower than 220.56 mg / l for the Quaternary reservoir. The Mio-Pliocene web gives an intermediate value of 199.4 mg / l. Mg²⁺ is generally present in dolomitic rocks and has a chemical affinity for Ca²⁺. The K⁺ contents are low, they do not exceed 28 mg / l. The Senono-Lower Eocene water table has a minimum average of 16.5 mg / l and the quaternary water has a value of 27.33 mg / l. The Mio-Pliocene sheet indicates a value of 18.12 mg / l.

Hydrochemical facies of waters:

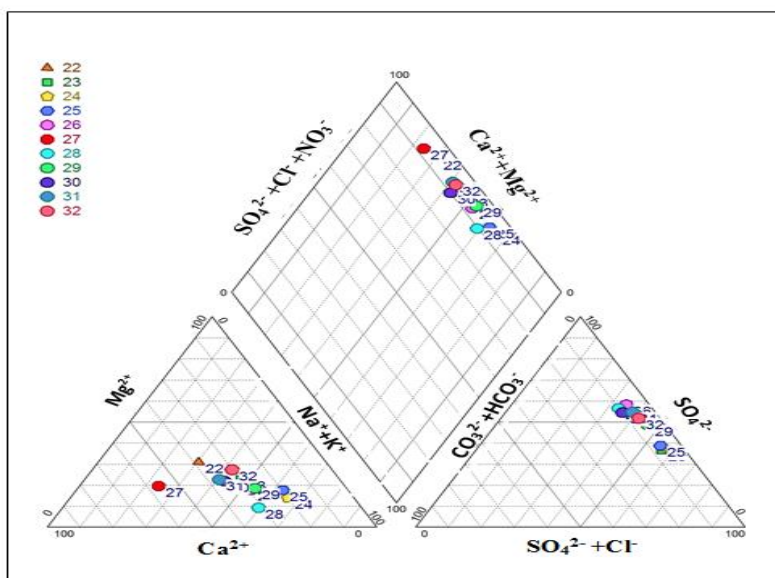
The graphical representations of the chemical facies according to the Piper diagram show that the majority of groundwater samples from the Quaternary aquifer ([Figure 3a](#)) are characterized by a cationic composition of the "no dominant cation" type. Ca²⁺ and Na⁺ cations are relatively poorly represented. The anionic representation is underlined by 3 types: Cl⁻, SO₄²⁻ and "no dominant anions" ([Figure 3a](#)). The dominant chemical facies is Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻ and to a lesser extent Na⁺, K⁺, Cl⁻, SO₄²⁻. The cationic procession of the waters of the Mio-Pliocene ([figure 3b](#)) and lower Eocene aquifers shows the dominance of Na⁺ and "no dominant cations". The anionic representation is dominated by Cl⁻ and weakly by SO₄²⁻ for the Mio-Pliocene aquifer while for the Senono-Lower Eocene reservoir SO₄²⁻ dominates Cl⁻ ([Figure 3c](#)). The facies are Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻ and Na⁺, K⁺ and Cl⁻.



a- Quaternaire



b- Mio-Pliocene

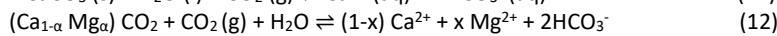
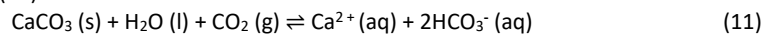


c - Senono-Lower Eocene

Figure 3: Chemical facies of the different layers according to the Piper diagram

Saturation index:

The saturation index (SI) of the minerals (calcite, dolomite, anhydrite, gypsum, halite) are calculated using the geochemical modelling software PHREEQC v2.16, which determines the chemical equilibrium between minerals and water. The solubility of carbonate minerals (calcite and dolomite) is mainly influenced by the fugacity of CO₂ and pH, according to reactions (11) and (12).



Compared to the carbonate minerals mainly calcite and dolomite, we note that the groundwater samples from the three aquifers have an SI > 0. The SI of the Quaternary reservoir is relatively higher than those of the Mio-Pliocene and Senono-Lower Eocene layers. Indeed, the average values of calcite and dolomite are respectively 0.33 and 0.74. They show saturation in the water (Figure 4) and a deposit.

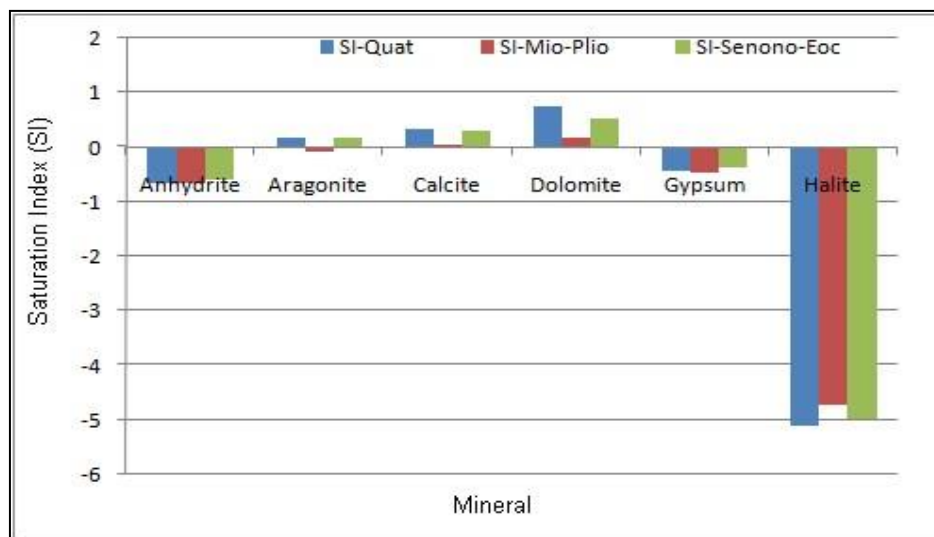


Figure 4: Groundwater's saturation index

As for anhydrite, gypsum and halite, the SI values are <0. These result in under-saturation at the level of the 3 aquifers. Halite, with an SI close to -5, is largely under-saturated. These results show that these minerals dissolve further in aquifers. These results confirm the influence of evaporitic rocks in the salinity of the analyzed waters and is the main mechanism responsible for the chemical composition of the groundwater of these aquifers.

The Chloro Alkaline Index:

The calculated Chloro Alkaline index or Schoeller index (CAI-1 and CAI-2) for the quaternary aquifer range between -0.24 (-0.18) and 0.50 (0.43). This interval shows that the exchanges between the groundwater and the rock are variable from one water point to another. Negative values indicate that Ca and Mg of water are substituted for Na and K of the solid matrix. Positive values show inverse exchanges. The Na and K of the water are exchanged for the Ca and Mg of the surrounding lands. We obtain a slight dominance of the positive indices on the negative indices. For the Mio-Pliocene sheet, Schoeller index values range from -0.94 (-0.27) to 0.26 (0.73). The majority of the samples have a negative index, indicating that groundwater is enriched in Na and K to the detriment of Ca and Mg. Indices calculated for the Senono-Lower Eocene water table oscillate between -1.15 (-0.57) and 0.44 (0.29). These results are similar to those of the Mio-Pliocene reservoir where the waters lose their Ca and Mg and enrich themselves in Na and K. These results are consistent with the chemical facies of the water of the Mio-Pliocene and Senono-Lower Eocene layers where the sodium occupies an important place in the cationic procession.

Irrigation water quality:

In reference to FAO's work on water quality, the parameters selected are EC, Sodium Absorption Ratio (SAR), (%Na), residual sodium carbonate (RSC), the permeability index (PI), the Kelly index (KI) are important in assessing the suitability of water for irrigation (Ayers and Westcot, 1985). The obtained results are shown in Table 3.

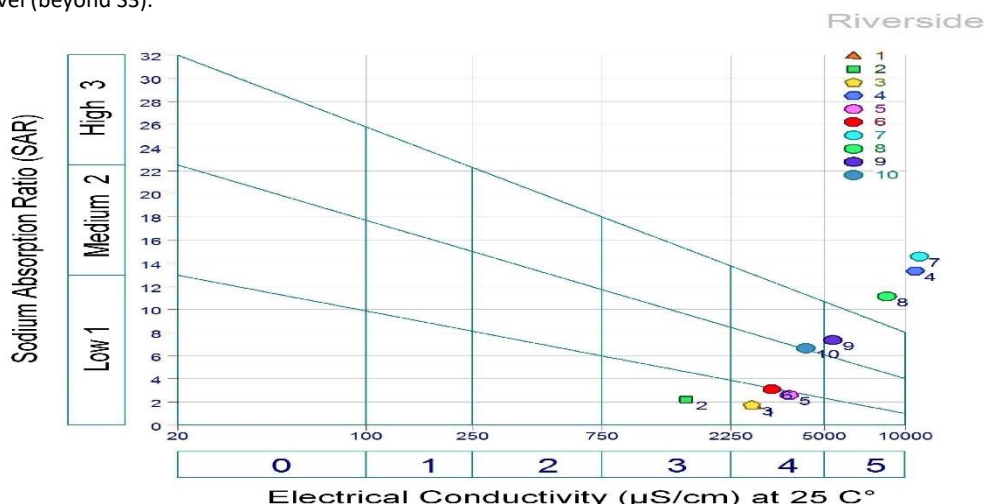
Table 3: Water Quality Parameters for Irrigation

Parameters	Quaternary water table (10 samples)			Mio-Pliocene water table (11 samples)			Senono - Lower Eocene (11 samples)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
EC (µS/cm)	1 536	11 210	5 450,6	2 880	7 990	5 446,36	1924	8 890	4 221,27
% Na ⁺	19,56	58,93	36,95	32,61	66,99	52,44	24,09	66,06	47,43
RSC	-56,24	-15,79	-36,01	-46,56	-20,40	-30,90	-47,6	-15,2	-29,2
Permeability index	24,91	60,49	40,32	37,26	69,47	54,97	28,02	68,50	50,32
Kelly index	0,23	1,41	0,67	0,48	2,01	1,21	0,31	1,93	1,00

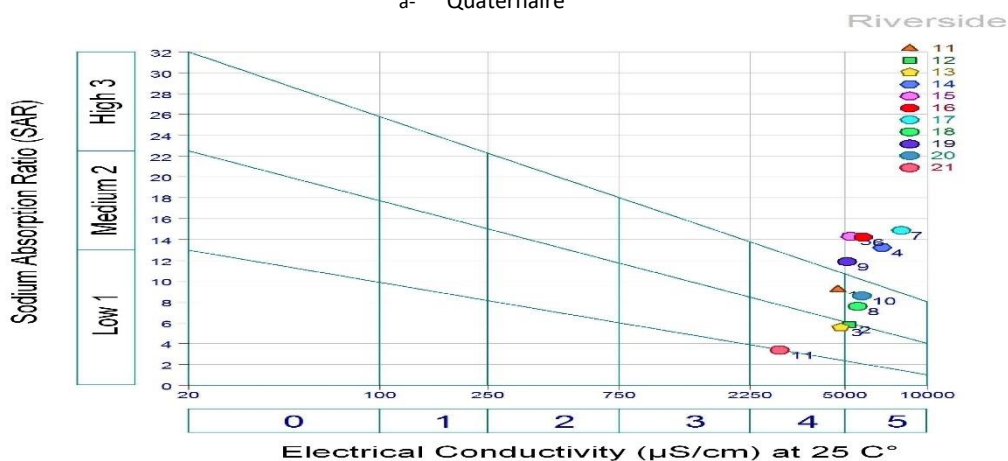
1 Sodium Absorption Ratio (SAR), % Sodium (% Na⁺) and Electrical Conductivity (EC)

3.2.1.1 Water classification according to Riverside diagram

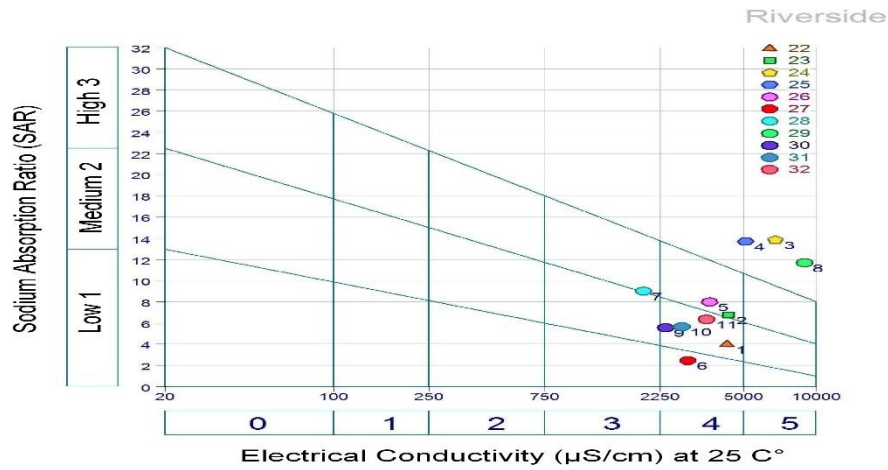
The classification suggested by the Riverside American laboratory is based on two main characteristics: Risk of salinization and danger of alkalization of the soil. The Riverside diagram is based on EC and SAR, taking into account the balance between these two variables, one of which influences the other. The risk of sodicity due to SAR is mitigated in the presence of high salinity. According to the Riverside diagram for groundwater of the Quaternary aquifer (Figure 5a), there are salinity and SAR classes that are divided into different classes C3S1, C4S1, C4S3, C5S3 and beyond of C5S3. These classes indicate waters of poor quality for irrigation because they present a very high danger of salinization with a risk of alkalization very strong or very strong. According to the Riverside diagram established for the waters of the Mio-Pliocene aquifer (Figure 5b), it appears the existence of several classes of salinity and SAR, of which C5S3 and beyond are the most widespread, expressing a very poor quality of water as they present excessive risks of salinization and alkalization. The other classes C4S2, C5S2, C5S3 present very high risk or even excessive risk of salinization with a danger of medium to high alkalization. The Riverside diagram for the waters of the limestone aquifer (Figure 5c) shows many classes. The majority of water points present a very high (C4) to excessive salinization risk (C5) whereas the risk of alkalization varies from a low level (S1) to a very high level (beyond S3).



a- Quaternaire



b- Mio-Pliocene



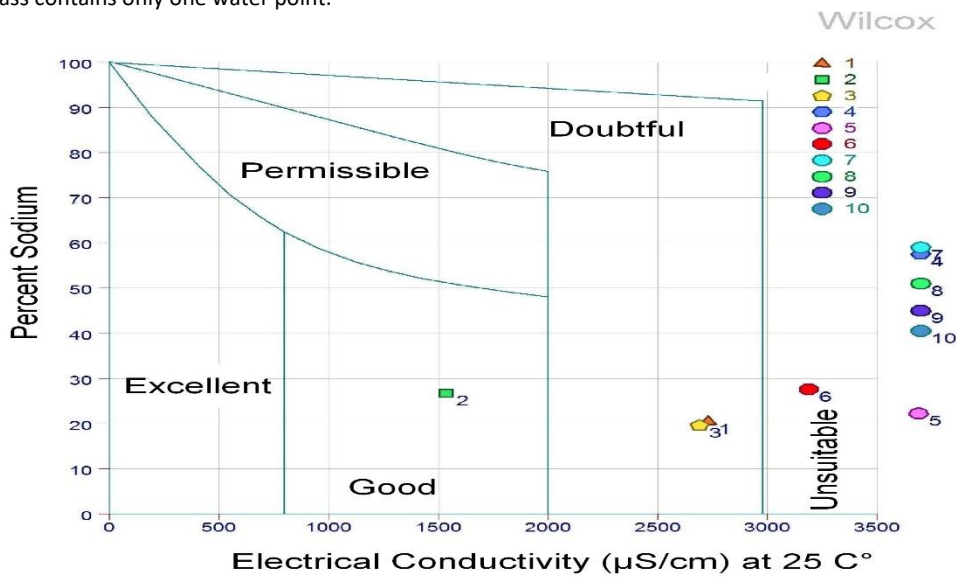
C- Senono- Lower Eocene

Figure 5: Representation of the waters of the aquifers according to the Riverside diagram

The results highlight that all aquifers have high risks of salinization and alkalization of soils with a relative stress for the Mio-Pliocene reservoir. This last layer indicates the most important SAR values (Table 2).

Classification of water irrigation quality according to (EC) and (% Na)

The Wilcox plot for % Na vs. EC, Quaternary water (Figure 6a) shows that the majority of groundwater samples are in the "poor" grade for irrigation. The representation of the irrigation water of the Mio-Pliocene aquifer diagram according to the Wilcox diagram (Figure 6b) mentions that apart from a water source of poor quality, all the other samples belong to the class of "Unsuitable" quality for agriculture. These waters are not recommended for irrigation. According to the Wilcox diagram representing the waters of the Senono-Lower Eocene aquifer (Figure 6c), we find that the majority of the water points analyzed have an "Unsuitable" quality for irrigation. The "Doubtful" quality is also met for 2 points whereas the admissible class contains only one water point.



a- Quaternaire

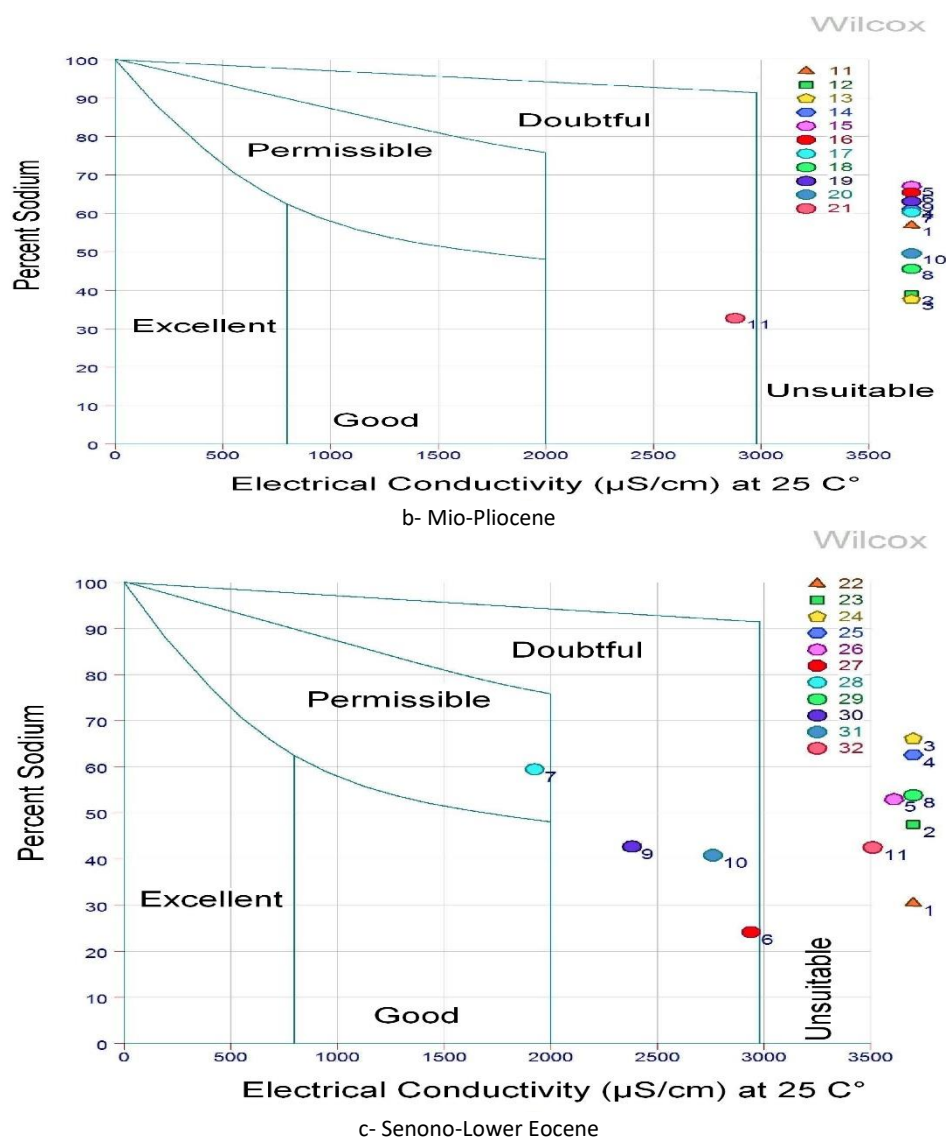


Figure 6: Representation of the waters of the aquifers according to the Wilcox diagram

Residual sodium carbonate (RSC):

The RSC values of the different aquifers are all negative (Table 2) because the calcium and magnesium contents largely exceed those of the bicarbonates and carbonates. In the case of a negative RSC, it is recommended to take account of sulphate contents. The calculation of RSC¹ showed negative values for the quaternary aquifer, reflecting a very low risk of sodization (Summer, 1993; Marlet and Job, 2006). The Mio-Pliocene and Senono-Lower Eocene hydrogeological reservoirs have respectively 7 and 8 negative values and 4 and 3 positive values. These latter water points present a danger of soil sodization.

Permeability index (PI):

Class 1 and Class 2 water types are suitable for irrigation with a maximum permeability of 75% or more, while Class 3 water types with 25% maximum permeability are unsuitable for irrigation.

The calculated PI values range from 24.91% to 60.49% (mean: 40.32) for the Quaternary aquifer between 37.26% and 69.47% (average: 54.97%) for the Mio-Pliocene sheet and between 28.02% and 68.50% (average: 50.32%) for the Senono-Lower Eocene aquifer (Table 2). From a classification point of view, the analyzed water points belong to class I. According to Doneen's interpretation, this class corresponds to 75% of the maximum permeability and consequently, the water is suitable for irrigation.

Kelly Index (KI):

The KI ranged from 0.23 to 1.41 (mean = 0.67) for the Quaternary aquifer samples, from 0.48 to 2.01 (mean = 1.21) for those from the aquifer. Mio-Pliocene and those of the Senono-Lower Eocene, the KI is between 0.31 and 1.93 (mean = 1.0). The majority of the Quaternary aquifer water samples have a KI <1, which qualifies the water for irrigation according to the Kelly index, whereas those of the Mio-Pliocene and Senono-Lower Eocene reservoirs present, as a whole, an index KI > 1, which translates water not recommended for irrigation according to Kelly's approach.

DISCUSSION

The groundwater is neutral to slightly alkaline. The average TDS values are above 3500 mg/l and suggest highly mineralised waters (TDS>1000mg/l) according to Fetter's classification (2018). The groundwater in all three aquifers is excessively mineralised. The aquifers formed from a lithology of evaporite nature probably confer this excessive mineralization. The high concentrations of Na are probably related to the basic exchanges on the one hand (Zaidi *et al.*, 2015) and to the geological formations present in the region (Hu and *et al.*, 2013), such as those in the Outaya region, which are exploited as salt ores of the sodium chloride type (halite) on the other (Abdennour *et al.*, 2020). The high concentrations found at a few water points tapping the Lower Eocene water table are related to the predominance of limestone soils (Helstrup *et al.*, 2007) Mg²⁺ is generally present in dolomitic rocks and has a chemical affinity with Ca²⁺ (Kasha *et al.*, 2015). Concerning sulphates, their presence in groundwater is mainly linked to the dissolution of calcium sulphates from gypsum rocks, which explains the high levels in the three aquifers in general and in the Mio-pliocene aquifer in particular, with a maximum of around 1343 mg/l. This variation in chlorides is explained essentially by the presence and percolation through the soil of evaporite (Long *et al.*, 2021). The nitrate concentrations are relatively low in relation to the portability standards, but some water points show effective signs of pollution with values above 45 mg/l. The IS of the Quaternary reservoir are relatively higher than those of the Mio-Pliocene and Seno-Eocene aquifers. They indicate over-saturation in the water and deposition. The IS results for anhydrite and gypsum show that these minerals dissolve more in aquifers. These results confirm the influence of evaporite rocks in the salinity of the analysed waters and is the main mechanism responsible for the chemical composition of groundwater in these aquifers (Gil-Márquez *et al.*, 2017).

The classification of the waters according to the Riverside diagram revealed that all the aquifers have high risks of salinisation and alkalinisation of the soils with a relative accentuation for the Mio-Pliocene reservoir. The latter shows the highest SAR values. The Wilcox diagrams indicated that the groundwater of the three aquifers studied is of poor quality and its use in irrigation is likely to cause serious problems in the agricultural environment. The results of the residual sodium carbonate (RSC) calculations showed that some of the water points are at risk of sodisation, which is far from negligible. The permeability indices (PI) applied to the 3 aquifers showed that according to Doneen's interpretation, the class obtained corresponds to 75% of the maximum permeability and therefore the waters are suitable for irrigation. Concerning the evaluation of the Kelly Index (KI), we note that the majority of the samples of the Quaternary aquifer have a KI < 1, which qualifies the waters as suitable for irrigation, whereas those of the Mio-Pliocene and Lower Eocene reservoirs present, as a whole, a KI > 1, which translates into waters that are not very recommended for irrigation.

CONCLUSION

The hydrochemical study conducted in the three aquifers (Quaternary, Mio-Pliocene and Senono- Lower Eocene) has shown that the groundwater is neutral to slightly alkaline and is excessively mineralized. The latter are underlined by high average EC and TDS values in relation to an evaporitically dominant lithology. The dominant chemical facies is of the Ca-Mg-Cl-SO₄ type for the quaternary reservoir while Na dominates the cationic procession in the Mio-Pliocene and Senono- Lower Eocene aquifers. Cl and SO₄ are required respectively in the Mio-Pliocene and Senono- Lower Eocene aquifers. Compared with carbonate minerals, mainly calcite and dolomite, the groundwater of the three aquifers has an SI > 0, indicating a supersaturation in the waters followed by a deposit. As for anhydrite, gypsum and halite, they are under saturation because the SI values are <0. The variable signs (positive and negative) of the Base Exchange index show exchanges of Ca and Mg of water against Na and K of the host formations or conversely of Na and K of water against Ca and Mg of the solid matrix. From the point of view of water quality in irrigation, the Riverside diagram indicates waters of poor quality for irrigation because they present a very high danger of salinization with a risk of alkalization very strong or very strong. The Wilcox diagram shows that the majority of groundwater samples are in the poor quality category for irrigation. The RSC values of the different aquifers indicate, apart from a few water points, a very low risk of soil sodization. According to the PIs, the waters are suitable for irrigation, whereas the results of the KIs reveal waters not recommended for agricultural use, in particular those of the Mio-Pliocene and Senono- Lower Eocene aquifers.

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الخصائص الهيدروكيميائية لخزانات المياه الجوفية وتأثيرها المتوقع على خواص التربة في منطقة بسكرة ، الجزائر

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الملخص

شهدت بسكرة تكثيفاً للأنشطة الزراعية في السنوات القليلة الماضية ، واستُغلت المياه الجوفية على نطاق واسع في الري. تم إجراء تحقيق حيث تم أخذ عينات المياه وفقاً للبروتوكول القياسي من 32 بئرًا وبئرًا حرفيًا ، مما يؤثر على طبقات المياه الجوفية الرئيسية الثلاثة (الرباعي ، Mio-Pliocene و Senono-Lower Eocene). تعتمد طرق الدراسة على تطبيق المخططات (باير ، ريفرسايد ، ويلكوكس) وفريك (مؤشر التشبع). يتم استخدام الموصلية الكهربائية (EC) ونسبة أيونات الصوديوم (% Na +) وكربونات الصوديوم المتبقية (RSC) ونسبة امتصاص الصوديوم (SAR) ومؤشر Kelly's (KI) ومؤشر النفاذية (PI) لتوصيف التأثيرات المحتملة على خصائص التربة. تظهر النتائج التحليلية التي تم الحصول عليها أن المياه الجوفية لخزانات المياه الجوفية الثلاثة محايدة و متعادنة للغاية (تصل EC من 5 ديسيبل / متر مربع). السحنات الكيميائية هي Na-Cl و Ca-Cl و Na-SO₄. فيما يتعلق بالظروف الجيولوجية ، فإن الكاتيونات والأنيونات السائدة في الموكب الأيوني هي Na + و Ca²⁺ و SO₄²⁻ و Cl⁻ على التوالي. تم العثور على معادن الكربونات (الدولوميت والكالسيت والأراغونيت) في الماء في حالة التشبع المفرط. تتطور معادن التبخر (الأنهيدريت والجبس والهاليت) من حالة قريبة من التوازن إلى مستوى شبه مشبع. تم تطبيق مخططات ريفرسايد (SAR) و Wilcox (EC) و Na + (% EC) على الخزانات الثلاثة التي تكشف عن وجود مياه معدنية بشكل مفرط ومن رديئة إلى منخفضة الجودة. تظهر قيم PI مؤشر RSC انخفاضاً في مخاطر تلحيم التربة إلى مياه ذات نوعية جيدة للاستخدام الزراعي. ومع ذلك ، فإن نتائج مؤشرات الأداء تشير إلى نوعية المياه الرديئة الموصى بها للري.

الكلمات المفتاحية: المياه الجوفية. تربة؛ الوضع الهيدروكيميائي الجزائر