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*Article*

# Hydro-Geochemistry and Groundwater Quality Assessment of Ouargla Basin, South of Algeria

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**Abstract:** This study aims to evaluate the hydro-chemical characteristics of Ouargla, Algeria basin groundwaters harvested from the Mio Pliocene aquifer. The study covered 70 samples; the physical parameters, potential of hydrogen (pH), and electrical conductivity EC $\mu S.cm^{-1}$ were determined in situ, using a multiparameter; the laboratory analysis included dry residuals DR (mg/L), calcium $Ca^{2+}$ (mg/L), magnesium $Mg^{2+}$ (mg/L), sodium $Na^{+}$ (mg/L), potassium $K^{+}$ (mg/L), bicarbonates $HCO_3^{-}$ (mg/L), sulfates $SO_4^{2-}$ (mg/L), and chloride $Cl^{-}$ (mg/L). The piper diagram shows that the Ouargla basin ground waters divided into two facies, sodic chlorinated in 93% and sodic sulphated in 7% of samples. The United States Salinity Laboratory Staff (USSL) diagram was used to detect the suitability of groundwater in irrigation where the results show that the groundwater was classed into two classes, poor water (C4 S4) and bad water (C4 S4). Furthermore, indices such as the Kelly index (KI), sodium adsorption ratio (SAR), sodium solubility percentage (Na%), and magnesium hazards (MH) confirm the negative effect of groundwater on soil permeability in 96%, 80%, 89%, and 53% of samples. The permeability index (PI) shows that the analyzed samples were considered as doubtful (71%) and safe (29%), otherwise there is no risk related to residual sodium carbonate (RSC). The geo-spatial distribution of deferent indices shows that all the study area has poor groundwater for irrigation, except the south-west part, where the groundwaters of this sub-area do not form a problem related to RSC.

**Keywords:** groundwater; Ouargla basin; hydrochemistry; irrigation; geo-spatial

## 1. Introduction

Groundwater quality and its suitability for drinking and irrigation uses were assessed and multivariate statistical analysis were applied to understand the chemical characteristics of groundwater [1]. In arid and semi-arid zones, one source that could be satisfying the needs of human, agricultural, and industrial use is groundwater. The problematic accessibility to this clean water source plays a primary role in holding back economic development. Water from the natural environment has a wide range of chemical compositions. It relies on the geological nature of the soil from where it came, as well as any reactive compounds it may have met during the flow. Therefore, the quality of groundwater is determined by its quantitative and qualitative content in suspended and dissolved particles, whether mineral or organic in origin [2]. These induce potential risks to the ecosystem, threaten the safety of drinking water, and increase the pressure of urban and rural water supply. The importance of water quality assessment has a place in the scientific community, where several researchers from all around the world were interested in the water-quality-related problems in their regions. In China's western Songnen Plain, the saline–alkaline degree of water bodies in salt marsh wetlands is high. Therefore, Zhang et al. [3] explain the movement laws of the region's saline–alkaline components and establish a set of four class discriminants for the evaluation of salt marsh water bodies. Additionally, the goal is to develop and use the region's water resources responsibly by preventing and controlling regional salinization.

Xia et. al. [4] studied the intrusion of sea water and its impact on salinization of water and soil, which is an extremely prominent environmental problem faced by many parts of the Yellow River Basin. The studies were conducted based on deferent statistical methods such as principal component analysis (PCA).

Zhou et. al. [5] studied the water quality of Xinle City which is located in the upper reaches of the Daqing River basin, north China. The problem of this study area is that the groundwater is influenced by intense and extensive industrial and agricultural activities and sodium and nitrate pollution. The study revealed that the groundwater of the study area is of a suitable quality for both drinking and irrigation. On the other hand, the high concentrations of nitrates were classed as an anthropogenic source.

To understand the chemical characteristics of groundwater in the upper part of the Luvuvhu sub-catchment in Limpopo, South Africa, groundwater quality and suitability for drinking and irrigation uses were assessed, and multivariate statistical analysis was used. The results revealed that water chemistry in the studied wells is affected by recharge process and surface contamination sources [6].

In the study area, groundwater quality has been investigated in a limited number of papers. Semar et. Al. [7] used 17 samples collected from the phreatic aquifer in Ouargla to evaluate the hydrochemistry based on a multivariate statistical technique, principal component analysis. The study results show that NaCl, $CaSO_4$, $HCO_3$, and $NO_3$ control a significant part (67%) of the chemistry of groundwater [7]. In 2019, the problem of salinity in Ouargla groundwaters was treated based on 114 samples taken from Mio Pliocene and Senonian aquifers. The dissolution of the evaporitic components of the intercalations in the aquifer matrix, as well as the old character (fossil) of water and cationic exchange reactions caused by water–rock interactions over time, explain the overall mineralization, which is dominated by the chloride sulfate, sodium, and magnesium facies. The salinity fluctuation follows a pattern that is in line with the flow direction of the groundwater. Water moving up and down in a vertical fashion was observed, with the deeper Albian sandstone aquifer sending saltier water down, and the phreatic aquifer sending softer water up. The western side of the basin was also found to have areas of low mineralization [8]. Another work concerning the suitability for irrigation was undertaken based on 13 samples collected from the Mio Pliocene aquifer. The assessment was based on Sodium Adsorption Ratio (SAR) calculation and Riverside diagram (Electrical Conductivity vs. SAR). The results revealed that the analyzed water had doubtful to unsuitable quality, with high to very high salinity hazard and medium to high sodium hazard where 61% of wells were found as unsuitable for agriculture activities and 39% can be used, but in special conditions [9]. The shallow waters in Ouargla basin have their own interest in the research community. Medjani et. al. [10] investigated possible mechanisms that might influence water quality changes under seasonal conditions in shallow aquifers, where they focused on observed changes in hydrogeochemical characteristics, and the possible responsible processes. Under arid conditions, high water mineralization results in hypersaline water or brine solution formation within shallow aquifers. Due to active physical and chemical mechanisms such as $Na^+/Ca^{2+}$ ion exchange, the successive precipitation of calcite, gypsum, mirabilite or blœdite, and halite is induced. Biological processes were also observed as prevalent; evidenced by large, measured variations in $CO_2$ load concentrations. These processes contributed to an inverse relationship between $CO_2$ and $O_2$ concentrations within the shallow aquifers studied [10]. Irrigational activities in Algerian Sahara have increased over the past few years, particularly in the Ouargla basin, which searches for suitable and sustainable water resources, where water availability plays a main role in the development of agricultural activities in arid zones [11]. From the previously mentioned papers, we could see that there is no overview all of suitability for irrigation assessments based on different indices and diagrams, using the statistical tools in the study of hydrochemistry mechanisms, applying thermodynamic lows in discovering the existing geochemistry relations in addition to the spatial distribution integration. For that, this paper will make a new result available regarding the hydrochemistry of the Mio Pliocene aquifer in the study area, this work aimed to: (1) study the groundwater quality of the Mio Pliocene aquifer to estimate the suitability of groundwater for irrigational uses; (2) to assess the impact of groundwater chemistry on crops and soils by calculating indices such as the Kelly index (KI), permeability index (PI), sodium percentage (% $Na^+$ or SSP), sodium absorption ratio (SAR) (meq/L), the residual sodium carbonate (RSC), and magnesium hazards (MH); and (3) to study the spatial distribution of calculated indices to detect suitable sub-areas for agricultural practices.

## 2. Materials and Methods

### *2.1. Study Area*

#### 2.1.1. Geographical Location

Ouargla basin is a part of five districts: Ouargla county, N'goussa, Rouissat, Ain El Beïda, and Sidi Khouiled. It is located in the state of Ouargla, Algeria. Ouargla basin spreads over a length of approximately 55 km in a south-western to north-eastern direction. On the north, it is bordered by Sebkhet Safioune; on the east by Eurg Touil and Arifdji; on the south by the dunes of Sedrata; and on the west by the valley of Me Zab. It has an area of about 750 $km^2$ [12]; where the average altitude is of about 128 m which extends between Easting 710,000, Northing 3,530,000 and Easting 730,000, Northing 36,000,001 based on Clarke's 1880 UTM projection on Zone 31R coordinates system. Figure 1 presents the study area location and sampling locations.

#### 2.1.2. Geological Settings

The Ouargla basin, Algeria was formed by the following geological formations: Tertiary age lands and Quaternary detrital deposits, a continental deposit of the Mio Pliocene, siliceous sands, Miocene continental sandstone geological formation, clays and sometimes marls, and Continental Pliocene constitutes the structure of the regs in the form of a calcareous crust, with puddings or water limestones. Based on the description of the various types of well oils or hydraulics [13], the study area has lithography and stratigraphy as follows:

Gault is made up of a continental sand deposit with clay or carbonate cement and the last layer of clay, which is on average 400 m thick.

Aptian, also known as the "Impermeable Bar of Aptian," is made up of 10–30 m of marls and dolomites.

Varronian (with a thickness of 50–100 m), characterized by an alternation of argillaceous and dolomitic levels, is only one term of passage between the Gault (top of the Continental Guide), and Cenomanian evaporitic-clay and carbonated (base Final Complex). It is indistinguishable from Gault or Cenomanian (thickness ranging from 150 to 250 m).

This layer is about 70 m thick and is made up of porous and chalky limestone. It sits on the solid Cenomanian series.

Sénonien legionnaire saliferous and anhydrite (350 m thick) is the impermeable substratum in carbonated Sénonien and Eocene. It is 150–200 m thick.

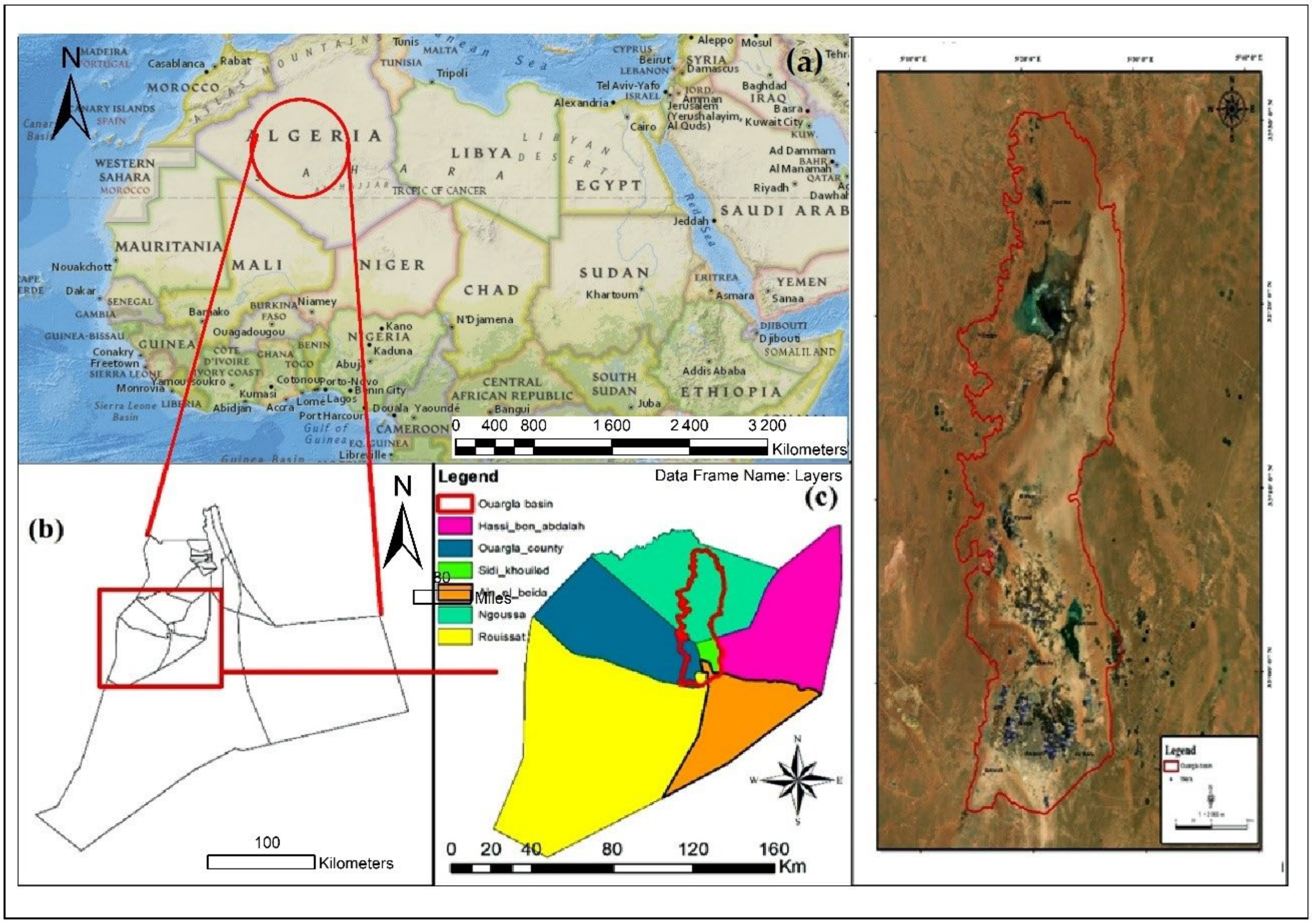


**Figure 1.** Geographical location of (**a**) Algeria, (**b**) Ouargla city and (**c**) Ouargla basin.

Eocene evaporitic: it is a legionnaire formation made up of limestones, clays, marls, and anhydrite. It is not porous and separates the carbonated Eocene sands from the Mio Pliocene sands.

The Mio Pliocene layer is a powerful formation of sands and clays, which rests in discordance on the Eocene and is characterized by a strong heterogeneity, as well in the vertical direction as in the horizontal directions.

The Quaternary, consisting of alluvial or eolian sands, fine to medium, and gypsum sands and sometimes clay or carbonate, rests unconformably and irregularly in the valley, on the middle series of the Terminal Complex (Senonian, Eocene, and Mio Pliocene) [13].

### 2.1.3. Hydrogeological Settings

Three exploited aquifers exist in the basement of the area of Ouargla, upwards we have the sandstones and sandy clays of Continental Intercalary from the Albienne aquifer. The Senone-Eocene is a carbonated aquifer formed of limestone and the Mio Pliocene aquifer allows the formation of the tablecloth phreatic aquifer [14]. In this work, all samples were harvested from the Complex Terminal (CT) aquifer, exactly from the Mio Pliocene part. The Mio Pliocene formations result from the dismantling of border reliefs generated by the Alpine orogeny, during a period during which the Sahara was completely exposed.

In the eastern basin, the Mio Pliocene is a powerful unit, made up of sands and clays, which rests, in unconformity, on various previous formations: Primary, Cenomanian, Turonian, Senonian, or Eocene. Figure 2 presents the hydrogeological profile of the study area.

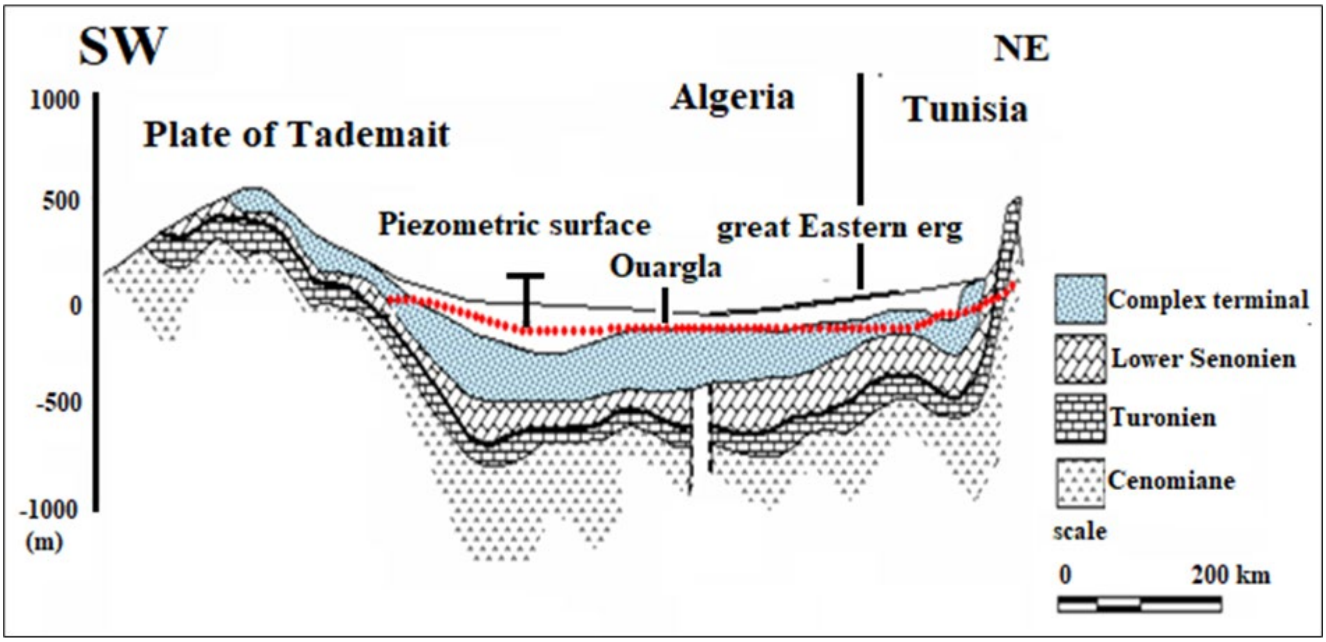


**Figure 2.** Cross-section of the hydrogeological layers in the study area.

The sandy, clayey, or clayey-sandy levels have a lenticular structure. The Mio Pliocene is therefore characterized by a strong heterogeneity, both in the vertical and horizontal directions.

Bel and Dermagne [15] tried to differentiate on the scale of the eastern basin of the Algerian Sahara, four different levels in the Mio Pliocene. Alternately, sandy or clayey are known as follows:

Level 1: Thin and essentially clayey, constitutes the lower part of the Mio Pliocene, represented especially in the center of the basin (Chott Melrhir, Merouane), following a north–south band. This level is represented in Ouargla by a bank of sandy red clay 1–20 m thick [16].

Level 2: Gréso-sandy is the thickest level (maximum in Gassi-Touil: 400 m) and the most constant. It spans the whole of Eastern Sahara and continues into Western Sahara. At its "base" we sometimes find gravel. The "summit" is composed of clay marking the passage to level 3. According to Cornet et. al. [16], this horizon at Ouargla is a detrital set of 12–35 m of coarse white or yellow sand, containing the Mio Pliocene aquifer.

Level 3: Represents a small clayey-sandy formation, whose lower and upper limits are rather poorly defined. This impermeable layer only exists in certain areas. It is thick and constant only in the region of the chotts. The sandy clays of level 3, separate levels 2 and 4. In our region, the above-mentioned formation is an impermeable 15–20 m of limestone and lacustrine marl, generally very hard, whose base is formed by a more or less sandy clay bank [16].

Level 4: Is the second sandy level of the Mio Pliocene. In some areas, it is confused with the second level when the third level is absent. At the level of the chotts, its thickness is considerable, its top, flush over large surfaces, is made up of a crust of sandstone limestone "Croûte Hammadienne". This level at Ouargla is 10–25 m of generally pink or red sands, with intercalation of pink sandstone banks, difficult to distinguish from the quaternary sands which surmount them [16].

## 2.2. Sampling and Laboratory Analysis

A total of 70 samples of groundwater were collected from different layers of wells of the Ouargla basin/Algeria to investigate the quality of this water for irrigation use. The location of each site, the coordinates, and the elevation of the sampling location were taken from Google Earth. All coordinates of wells and their depth are presented in the Appendix A Table A1. To collect the samples 1.5 L plastic bottles were used. All the bottles were cleaned with tap water and then distilled water. During field preparation, the bottles were washed by the sample water itself before sampling. The vials were rinsed thoroughly with the sample water to ensure that the sample was representative of the water source. After collecting the water samples, we gave each vial a proper label for identification, and then we packed it all in a special box and transported it to the Laboratory of Water and Environment Engineering in Saharan Environment, Ouargla, Algeria for analysis. Groundwater quality parameters used in the examination included potential hydrogen (pH), electrical conductivity (EC), temperature (°C), major cations include sodium ($Na^+$), potassium ($K^+$), magnesium ($Mg^{2+}$), and calcium ($Ca^{2+}$), and major anions include chloride ($Cl^-$), sulfate (${SO_4}^{2-}$), and bicarbonate (${HCO_3}^-$). To do the necessary analysis for calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), potassium ($K^+$), and sodium ($Na^+$) we relied on a flame Atomic Absorption Spectrophotometer (AAS). The material used for measuring the major anions and cations referenced under Analytik Jena, NovAA 350, Jena, Germany, a Spectrophotometer Visible UV, model DR 6000, HACH, Loveland, Colorado, United States, was used to analyze sulfates (${SO_4}^{2-}$), chloride ($Cl^-$) and bicarbonate (${HCO_3}^-$) were measured based on titration methods cited in the guidelines NFT 90-014 and NFT 0-036, respectively. While the physical parameters (pH, EC, and °C) were measured in the field using multi-parameter from HANNA company of model HI9829, Woonsocket, Rhode Island, USA, other calculation formulas were used to analyze the water quality variables. These various water quality parameters were calculated and classified to determine the suitability of irrigation groundwater quality based on the recommendation of Eaton [17], Ayers and Westcot [18], and Todd and Mays [19].

### *2.3. Laboratory Analysis Validation*

The precision of chemical analysis is identified by the calculation of ionic balances for each sample. If error values are below 5%, they are considered as the best analytical estimates, and the accepted error level is no more than ±10%. If the error percentage exceeds ±10%, it means that there are some errors in the measuring or in the sampling process [20].

The results of the calculation of ionic balance show that 62.82% of wells have values of ionic balance lower than or equal to 10%. These values vary between a minimum of 0.07% and a maximum of 9.66%. For the ionic balance lower or equal to 0.5%, it was marked on 23 wells with a minimum of 0.07% and a maximum of 4.95%.

### *2.4. Principle Component Analysis (PCA)*

The principal component analysis (PCA) is a powerful multivariate statistical technique, which is used for reducing many variables into smaller components to help interpret data quickly [16]. It provides vital information for the whole data set while maintaining the relationships in the original data. The vari max method was applied to execute the rotation of the PCA, and where the PCA had an eigenvalue greater than 1.00, they were retained and discussed. The strength of the physicochemical parameter loading is classified as 'strong' (>0.75), 'moderate' (0.75 to 0.50), or 'weak' (0.50 to 0.30).

### *2.5. GIS Integration*

The spatial distribution of an element needs a careful selection of interpolation methods to obtain correct spatial modeling. As such, seven geostatistical methods were compared to select the best method to use in the spatial modeling process, the methods are weight distance inverse (WDI), global polynomial interpolation (GPI), radial basis function (RBF), locally polynomial interpolation (LPI), and the Kriging with its three types, simple (SK), ordinary (OK), and universal (UK). From Table 1 which presents the performance of different methods in modeling the geo-spatial distribution of deferent indices, we could see that the Kriging methods are the best for modeling the distribution of all indices included in this study.

**Table 1.** Performance of interpolation methods.

| Algorithm | WDI | | GPI | | RBF | | LPI | | SK | | OK | | UK | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Indicators** | **RMSE** | **ME** | **RMSE** | **ME** | **RMSE** | **ME** | **RMSE** | **ME** | **RMSE** | **ME** | **RMSE** | **ME** | **RMSE** | **ME** |
| RSC | 50.86 | −2.95 | 59.35 | −0.46 | 50.45 | −2.93 | 52.16 | −0.66 | 51.19 | −0.10 | 49.99 | 0.67 | 49.99 | 0.67 |
| MH | 56.14 | 2.72 | 53.29 | 0.49 | 55.02 | 2.08 | 49.02 | −0.19 | 49.94 | −0.17 | 47.52 | 0.28 | 47.52 | 0.28 |
| SAR | 332.76 | −7.40 | 407.93 | −2.71 | 338.29 | −15.99 | 345.78 | −4.86 | 330.72 | 6.41 | 315.57 | 7.99 | 315.57 | 7.99 |
| PI | 400.04 | 32.94 | 357.64 | −1.85 | 364.88 | 8.46 | 362.19 | 8.37 | 340.28 | 15.28 | 350.95 | −13.25 | 350.95 | −13.25 |
| SSP | 33.45 | −1.03 | 32.53 | 0.11 | 32.01 | −0.61 | 31.94 | −1.97 | 29.62 | −0.85 | 31.64 | −0.13 | 31.64 | −0.13 |
| KI | 26.27 | −1.32 | 23.37 | 0.001 | 24.96 | −0.31 | 23.48 | 0.25 | 23.28 | −0.45 | 24.41 | 0.72 | 23.28 | −0.45 |

## 3. Results and Discussion

### 3.1. Hydrochemistry

A statistical overview of the results obtained is presented in Table 2, where the detailed results of ion analysis are presented in Appendix A Table A2. The pH determines the acidity or the alkalinity of water by measuring the concentration of the $H^+$ ions. It varies according to a scale from 0 to 14, where 7 is the pH of neutrality [20]. Values of pH measured appear close to neutrality with slightly alkaline in the basin. The maximum value of pH 8.87 located in the district of the Ouargla was observed with well F2; the minimum value was 7.2 observed in the district of Ain el Baida at well F165. The average value was found to equal 7.99.

**Table 2.** Statistical presentation of the groundwater analysis.

| N of Samples | | Depth (m) | DR (mg/L) | EC (µs/cm) | pH | $Ca^{2+}$ (mg/L) | $Mg^{2+}$ (mg/L) | $Na^+$ (mg/L) | $K^+$ (mg/L) | $NO_3^-$ (mg/L) | $Cl^-$ (mg/L) | $SO_4^{2-}$ (mg/L) | $HCO_3^-$ (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 70 | Average | 83.26 | 4123.34 | 4840 | 8.00 | 214.76 | 256.85 | 1170.88 | 43.93 | 389.25 | 2153.88 | 1147.46 | 106.92 |
| 70 | Maximal | 360 | 7574 | 7740 | 8.87 | 322.4 | 386 | 1981.8 | 58 | 97 | 3232 | 2290 | 189 |
| 70 | Minimal | 32 | 1832.00 | 2640 | 7.2 | 74.00 | 105 | 304 | 7 | 24.12 | 474 | 476.00 | 10.00 |
| 70 | SD | 44..61 | 1112.03 | 1210 | 0.35 | 61.85 | 56.82 | 419.98 | 8.31 | 10 | 634.86 | 345.90 | 33.31 |
| WHO guidelines | | / | | 1500 | 6.5–8.5 | 200 | 150 | 200 | 30 | 50 | 250 | 400 | 380 |

Notes: The concentration of ions and DR in (mg/L); DR: dry residue; SD: standard deviation.

The electric conductivity of water gives an idea of the total mineralization of a sample (salt minerals). It is measured at a temperature of water between 20 and 25 °C. It increases with the temperature and is expressed in $\mu S/cm^{-1}$ [21]. According to the analysis results, the maximum value of 7740 (µS/cm) located in the district of Ain el Baida was observed with well F165; and the minimal value of about 2640 (µS/cm) is observed in the district of N'Goussa on the level of well F210; the average of electric conductivity (EC) was 4840 (µS/cm).

The dry residue represents the "mineralization" (the more the residue is raised, the more water contains minerals). It indicates the degree of mineralization of water [22]. It is noticed that the maximum value was 7574 mg/L localized in the of Ain el Baida observed in the F165 well; the minimal value of 1832 mg/L is observed in the district of Sidi-Khouiled on the level of the F102 well with a mean of 4123.34 mg/L

Generally, calcium in water comes from two natural origins: the dissolution of the gypsum-containing rocks and the carbonate-containing rocks [23]. According to the analysis results, the calcium concentration has a minimum value of 74 mg/L in two wells F108 and F109 in the district of Rouissat, where the maximum value achieved 322.4 mg/L in the same municipal at two wells F122 and F131, the average value found is 214.75 mg/L.

The sources of magnesium could be the volcanic rocks or infiltrations of surface water through the dolomitic formations (dissolution of the carbonated formations) [24]. According to the results of the analyses, the maximum value was recorded in the district Rouissat with a value of 386 mg/L using well F121 and the minimal value was 105 mg/L registered in the district of N'Goussa at well F210.

The presence of sodium ions ($Na^+$) in water is due to the scrubbing of the formations rich in $Na^+$ and $Cl^-$ (the Clay-Marne) and of water for agricultural or domestic use [24]. Based on the results of the analyses, the minimal concentration found was 304 mg/L in the district of N'Goussa at the well F210, and the maximum concentration recorded in the district of Rouissat at the well F131 with a value equal to 1981.8 mg/L. Whereas, the average value was 1170.87 mg/L.

Bicarbonate ($HCO_3^-$) is formed initially from the reactions between carbonated rocks and the presence of carbonic acid. Calcite can dissolve to give calcium bicarbonate:

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \Leftrightarrow 2H^+ + CO_3^{2-} \quad (1)$$

The maximum value of 189 mg/L was localized in the Sidi-Khouiled district observed in well F90 ErgTouil96; the minimal value of 67 mg/L is observed in the district of Ouargla at well F11. The average is 110.37 mg/L.

The origins of chlorides in water are the interactions between water/rock, many igneous and volcanic rocks of minerals rich in chlorine, a marine origin (salted bevel), or an anthropic origin (manures and pesticides) [24]. According to the results of the analyses, the minimal value of 474 mg/L is in the district of N'Goussa at well F210, and the maximum value of 3232 mg/L is marked in the district of Rouissat at well F131.

The origin of sulfates ($SO_4^{2-}$) included in groundwater composition varies between oxidation of sulfur-rich minerals (e.g., pyrite), washing of evaporate formations (e.g., gypsum), oxidation of sulfides in atmospheric precipitation (the acid rain phenomenon), and an anthropic origin (manure) [24].

The findings show that: the maximum value of 2290 mg/L localized in the district of N'Goussa was observed with well F225; the minimal value of 620 mg/L was observed in the district of Ouargla at well F18. For an overview of groundwater ions' constitution, a presentation of statistical indices as maximum values, minimum values, and average values is presented in Figure 3. From Figure 3, we could see that the highest concentrations were recorded in $Cl^-$, $SO_4^{2-}$, and $Na^+$. These high values make these ions the controlling ions of groundwater quality. The impact of $Ca^{2+}$, $Mg^{2+}$, and $HCO_3^-$ was found to be secondary with average values of 74, 105 L and 15 mg/L, respectively.

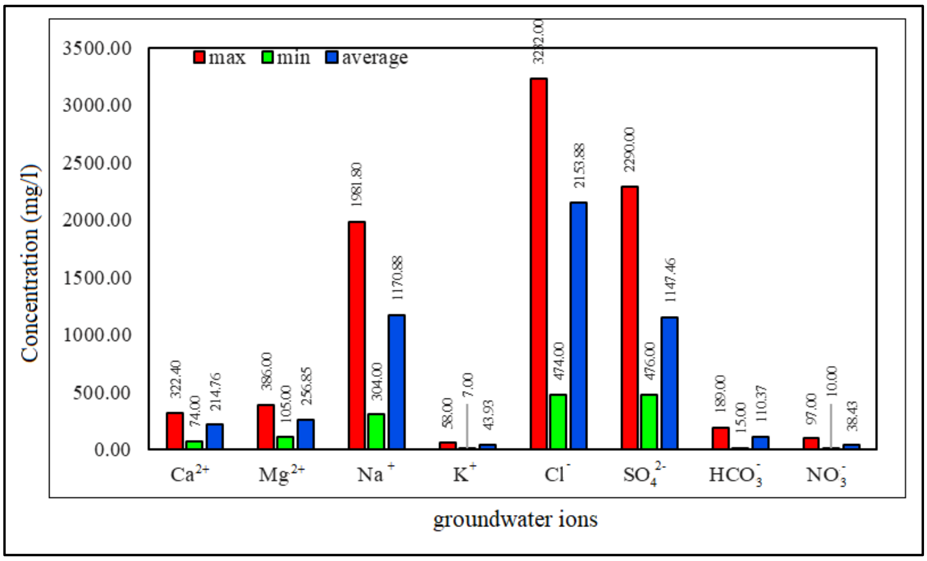


**Figure 3.** Statistical presentation of groundwater ions.

### 3.2. *Groundwater Geochemistry*

According to the piper diagram presented in Figure 4, the Ouargla basin groundwater has two types of water, chloride water (Na-Cl type) found in 65 wells and sulphated sodic existing in 05 wells. These types of water indicate an evaporated dissolution rich in salts and gypsum. The distribution of type of water of harvested samples arises as follows: 92, 85% have sodium chloride water (Na-Cl type) and 7.14% have sodium sulfate ($Na\text{-}SO_4^{2-}$ type). The classification of Ouargla basin groundwater is presented in Table 3.

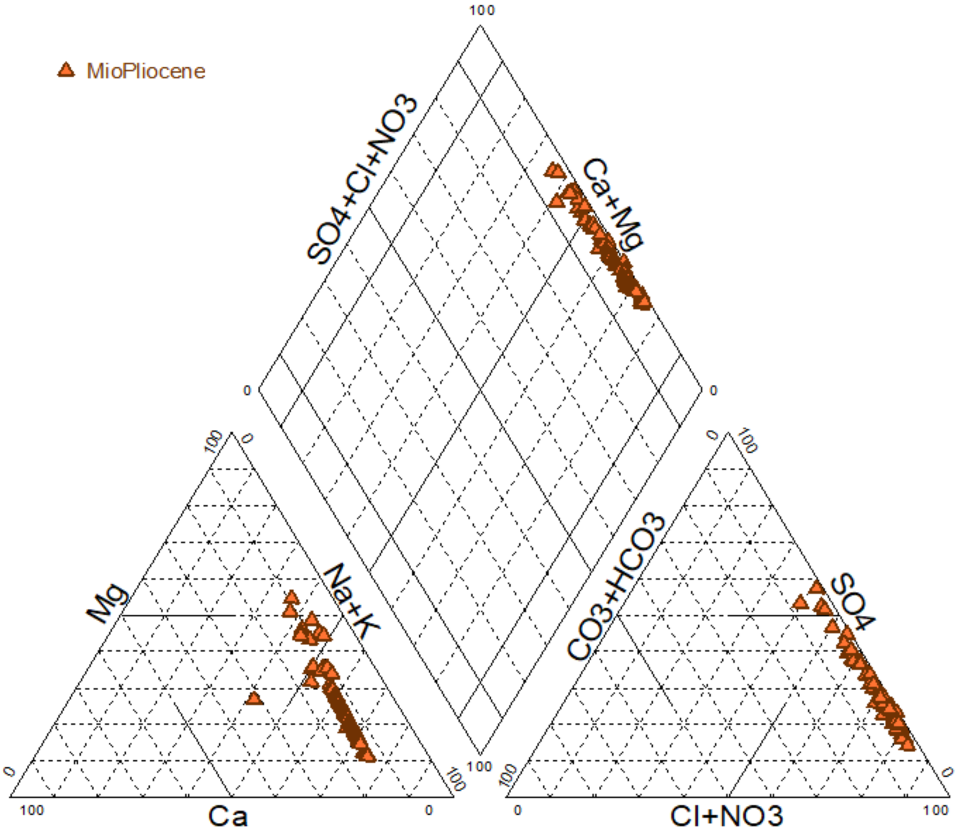


**Figure 4.** Groundwater samples plotted on the Piper diagram.

**Table 3.** Classification of Ouargla basin groundwater.

| Samples | Formula | Chemical Facies |
|---|---|---|
| F212, F213, F215, F217, F218, F222, F223, F224, F225, F227, F229; F89, F90, F91, F93, F94, F95, F97, F98, F100, F101, F102, F108, F111, F112, F113 F121, F150, F155, F156, F157, F161, F166, F169, F171 | $Cl^- > SO_4^{2-} > HCO_3^-$ $Na^+ > Mg^{2+} > Ca^{2+}$ | Sodium chloride water (Na-Cl type); magnesium |
| F122, F123, F125, F126, F130, F131, F163, F165, F1, F2, F3, F5, F8, F9, F11, F13, F14, F15, F16, F17, F18, F19, F23, F24, F25, F26, F27, F28, F29, F30 | $Cl^- > SO_4^- > HCO_3^-$ $Na^+ > Ca^{2+} > Mg^{2+}$ | Sodium chloride water (Na-Cl type) and calcium |
| F210, F221, F109, F110, F120 | $SO_4^- > Cl^- > HCO_3^-$ $Na^+ > Ca^{2+} > Mg^{2+}$ | Sodium sulfate ($Na\text{-}SO_4$-type) and calcium |

The nature of the minerals likely to precipitate in the waters of the Ouargla Basin was defined using thermodynamic considerations. The thermodynamic study makes it possible to study the chemical evolution of water according to its state of equilibrium (or imbalance) with respect to the primary and newly formed minerals of the rock reservoir. It counts electrostatic interactions between the different "i" ions represented by the ionic activity. The saturation indices of each rock reservoir were extracted on the basis of geochemical modeling using the Diagrams software (Avignon Hydrogeology Laboratory, Avignon, France). The extracted results show that the following six minerals, calcite, aragonite, dolomite (carbonates), gypsum, anhydrite (evaporites), and chalcedon (silicates), influence the chemical composition of the waters of the superficial aquifer of the Basin de Ouargla to varying degrees. When the saturation index (IS) = 0, the solution is in equilibrium with a mineral phase (flow of dissolution equal to the flow of precipitation). It is said to be undersaturated when IS < 0 and oversaturated when IS > 0. Paces (1972) [25] suggests considering saturated water with a saturation index between −0.5 and 0.5. Figure 5 presents the state percentage of the samples per rock reservoir, the blue presents the state of under-saturation, the green presents the state of equilibrium, and the red presents the state of supersaturation. From Figure 5, we find that the samples taken are characterized by supersaturated waters towards anhydrite and gypsum, which indicates that the waters take their chemical property from these two rocks. On the other hand, it was found that the waters are stable towards aragonite, calcite, chalcedony, and dolomite in 61%, 52%, 15%, and 31% of the samples, respectively. The state where the rock takes chemical properties from the waters was recorded in 37%, 47%, 82%, and 64% with aragonite, calcite, chalcedony, and dolomite. The results of all samples are presented in the Appendix A Table A2.

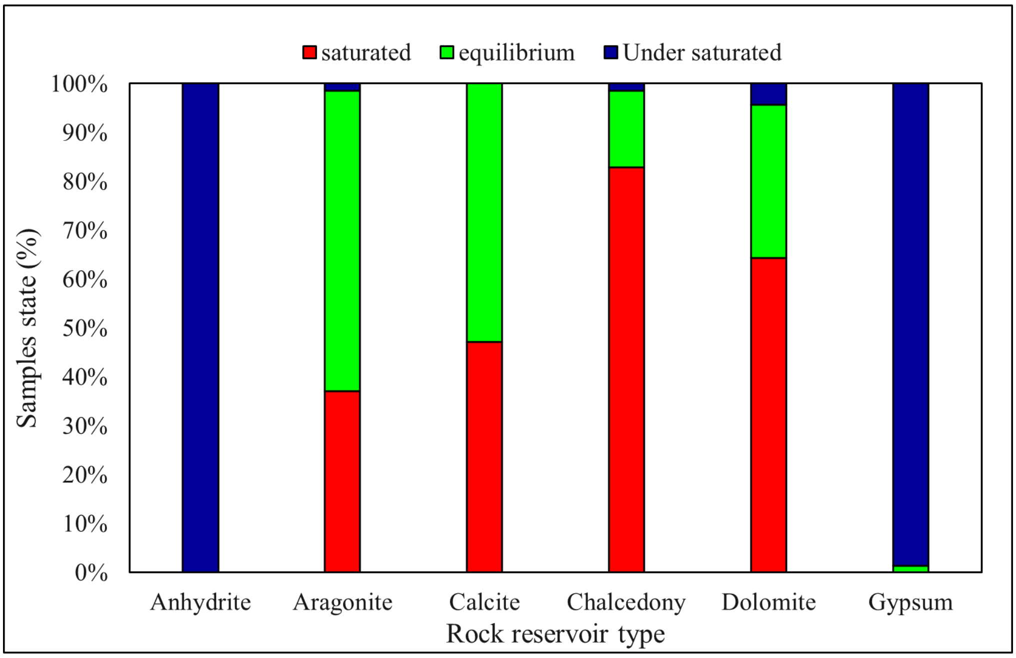


**Figure 5.** Variation in saturation indices of reservoir rocks.

### *3.3. Suitability for Irrigation Purposes*

The aptitude of groundwater for irrigation makes it possible to evaluate the effect of salinity on the grounds and the cultures according to the nature of the salts dissolved [26]. For that, six indices were used to evaluate the impact of chemical groundwater content on soil permeability and determine whether the Mio Pliocene groundwaters in Ouargla basin are suitable for irrigation or not.

#### 3.3.1. Residual Sodium Carbonate (RSC)

The RSC was considered to be an indicator of sodicity hazard. Wilcox et. al. [17] concluded that water with more than 2.5 mmol (+)/1 of RSC is not suitable for irrigation. Water containing 1.25–2.5 mmol (+)/1 was considered marginal and that with less than 1.25 mmol (+)/1 was probably safe [17]. The maximum value in analyzed samples was −9.83, the minimum the value was −21.62; the means value was −17.88. The RSC values under 1.25 indicate safe water for irrigation use, the risk of sodicity is then very weak [17].

#### 3.3.2. Magnesium Hazards

The presence of magnesium in high concentrations in irrigation water negatively affects the soil quality by converting it to alkaline soils, which leads to a decrease in the yield of agricultural crops [27]. In 1964, Szabolcs [28] proposed an indicator called MH to determine whether water samples were suitable for use in irrigation.

$$MH = Mg^{2+}/[Ca^{2+} + Mg^{2+}] \times 100 \quad (2)$$

The values of MH vary between a maximum of 76.18% in well F109 and a minimum of 29.18% at well F131, whereas the MH $\geq$ 50% recorded in 37 wells presents a percentage of 52.86% of the analyzed samples, the MH values $\leq$ 50% were recorded in 33 wells with a percentage of 47.14%; the mean of MH is equal to 50.43%. These results of MH are placed into two categories:

MH $\leq$ 50% was found in 47.14% of water samples (33 wells) which indicates that they are accepted for irrigation. Additionally, 52.86% of samples (37 wells) with an MH $\geq$ 50% are doubtful for agricultural use.

#### 3.3.3. Sodium Absorption Ratio (SAR) (meq/L)

The SAR was calculated using formula (3) where all concentrations are expressed in meq/L [26].

$$SAR = Na^{+}/((Ca^{2+} + Mg^{2+})/2)^{1/2} \quad (3)$$

The computation results of SAR show that 20% of analyzed samples (14 wells) were lower than 10 meq/L with a minimum of 4.90 meq/L, and a maximum of 25.54 meq/L. In total, 56 wells (80%) are characterized by contents largely higher than 10 meq/L corresponding to the risk of alkalization.

#### 3.3.4. The Permeability Index (PI)

Doneen suggested a method of classification of irrigation water based on the permeability index (PI). The expression of PI is calculated using formula (4) [29].

$$PI= (Na^{++}\sqrt{HCO_3^{-}}) \times 100/[Ca^{++} + Mg^{++} + Na^{+}] \quad (4)$$

PI values > 75, 25–75, and <25 fall in class I (safe), class II (marginally safe), and class III (unsafe), respectively. The permeability index (PI) presents the minimum value equal to 0.52 whereas the maximum value was recorded at the level of five wells F123, F125, F126, F130, and F131 and the mean value was found to be 0.70.

#### 3.3.5. Sodium Percentage SSP (Na%)

The sodium percentage (Na%) is calculated using the formula (5) of Todd [19] given below:

$$SSP(Na\%) = [(Na^{+} + K^{+}) \times 100]/[Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}] \quad (5)$$

The highest percentage of sodium was found in well F131 with a value of 79.37%; the minimum value was observed in well F210 with a value equal to 47.89%. The mean value was 68.94%

#### 3.3.6. Kelly Index (KI)

The Kelly index describes the presence of $Na^{+}$ in the water according to the presence of $Ca^{2+}$ and $Mg^{2+}$ and is calculated using formula (6) [11].

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

The mean value was found to be equal to 2.34 (meq/L); the minimum value was 0.91 (meq/L) recorded in well F210 and the maximum value was marked at well F131 with a value equal to 3.79. A statistical presentation of different index results is shown in Table 4.

**Table 4.** Statistical presentation of irrigation indices for groundwater suitability.

| | RSC | MH% | SAR | PI | Na% | KI |
|---|---|---|---|---|---|---|
| Maximum | −9.83 | 76.18 | 25.54 | 80 | 79.37 | 3.79 |
| Minimum | −21.62 | 29.18 | 4.90 | 52 | 47.89 | 0.91 |
| Average | −17.88 | 50.43 | 15.42 | 70 | 68.94 | 2.34 |
| SD | 2.29 | 12.51 | 5.21 | 7 | 7.48 | 0.74 |

From the USSL diagram (Figure 6), we find that all samples from different wells fall into C4-S2 (very high salinity with medium sodium), C4-S3 (very high salinity with high sodium), and C4-S4 (very high salinity with very high sodium) categories. According to the USSL plot, the groundwater of the Mio Pliocene in Ouargla basin is not safe for irrigation purposes.

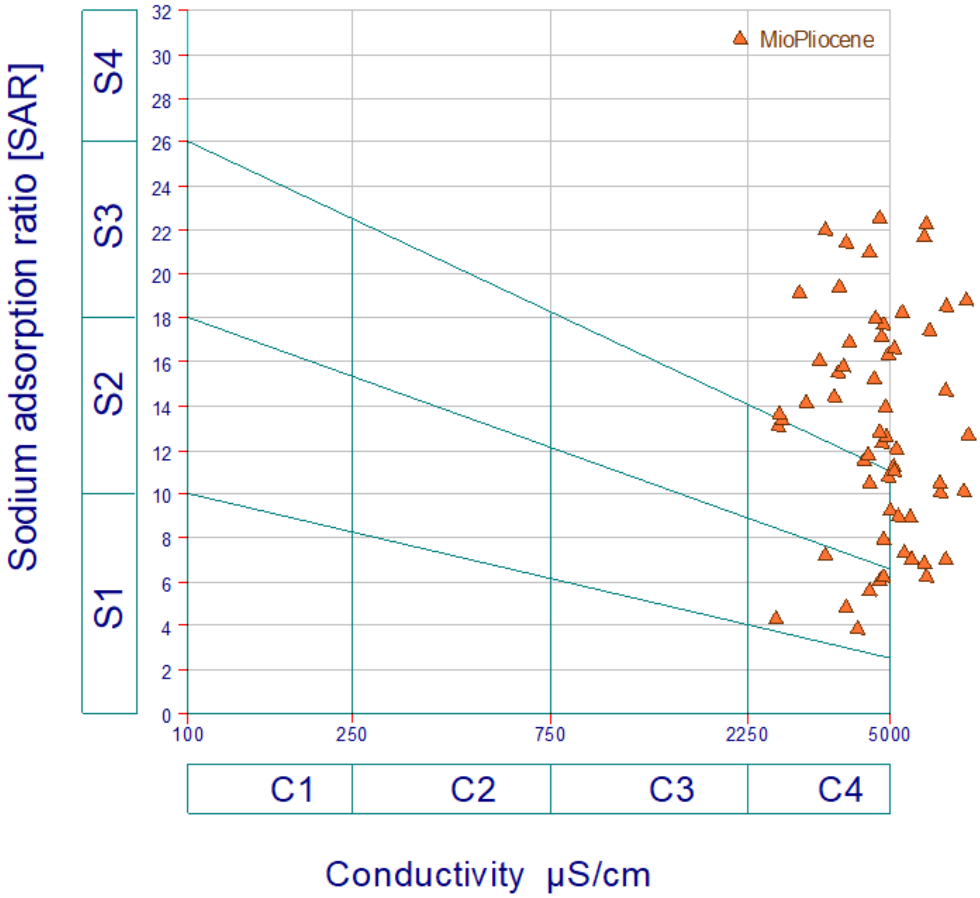


**Figure 6.** USSL diagram for EC and sodium percentage of groundwater suitability in irrigation.

### *3.4. Principal Component Analysis Results*

Table 5 presents the correlation matrix between the chemical parameters. The matrix shows the values of Pearson's correlation between the parameters involved. It is clear that there is a strong correlation between calcium and sodium (r = 0.933), calcium and chloride (r = 0.898), sodium and potassium (r = 0.832), sodium and chloride (r = 0.96), and potassium and chloride (r = 0.8767). These correlations indicate that the groundwater acquires chemical properties from a main source of these minerals. Figure 7 shows two homogeneous groups as a confirmation of the matrix correlation results. The first group consists of calcium, sodium, potassium, and chloride which are the control parameters of the chemical properties. The second group consists of mineralization, electrical conductivity, and dry residue. This group explained the source of dry residue in water which is the high mineralization.

**Table 5.** Correlation matrix of chemical elements.

| | $Ca^{2+}$ | $Mg^{2+}$ | $Na^{+}$ | $K^{+}$ | $Cl^{-}$ | $SO_4{}^{2-}$ | $HCO_3{}^{-}$ | $NO_3{}^{-}$ | DR | Min | EC | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $Ca^{2+}$ | 1.000 | | | | | | | | | | | |
| $Mg^{2+}$ | 0.707 | 1.000 | | | | | | | | | | |
| $Na^{+}$ | 0.933 | −0.653 | 1.000 | | | | | | | | | |
| $K^{+}$ | 0.694 | −0.335 | 0.832 | 1.000 | | | | | | | | |
| $Cl^{-}$ | 0.898 | −0.621 | 0.960 | 0.867 | 1.000 | | | | | | | |
| $SO_4{}^{2-}$ | 0.047 | 0.032 | 0.113 | 0.121 | 0.041 | 1.000 | | | | | | |
| $HCO_3{}^{-}$ | 0.102 | −0.010 | 0.031 | −0.038 | 0.048 | −0.158 | 1.000 | | | | | |
| $NO_3{}^{-}$ | 0.018 | 0.234 | 0.003 | 0.148 | −0.011 | 0.273 | −0.116 | 1.000 | | | | |
| DR | −0.093 | 0.199 | −0.058 | 0.184 | 0.033 | 0.470 | 0.094 | 0.284 | 1.000 | | | |
| Miniral | −0.126 | 0.229 | −0.029 | 0.185 | 0.024 | 0.530 | 0.087 | 0.242 | 0.904 | 1.000 | | |
| EC | −0.177 | 0.240 | −0.061 | 0.153 | −0.002 | 0.520 | 0.110 | 0.221 | 0.884 | 0.979 | 1.000 | |
| pH | 0.184 | −0.199 | 0.104 | −0.082 | 0.113 | −0.078 | 0.397 | −0.378 | 0.008 | −0.015 | −0.058 | 1.000 |

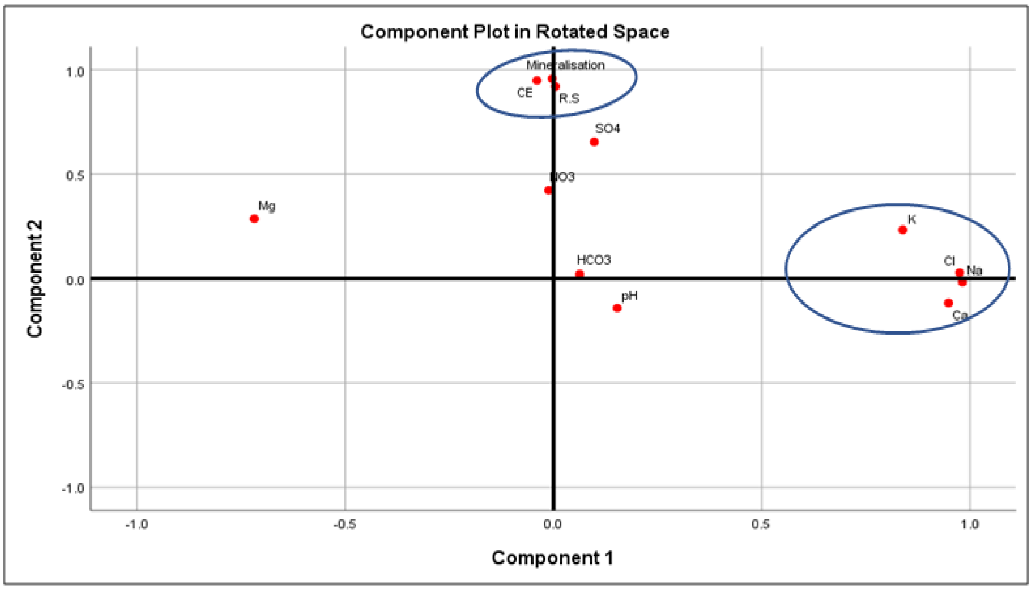


**Figure 7.** Correlation circles on the F1–F2 factors plane.

### *3.5. GIS Mapping*

The geospatial distribution of deferent indices is presented in Figure 8. From the maps we found that:

#### 3.5.1. The Residual Sodium Carbonate (RSC)

Sodium carbonate ($Na_2CO_3$) can be found in natural water as a result of the alteration of igneous rocks (basalt, etc.), as it can have other origins since sodium can be present in irrigation water in various types of soils and can participate in several possible constituent combinations of soils. This is what allows us to say that this index (RSC) varies from 1.25 to 2.25 over the entire map excluding that it is seen increasing in the extreme south (F126, F131) and southwest (F3, F5, F8, F9, F17, F18, F28, F30).

In the case where the dissolved sodium concerning the dissolved calcium and magnesium is rich in water, the clay soils can swell or undergo a dispersion which can be at the origin of a considerable reduction in its capacity of infiltration, which contributes to limiting the osmotic pressure and thus asphyxia of the plants, with the conjugation of the other parameters (T °C) and climatic hazards, to the formation of alkaline soils.

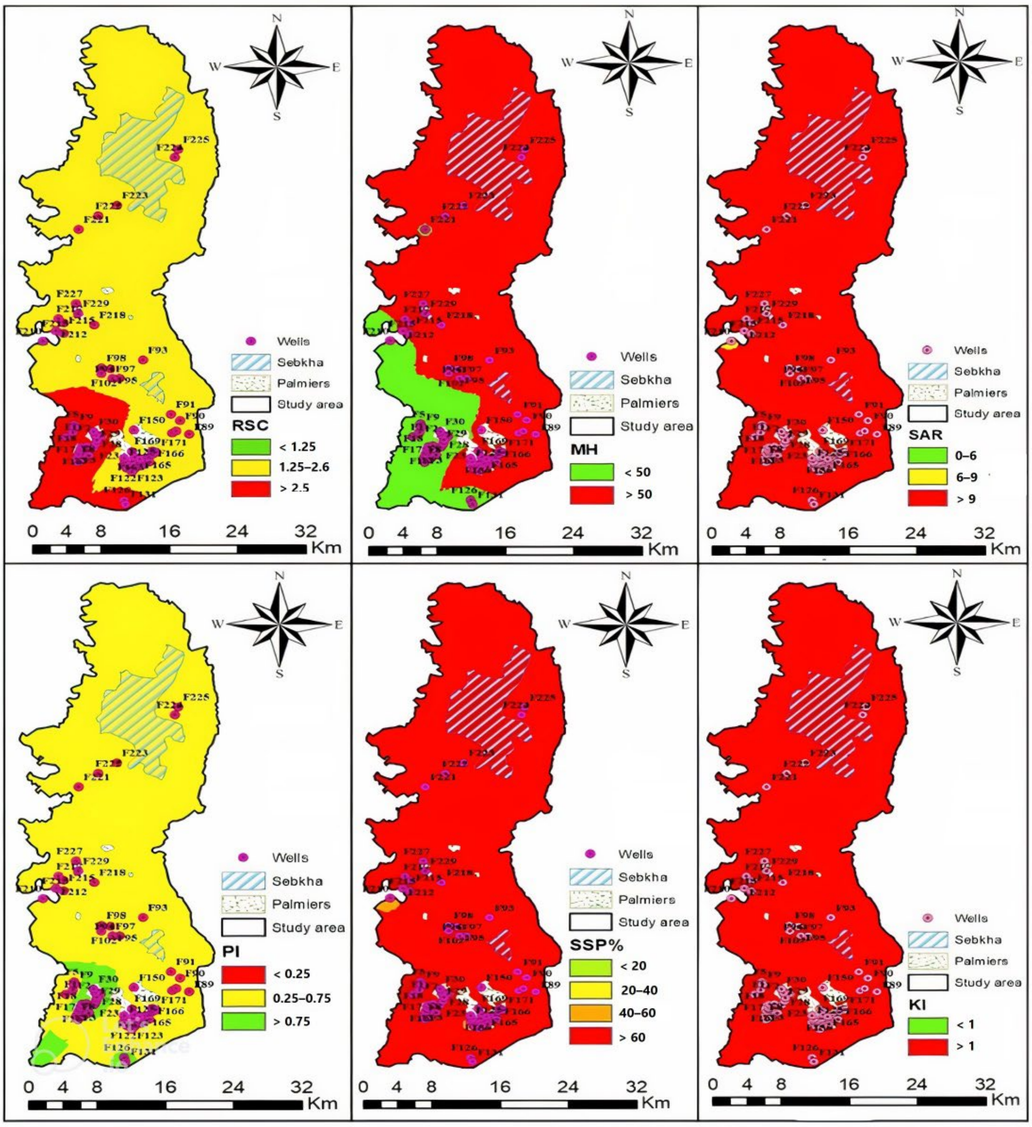


**Figure 8.** Geo-spatial distribution of suitability for irrigation indices.

### 3.5.2. Magnesium Hazards (MH) 40–60 to 40–60

The observation of this map shows that, overall, the highest concentrations (>50) are the most widespread and occupy almost the entire area, except for the extreme south and southwest where they are seen to decrease (<50). Knowing pertinently that this element is the product of the sequential addition of three nuclei of helium to a carbonaceous nucleus, and therefore its atoms exist in nature only in combination with other elements in the form of magnesium salts (magnesium chloride, magnesium carbonate, magnesium oxide, magnesium hydroxide, etc.). This is the reason why we notice that distribution goes hand in hand with its various contents and that it is uniformly distributed in the soil where several minerals (about 80) consist (to 20% or more) of magnesium (the dolomite, magnesite, apatite, olivine, etc.). All this is combined with the fact that magnesium is one of the constituent elements of chlorophyll. This last one catalyzes with the photosynthesis according to the following reaction (7):

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 \text{ (Glucose)} + 6O_2 \quad (7)$$

#### 3.5.3. Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) provides information on a possible relationship with recalcitrant calcium after irrigation, and on the Na content which (if in excess) impairs permeability and disturbs crops. On the representative map, we notice that the SAR index is higher than 9 and, on the whole area, except around F210 (in the center-west) where it is lower ($6 < SAR < 9$).

This can be translated by the nature of the soil (presence of atoms of sodium, calcium, and magnesium), its permeability, and the activities carried out in the region including cultivation practices, since the region is known for the cultivation of the palm and many other crops and therefore irrigation may be the cause of the spread of this element in the soil.

#### 3.5.4. Permeability Index (PI)

The observation of this map allows us to say that most of the study area is characterized by a permeability index that varies from 0.25 to 0.75. More important values ($PI > 0.75$) are reported on the southwest side (F3, F28, F29, F30) and in the extreme south (F126, F131). The nature of the soil contributes, in large part, by small (for soft soils) or large (for cracked or fractured soils) permeability, increasing this index that informs on areas where the permeability is good and therefore a risk of vulnerability is great. Consequently, areas are at high risk of pollution because these areas are conducive to the spread of certain salts and pollutants resulting from the effects of percolation/concentration that decrease or even destroy the ability of self-purification of the soil.

#### 3.5.5. Sodium Percentage (% $Na^+$/SSP)

Sodium is one of the major elements and therefore one of the most widespread in nature (either in combined or isolated form). This is the reason why we notice that the percentage of sodium is higher than 60 on the whole map, except for F210 where it is a slightly lower ($20 < SSP\% < 40$). This can be attributed to a combination of several factors including:

The nature of the soil where this element enters in various constituent combinations.

The permeability of the soil (loose, poorly consolidated, or cracked). Presence of marshy grounds and sebkha. The temperature, especially in the summer season when it is too high which favors the phenomenon of evaporation and therefore the concentration of salts. The cultivation practices and the need for irrigation. All these parameters can act together or separately, which generates the spread of certain salts including sodium, especially when the nature of the soil allows it, during periods of irrigation that are required following the vagaries of climate, since the soil is permeable which facilitates the percolation of irrigation water, transfer and exchange of these salts.

#### 3.5.6. Kelly Index (KI)

From this spatial distribution, we notice that the Kelly index (KI) is greater than unity (>1). This informs about the important properties of the soil, particularly its ability to retain cations and reason for their mobility while establishing the possible relationships with the texture, organic carbon content, and pH of the soils. Nowadays, it is admitted that the reaction of soils (to saline conditions) depends on the content, the nature of the clay fraction, the saline concentration of the soil solution, and the nature of the cationic and anionic filling of the adsorbent complex, etc., since in soils, it is the fine clay fraction that ensures (for the most part) the regulation of the physicochemical phenomena. It plays a vital role in water retention, and soil structuring, but also in the retention and bioavailability of chemical elements essential to plants. The soils are likely affected by salinity due mainly to capillary rise originating from the shallow water table. In addition, as a result of cultivation practices and irrigation, especially by submersion, the water table rises to the soil surface. Do not forget also that the area is dotted with sebkhas. The origin of salinity can be one or the other. This salinity can be accompanied by an increase in sodium in the adsorbent complex, which consequently leads to a decrease in structural stability and infiltration.

## 4. Conclusions

In this paper, we evaluated the quality of groundwaters of the Ouargla basin extracted from the Mio Pliocene aquifer. the sensitive issue and its importance in the local development. Especially, the increased demand for water due to the agricultural activities (irrigation) in the study area was the motivation to undertake this work. The results of analyses of sampled groundwaters made it possible to note a strong salinity.

Two factors can be held responsible for this high salinity; the lithology which showed a heterogeneity in the formations (alluvium, clay, sand, sandstone, and evaporites rich in Cl, Na, $SO_4$, and Ca), and climatic conditions that are characterized by high temperatures that cause evapotranspiration and consequently an increase in the salinity of groundwater.

The interpretation of the results of the physical-chemical analyses shows that there are two essential types of water: chloride water (Na-Cl) type and sodium sulfate (Na-$SO_4$) type.

The SAR according to conductivity allows to deduct two classes (poor toilets (C4 S3) and bad toilets (C4 S4)). By taking into account these considered chemicals, we can say that water of the studied wells is not suitable for irrigation.

The impact of groundwater chemical components on soil permeability was assessed using KI, PI, Na%, SAR, MH. and RSC. The results revealed that the Mio Pliocene formed a risk on soil permeability based on MH, SAR, Na%, PI, and KI, while RSC indicates no negative effect related to bicarbonate.

The spatial distribution of these six indices shows that the south-west part is a less hazardous sub-zone for agricultural practices, where the impact of MH and PI is lower compared to the rest of the study area.

Finally, many studies in the literature confirmed the existence of a relation between surface water and ground water quality [30–36]; the preservation of this precious resource is considered as a main responsibility of the local authorities by applying several policies to organize the rational exploitation of water resources in the study area and control the use of chemical fertilizers that accompanies agricultural activity.

As a limitation of this study, the inclusion of more parameters in the hydro-chemical assessment such as heavy metals and bacterial analysis was not possible, which would be interesting to include in future works for better judgment and assessment of groundwater quality in Ouargla basin.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Well longitude and latitude coordinates.

| District | Well ID | X | Y | Depth (m) | District | Well ID | X | Y | Depth (m) |
|---|---|---|---|---|---|---|---|---|---|
| N'Goussa | F210 | 712976 | 3553915 | 85 | Rouissat | F126 | 722490 | 3530716 | 32 |
| N'Goussa | F212 | 714527 | 3555376 | 87 | Rouissat | F130 | 723905 | 3522580 | 32 |
| N'Goussa | F213 | 715402 | 3555038 | 86 | Rouissat | F131 | 722659 | 3530068 | / |
| N'Goussa | F215 | 715424 | 3556572 | 90 | Ain-Beida | F150 | 723653 | 3540934 | 54.25 |
| N'Goussa | F217 | 714786 | 3557122 | 90 | Ain-Beida | F155 | 725005 | 3536784 | 67 |
| N'Goussa | F218 | 719002 | 3556268 | 181 | Ain-Beida | F156 | 725077 | 3536417 | 73 |
| N'Goussa | F221 | 717154 | 3570195 | 127 | Ain-Beida | F157 | 725492 | 3536253 | 76 |
| N'Goussa | F222 | 719472 | 3572152 | 364 | Ain-Beida | F161 | 723383 | 3537835 | 65 |
| N'Goussa | F223 | 721650 | 3573704 | 135 | Ain-Beida | F163 | 723727 | 3536962 | 65 |
| N'Goussa | F224 | 728433 | 3580717 | 95 | Ain-Beida | F165 | 724297 | 3536648 | 70 |
| N'Goussa | F225 | 728798 | 3581817 | 108 | Ain-Beida | F166 | 725840 | 3537408 | 79 |
| N'Goussa | F227 | 716885 | 3559335 | 237 | Ain-Beida | F169 | 725814 | 3537890 | 70 |
| N'Goussa | F229 | 717118 | 3557918 | 66 | Ain-Beida | F171 | 726258 | 3537662 | 70 |
| Sidi-Khouiled | F89 | 730095 | 3540281 | 113 | Ouargla | F1 | 715669 | 3539932 | 80 |
| Sidi-Khouiled | F90 | 729051 | 3542324 | 93 | Ouargla | F2 | 716471 | 3540534 | 86.47 |
| Sidi-Khouiled | F91 | 727984 | 3543181 | 83 | Ouargla | F3 | 717059 | 3536212 | 64 |
| Sidi-Khouiled | F93 | 724693 | 3551107 | 72 | Ouargla | F5 | 716603 | 3541797 | 95 |
| Sidi-Khouiled | F94 | 721994 | 3548482 | 49 | Ouargla | F8 | 716888 | 3536698 | 70 |
| Sidi-Khouiled | F95 | 721136 | 3548453 | 110 | Ouargla | F9 | 716653 | 3541407 | 73 |
| Sidi-Khouiled | F97 | 720870 | 3549841 | 55 | Ouargla | F11 | 717707 | 3536708 | 62 |
| Sidi-Khouiled | F98 | 719830 | 3550021 | 86 | Ouargla | F13 | 718387 | 3537217 | 69.1 |
| Sidi-Khouiled | F100 | 728135 | 3540438 | 80 | Ouargla | F14 | 717631 | 3537390 | 70.6 |
| Sidi-Khouiled | F101 | 728623 | 3540767 | 90 | Ouargla | F15 | 717177 | 3537402 | 62 |
| Sidi-Khouiled | F102 | 719851 | 3549185 | 52 | Ouargla | F16 | 717343 | 3537766 | 68 |
| Rouissat | F108 | 722453 | 3535889 | 63 | Ouargla | F17 | 717392 | 3538005 | 80 |
| Rouissat | F109 | 723093 | 3535833 | 74 | Ouargla | F18 | 717529 | 3538487 | 79 |
| Rouissat | F110 | 722827 | 3535330 | 62 | Ouargla | F19 | 718074 | 3538596 | 80 |
| Rouissat | F111 | 723204 | 3535902 | 61 | Ouargla | F23 | 718972 | 3538435 | 60 |
| Rouissat | F112 | 723582 | 3535739 | 67.92 | Ouargla | F24 | 719260 | 3538953 | 79 |
| Rouissat | F113 | 722645 | 3536261 | 73 | Ouargla | F25 | 719395 | 3539828 | 72 |
| Rouissat | F120 | 724454 | 3535678 | / | Ouargla | F26 | 719626 | 3540066 | 68 |
| Rouissat | F121 | 723684 | 3535171 | 62 | Ouargla | F27 | 719792 | 3540031 | 72 |
| Rouissat | F122 | 723723 | 3535312 | 70 | Ouargla | F28 | 719323 | 3539435 | 70 |
| Rouissat | F123 | 723392 | 3534864 | 67 | Ouargla | F29 | 719120 | 3540148 | 70 |
| Rouissat | F125 | 722493 | 3536785 | 60.74 | Ouargla | F30 | 718886 | 3540688 | 82.11 |

**Table A2.** Ion concentrations of analyzed samples.

| District | Well ID | $Ca^{2+}$ | $Mg^{2+}$ | $Na^{+}$ | $K^{+}$ | $Cl^{-}$ | $SO_4{}^{2-}$ | $HCO_3{}^{-}$ | $NO_3{}^{-}$ |
|---|---|---|---|---|---|---|---|---|---|
| N'Goussa | F210 | 204 | 105 | 304 | 7 | 474 | 875 | 147 | 10 |
| N'Goussa | F212 | 210.24 | 272.02 | 1121.39 | 44.27 | 2133.45 | 625.00 | 113.00 | 40.00 |
| N'Goussa | F213 | 213.19 | 269.05 | 1144.03 | 44.53 | 2162.36 | 1000.00 | 125.00 | 26.00 |
| N'Goussa | F215 | 216.15 | 266.09 | 1166.67 | 44.80 | 2191.27 | 1565.00 | 134.00 | 35.00 |
| N'Goussa | F217 | 219.10 | 263.13 | 1189.32 | 45.07 | 2220.18 | 950.00 | 131.00 | 34.00 |
| N'Goussa | F218 | 83.00 | 308.00 | 616.00 | 36.00 | 1500.00 | 1275.00 | 130.00 | 34.00 |
| N'Goussa | F221 | 222.05 | 260.16 | 1211.96 | 45.33 | 2249.09 | 640.00 | 101.00 | 48.00 |
| N'Goussa | F222 | 192.53 | 289.80 | 985.53 | 42.67 | 1960.00 | 1165.00 | 113.00 | 27.00 |
| N'Goussa | F223 | 195.48 | 286.84 | 1008.18 | 42.93 | 1988.91 | 1000.00 | 189.00 | 31.00 |
| N'Goussa | F224 | 198.44 | 283.87 | 1030.82 | 43.20 | 2017.82 | 1040.00 | 95.00 | 34.00 |
| N'Goussa | F225 | 201.39 | 280.91 | 1053.46 | 43.47 | 2046.73 | 2290.00 | 50.00 | 28.00 |
| N'Goussa | F227 | 204.34 | 277.95 | 1076.10 | 43.73 | 2075.64 | 565.00 | 92.00 | 26.00 |
| N'Goussa | F229 | 207.29 | 274.98 | 1098.75 | 44.00 | 2104.55 | 1265.00 | 88.00 | 26.00 |
| Sidi-Khouiled | F89 | 192.53 | 289.80 | 985.53 | 42.67 | 1960.00 | 1165.00 | 113.00 | 27.00 |
| Sidi-Khouiled | F90 | 195.48 | 286.84 | 1008.18 | 42.93 | 1988.91 | 1000.00 | 189.00 | 31.00 |
| Sidi-Khouiled | F91 | 198.44 | 283.87 | 1030.82 | 43.20 | 2017.82 | 1040.00 | 95.00 | 34.00 |
| Sidi-Khouiled | F93 | 204.34 | 277.95 | 1076.10 | 43.73 | 2075.64 | 565.00 | 92.00 | 26.00 |
| Sidi-Khouiled | F94 | 207.29 | 274.98 | 1098.75 | 44.00 | 2104.55 | 1265.00 | 88.00 | 26.00 |
| Sidi-Khouiled | F95 | 210.24 | 272.02 | 1121.39 | 44.27 | 2133.45 | 625.00 | 113.00 | 40.00 |
| Sidi-Khouiled | F97 | 213.19 | 269.05 | 1144.03 | 44.53 | 2162.36 | 1000.00 | 125.00 | 26.00 |
| Sidi-Khouiled | F98 | 216.15 | 266.09 | 1166.67 | 44.80 | 2191.27 | 1565.00 | 134.00 | 35.00 |
| Sidi-Khouiled | F100 | 219.10 | 263.13 | 1189.32 | 45.07 | 2220.18 | 950.00 | 131.00 | 34.00 |
| Sidi-Khouiled | F101 | 83.00 | 308.00 | 616.00 | 36.00 | 1500.00 | 1275.00 | 130.00 | 34.00 |
| Sidi-Khouiled | F102 | 222.05 | 260.16 | 1211.96 | 45.33 | 2249.09 | 640.00 | 101.00 | 48.00 |
| Rouissat | F108 | 74.00 | 265.00 | 315.00 | 29.00 | 1140.00 | 476.00 | 100.00 | 10.00 |
| Rouissat | F109 | 74.00 | 284.00 | 470.00 | 29.00 | 760.00 | 1434.00 | 49.00 | 10.00 |
| Rouissat | F110 | 123.00 | 336.00 | 455.00 | 30.00 | 775.00 | 1300.00 | 88.00 | 85.00 |
| Rouissat | F111 | 91.00 | 326.00 | 620.00 | 39.00 | 1140.00 | 1434.00 | 122.00 | 10.00 |
| Rouissat | F112 | 154.00 | 227.00 | 600.00 | 26.00 | 1170.00 | 1025.00 | 107.00 | 24.00 |
| Rouissat | F113 | 143.00 | 361.00 | 613.00 | 37.00 | 1310.00 | 1250.00 | 134.00 | 42.00 |
| Rouissat | F120 | 140.00 | 321.00 | 565.00 | 35.00 | 875.00 | 1400.00 | 85.00 | 92.00 |
| Rouissat | F121 | 158.00 | 386.00 | 750.00 | 42.00 | 1625.00 | 1500.00 | 98.00 | 80.00 |
| Rouissat | F122 | 322.40 | 170.00 | 1872.00 | 54.00 | 3112.00 | 1434.00 | 49.00 | 10.00 |
| Rouissat | F123 | 310.59 | 171.25 | 1891.23 | 53.33 | 3116.36 | 1300.00 | 88.00 | 85.00 |
| Rouissat | F125 | 313.55 | 168.29 | 1913.87 | 53.60 | 3145.27 | 1434.00 | 122.00 | 10.00 |
| Rouissat | F126 | 316.50 | 165.33 | 1936.52 | 53.87 | 3174.18 | 1025.00 | 107.00 | 24.00 |
| Rouissat | F130 | 319.45 | 162.36 | 1959.16 | 54.13 | 3203.09 | 1250.00 | 134.00 | 42.00 |
| Rouissat | F131 | 322.40 | 159.40 | 1981.80 | 54.40 | 3232.00 | 1400.00 | 85.00 | 92.00 |
| Ain-Beida | F150 | 195 | 372 | 1038 | 55 | 1825 | 1130 | 119 | 90 |
| Ain-Beida | F155 | 168 | 306 | 840 | 37 | 1790 | 1150 | 122 | 69 |
| Ain-Beida | F156 | 153 | 336 | 600 | 33 | 1300 | 1390 | 116 | 73 |
| Ain-Beida | F157 | 83 | 308 | 616 | 36 | 1500 | 820 | 51 | 10 |
| Ain-Beida | F161 | 174 | 279 | 725 | 31 | 1400 | 1200 | 128 | 25 |
| Ain-Beida | F163 | 260 | 305 | 925 | 40 | 2500 | 675 | 146 | 40 |
| Ain-Beida | F165 | 190 | 150 | 963 | 58 | 2625 | 1250 | 73 | 65 |
| Ain-Beida | F166 | 180 | 297 | 840 | 36 | 1520 | 1250 | 82 | 25 |
| Ain-Beida | F169 | 182 | 364 | 1025 | 33 | 1900 | 1550 | 107 | 63 |
| Ain-Beida | F171 | 178 | 344 | 1038 | 53 | 1650 | 1600 | 98 | 68 |
| Ouargla | F1 | 225.00 | 257.20 | 1234.60 | 45.60 | 2278.00 | 760.00 | 100.00 | 49.00 |
| Ouargla | F2 | 227.95 | 254.24 | 1257.24 | 45.87 | 2306.91 | 736.00 | 128.00 | 36.00 |
| Ouargla | F3 | 230.90 | 251.27 | 1279.88 | 46.13 | 2335.82 | 1275.00 | 116.00 | 41.00 |
| Ouargla | F5 | 233.85 | 248.31 | 1302.53 | 46.40 | 2364.73 | 865.00 | 95.00 | 17.00 |
| Ouargla | F8 | 236.81 | 245.35 | 1325.17 | 46.67 | 2393.64 | 996.00 | 15.00 | 10.00 |
| Ouargla | F9 | 239.76 | 242.38 | 1347.81 | 46.93 | 2422.55 | 1300.00 | 130.00 | 34.00 |
| Ouargla | F11 | 245.66 | 236.45 | 1393.10 | 47.47 | 2480.36 | 1300.00 | 67.00 | 97.00 |
| Ouargla | F13 | 248.61 | 233.49 | 1415.74 | 47.73 | 2509.27 | 1100.00 | 88.00 | 77.00 |
| Ouargla | F14 | 251.56 | 230.53 | 1438.38 | 48.00 | 2538.18 | 915.00 | 121.00 | 10.00 |
| Ouargla | F15 | 254.52 | 227.56 | 1461.02 | 48.27 | 2567.09 | 1250.00 | 131.00 | 44.00 |

**Table A2.** *Cont.*

| District | Well ID | $Ca^{2+}$ | $Mg^{2+}$ | $Na^{+}$ | $K^{+}$ | $Cl^{-}$ | $SO_4{}^{2-}$ | $HCO_3{}^{-}$ | $NO_3{}^{-}$ |
|---|---|---|---|---|---|---|---|---|---|
| Ouargla | F16 | 257.47 | 224.60 | 1483.67 | 48.53 | 2596.00 | 850.00 | 149.00 | 25.00 |
| Ouargla | F17 | 260.42 | 221.64 | 1506.31 | 48.80 | 2624.91 | 1125.00 | 95.00 | 39.00 |
| Ouargla | F18 | 263.37 | 218.67 | 1528.95 | 49.07 | 2653.82 | 620.00 | 143.00 | 35.00 |
| Ouargla | F19 | 266.32 | 215.71 | 1551.59 | 49.33 | 2682.73 | 948.00 | 183.00 | 10.00 |
| Ouargla | F23 | 269.27 | 212.75 | 1574.24 | 49.60 | 2711.64 | 1750.00 | 146.00 | 40.00 |
| Ouargla | F24 | 272.22 | 209.78 | 1596.88 | 49.87 | 2740.55 | 1440.00 | 134.00 | 19.00 |
| Ouargla | F25 | 275.18 | 206.82 | 1619.52 | 50.13 | 2769.45 | 1000.00 | 131.00 | 11.00 |
| Ouargla | F26 | 278.13 | 203.85 | 1642.16 | 50.40 | 2798.36 | 1250.00 | 98.00 | 37.00 |
| Ouargla | F27 | 281.08 | 200.89 | 1664.81 | 50.67 | 2827.27 | 2000.00 | 95.00 | 52.00 |
| Ouargla | F28 | 284.03 | 197.93 | 1687.45 | 50.93 | 2856.18 | 1800.00 | 128.00 | 65.00 |
| Ouargla | F29 | 286.98 | 194.96 | 1710.09 | 51.20 | 2885.09 | 1000.00 | 116.00 | 21.00 |
| Ouargla | F30 | 289.93 | 192.00 | 1732.73 | 51.47 | 2914.00 | 1020.00 | 88.00 | 17.00 |

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