Environment and Natural Resources Journal

Volume 24
Issue 1
2026

Suitability and Evaluation of the Quality of Groundwater Used in Irrigation, Case of the Region of Oum El-Bouaghi (Northeast Algeria)

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ARTICLE INFO

Received: 26 May 2025
Received in revised: 21 Aug 2025
Accepted: 27 Aug 2025
Published online: 8 Oct 2025
DOI: 10.32526/ennrj/24/20250135

Keywords:
Irrigation/ Salinity/ Spatial Autocorrelation/ Groundwater/ Wilcox/ Richards

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ABSTRACT

This study assesses the quality of groundwater for irrigation in the plains of Bir Chouhada, Souk Naamane, and Ouled Zouai, focusing on physico-chemical parameters including Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), sodium percentage (%Na), and chloride toxicity. Results show EC values ranging from 993 to 9,322 µS/cm, indicating poor to unsuitable water quality for irrigation in most wells. The SAR values vary between 8.86 and 43.6 meq/L, reflecting a high risk of soil sodification. The %Na ranges from 19.18% to 61.41%, with over 66% of samples exhibiting high mineralization. Using Richards classification, 58.78% of samples fall in the highly unsuitable C4S4 class, while Wilcox classification indicates 48.78% of dry season samples as unsuitable for irrigation. Seasonal variation shows slight quality improvement during the wet season, with good-quality water increasing from 4.87% (dry) to 7.31% (wet). Hydrochemical facies analysis identifies 46.34% of samples as calcic chloride type, linked to mineralization from gypsiferous formations. Spatial autocorrelation using Moran's I reveals moderate positive clustering of SAR (0.21-0.27) and %Na (0.15-0.23), with stable patterns across seasons. Statistical analysis via ANOVA confirms the significance of the model with F=29.48 (p<0.000005) and explains 43% of variation in water quality parameters. These findings highlight the critical challenges of irrigation water quality in the region and underscore the need for integrated management strategies including the use of salt-tolerant crops and soil drainage improvements.

HIGHLIGHTS

This study evaluated groundwater quality for irrigation using EC, SAR, %Na, and chloride toxicity. Classification by Richards and Wilcox methods showed that over 58% of samples were highly unsuitable for irrigation. Spatial analysis using Moran's I revealed moderate clustering of SAR and %Na values, consistent across seasons. ANOVA confirmed the model's significance, explaining 43% of the variation in water quality. The findings highlight serious salinity and sodicity risks, emphasizing the need for integrated water management and salt-tolerant agricultural practices.

1. INTRODUCTION

Irrigation water supply in arid and semi-arid areas is crucial for agricultural production, influencing both crop intensification and the expansion of irrigated areas (Jabeen et al., 2022; Jarray et al., 2023; Khechekhouche et al., 2020). While surface water is the main source of irrigation in temperate regions, groundwater is increasingly relied upon in semi-arid areas where surface water is scarce or absent (DHW, 2004; Ayers and Westcot, 1988; Person, 1978). However, agriculture development in such regions faces significant challenges, primarily due to water scarcity and emerging issues like soil salinization and alkalization. These problems directly affect soil fertility and crop productivity, posing serious obstacles to sustainable agricultural practices. Soil salinization occurs when soluble salts accumulate in the soil to levels that hinder plant growth, often

Citation: Ibtissem K, Nadjet Z, Abderrahmane K, Badra A, Abdelmonem M. Suitability and evaluation of the quality of groundwater used in irrigation, case of the region of Oum El-Bouaghi (Northeast Algeria). Nat. Resour. J. 2026;24(1):10-28. (https://doi.org/10.32526/ennrj/24/20250135)

resulting from improper irrigation practices or the use of saline water (Gouaidia, 2011; Pan et al., 2024). Alkalization, involving the buildup of exchangeable sodium in the soil, deteriorates soil structure and reduces permeability, further complicating water management and crop growth. To address these challenges in semi-arid agricultural regions, integrated water management strategies and innovative agricultural practices are essential to maintain soil health and ensure long-term sustainability (Liu et al., 2024; Miloudi et al., 2024; Zair et al., 2024; Attoui et al., 2024a). These issues mainly arise from ionic exchanges between irrigation water and soil, altering soil chemistry and reducing fertility over time (Bremond and Perredon, 1979; Devez, 2004; Zair et al., 2024; Attoui et al., 2024b). Effective mitigation requires proper irrigation management, soil amendments, and the use of salt-tolerant crops (Lado et al., 2024; Anyango et al., 2024). Similar challenges related to groundwater quality, salinity, and sustainable irrigation have been extensively documented in Pakistan's Punjab Province, a key agricultural region heavily dependent on groundwater resources (Khan et al., 2024; Malik et al., 2023; Baloch et al., 2025; Meng et al., 2024; Iqbal et al., 2023; Hussein et al., 2023; Baloch et al., 2022a; Baloch et al., 2022b). These studies reveal widespread contamination issues such as fluoride and nitrate pollution, risks associated with land use changes, and the potential of machine learning for water quality prediction and risk assessment. Collectively, they underscore the importance of integrated approaches combining groundwater quality monitoring, adaptive irrigation strategies, and crop selection to mitigate soil degradation and sustain agricultural productivity under increasing environmental pressures. Placing the present study within this global and regional framework emphasizes the crucial role of comprehensive water quality assessments such as those employing Wilcox and Richards's methods in informing water management policies that protect agricultural livelihoods and ecosystem health. Understanding seasonal variations in water quality, as done here over dry and wet seasons, further aids in developing targeted strategies to limit the negative impacts of salinization and alkalization, ensuring long-term agricultural sustainability in semi-arid regions such as Bir Chouhada, Souk Naamane, and Ouled Zouai. The accumulation of water-soluble salts in the root zone negatively impacts plant growth by altering soil permeability and aeration, as well as disrupting the plants' osmotic processes (Sousa et al., 2017; Attoui et al., 2024a; Zair et al., 2024). Regions like Bir Chouhada, Souk Naamane, and Ouled Zouai face significant risks of soil salinization (Zair, 2017; Rouabhia and Djabri, 2010). These areas are characterized by low rainfall, high evaporation rates, and groundwater rich in chlorides and sulfates, which exacerbate salinization and alkalization risks. Understanding the water and saline regimes in these regions is essential for sustainable water and soil resource management (Habiba et al., 2024; Zair et al., 2024). Various methods can help evaluate the type and quality of water intended for irrigation, including the Water Quality Index, Wilcox method, and Sodium Adsorption Ratio (SAR) method (Richards, 1954). In this study, we assessed irrigation water quality using the Wilcox and Richards methods. The Wilcox method focuses on salinity issues by assessing sodium percentage and electrical conductivity (Habiba et al., 2024; Miloudi et al., 2024; Zair et al., 2025), while the Richards method evaluates water quality based on sodium concentration (Na^+), a key indicator of water suitability for agriculture (Zair et al., 2021). Both methods rely on the chemical composition of water, which directly impacts plant growth and human health. We applied both the Wilcox (Na%) and Richards (SAR) methods to evaluate potential alterations in irrigation water quality, aiming to identify and mitigate issues that may affect irrigated soils and crops. Evaluations were conducted over dry and wet seasons to understand seasonal variations and better inform sustainable water management practices in the region. In the context of scarce water resources and risks of soil salinization and alkalization, this study addresses: How can we assess the quality of water intended for irrigation in Bir Chouhada, Souk Naamane, and Ouled Zouai? What strategies can be implemented to limit the negative effects of these phenomena on agriculture?

2. METHODOLOGY

2.1 Geographic situation of the study region

The study area includes the communes of Bir Chouhada, Souk Naamane and Ouled Zouai. These communes are located at the south-eastern end of the city of Oum El Bouaghi, located in the northeast of Algeria. Administratively, these communes are bordered by the cities of Mila to the north and Batna to the south as shown in Figure 1.

According to the hydrogeological study of the plain of Bir Chouhada, Souk Naamane and Ouled

Zouai, carried out by the Directorate of Hydraulics of the Wilaya (DHW) of Oum El Bouaghi in 2004, the geology of the region has four stratigraphic sets:

- The allochthonous Setifian in Djebel Amsid (northwest of Bir Chouhada), it consists of marls and gypsiferous clays of Miocene age and massive limestone of middle Cretaceous age.
- The autochthonous north Aurassian, represented by the djebels of Ain Yagout, Hanout, Harshel and Terbenut. The grounds are constituted of conglomerate, marl and marl-limestone.
- The Constantine neritic nappe and the nappe moi-plio quaternary extends on the plain, they are especially represented by the formations mio-plio-quaternary, represented by the alluvium, clays, marls, conglomerates, gravels, sands and dolomitic limestones as shown in Figure 2.

Figure 3 illustrates the piezometric map of the water table in the studied region. The area is characterized by a semi-arid climate, with cool winters and hot, dry summers. The average annual precipitation is approximately 465.30 mm, while the average annual temperature is around 16°C (DHW, 2004; Zair et al., 2017; Gouaidia et al, 2020). From a hydrogeological perspective, the piezometric surface observed during the wet season indicates that the general direction of groundwater flow is from west to east. The main drainage axes are located near the limestone massifs of the Lower Cretaceous and along the edge of the Miocene lacustrine limestone, particularly west of Bir Chouhada.

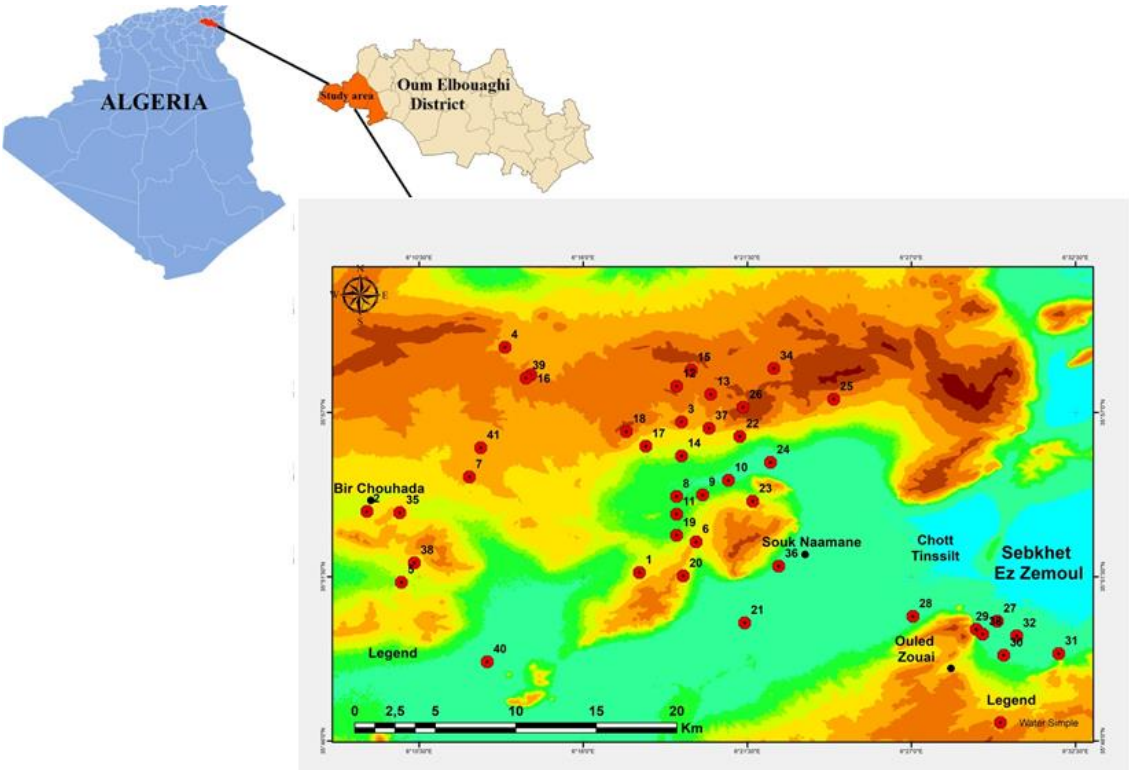


Figure 1. Geographic situation of the study region and well sampling repartition

As part of our study on groundwater quality for irrigation, we selected more than 40 water points strategically distributed across different geographical areas: near chotts, upstream (in the mountains), and in agricultural areas. This distribution provides a better understanding of the impact of geological and hydrological characteristics on water quality. Areas near chotts, often rich in dissolved salts due to evaporation, can have high sodium levels, increasing the risk of soil salinization and sodification. In contrast, water from the mountains, naturally filtered by the soil, should have lower sodium levels. Agricultural areas, depending on irrigation practices and local characteristics, offer another perspective on water salinity. By measuring SAR and Na% indices, you will be able to accurately assess soil degradation risks and recommend appropriate solutions, such as specific irrigation techniques or water management strategies to preserve soil fertility and optimize agricultural production. In situ measurements of pH, and electrical conductivity (EC) were conducted using a WWT 82 362 multi-parameter probe. Geographic coordinates of each sampling point were recorded with the GPS Status device. The sampling network is illustrated in Figure 1. Water samples were stored at 4°C in a cooler during transportation to the laboratory. In addition, major ions (Na^+, K^+, HCO_3^-, Cl^-, Ca^{2+}, Mg^{2+}, SO_4^{2-}) were analyzed in the laboratory following APHA (1989) standard methods during May and September 2019 sampling campaign.

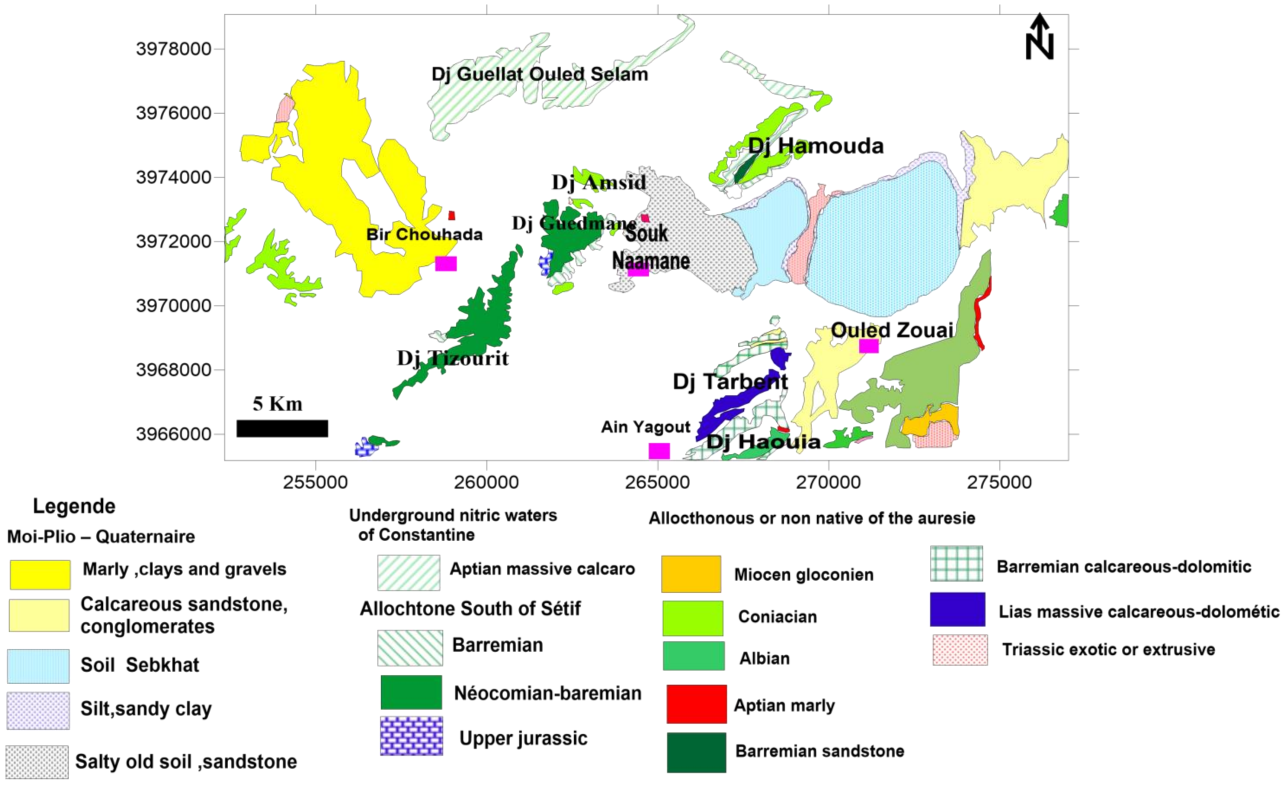


Figure 2. Extract of the geological map of the study area (DHW, 2004)

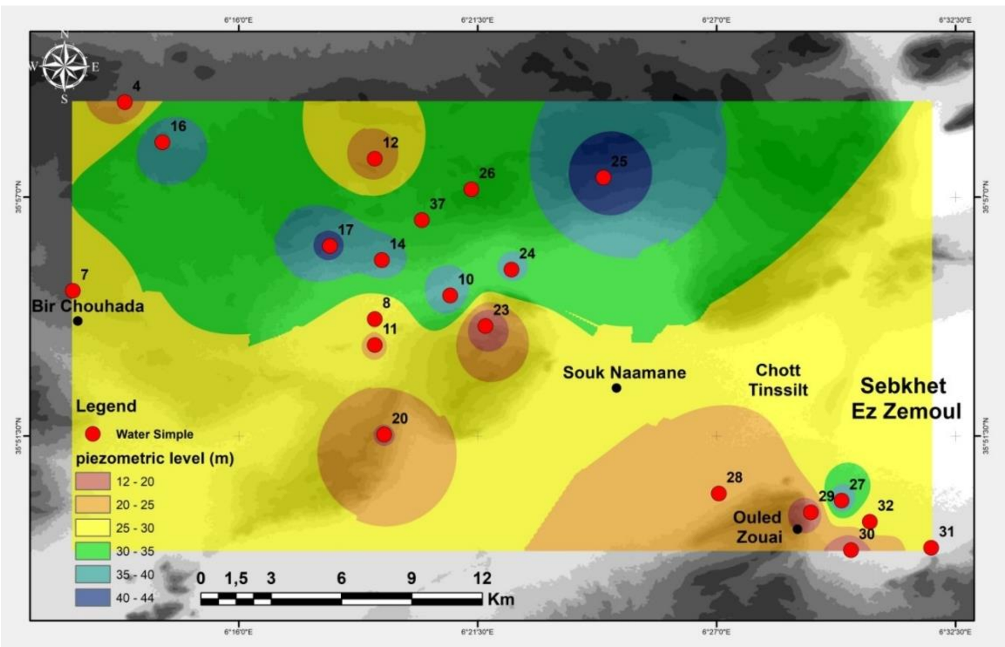


Figure 3. Water table of the phreatic aquifer

Different agricultural practices and the implementation of many irrigation systems have had an effect on the quality of groundwater, particularly that which returns to the aquifer after irrigation (Hemila, 1988; Zair at al., 2025). It should be noted that mineral salts in water have an impact on soil and plants. Indeed, salts can cause changes in soil structure (on its permeability and aeration), directly affecting plant development (Zair et al., 2017; Zair, 2017; Gouaidia, 2011). In this study, we have highlighted the evaluation of the quality of groundwater in Bir Chouhada, Souk Namaane and Ouled Zouai for agricultural purposes. This assessment is based on the Piper diagram for the determination of chemical facies, and on the universal diagrams of Riverside and Wilcox to assess the risk of salinization and sodisation of soils (Figure 4). The SAR (Sodium Adsorption Ratio) method and the Na% (sodium percentage) method are commonly used tools to assess the quality of groundwater intended for irrigation. Each of these methods allows measuring the compatibility of water with soils and identifying the potential risk of deterioration of agricultural land due to excess sodium, which can harm soil structure and affect plant growth. The Wilcox approach and the Riverside approach are widely used to assess the suitability of water for irrigation based on salinity and sodicity (SAR) (Sumner, 1993; Devez, 2004; Eaton, 1950). The Riverside and Wilcox methods are widely used to assess the quality of water for irrigation. The Riverside method plots the Sodium Adsorption Ratio (SAR) against Electrical Conductivity (EC), categorizing water into Good, Acceptable, Marginal, and Hazardous based on levels of salinity and sodicity (Table 1). The Wilcox method uses sodium percentage (Na%) and EC to classify water into four categories: Excellent, Good, Fair, and Unsuitable, based on the salinity and sodium content of the water (Wilcox, 1955) (Table1). Both methods provide critical insights into water quality, helping guide water management practices and crop selection by highlighting risks to soil structure and crop health.

Table 1. Summary table for classification of water quality

Diagram	Parameter	Classification	EC (μS/cm)	SAR	Na%
Wilcox	Salinity and Sodicity	Excellent	≤700	≤3	≤20
		Good	700-1,400	3-6	20-40
		Fair	1,400-2,800	6-12	40-60
		Unsuitable	>2,800	>12	>60
Riverside	Salinity and SAR	Good	≤2,000	≤6	
		Acceptable	2,000-4,000	6-9	
		Marginal	4,000-6,000	9-12	
		Hazardous	>6,000	>12	

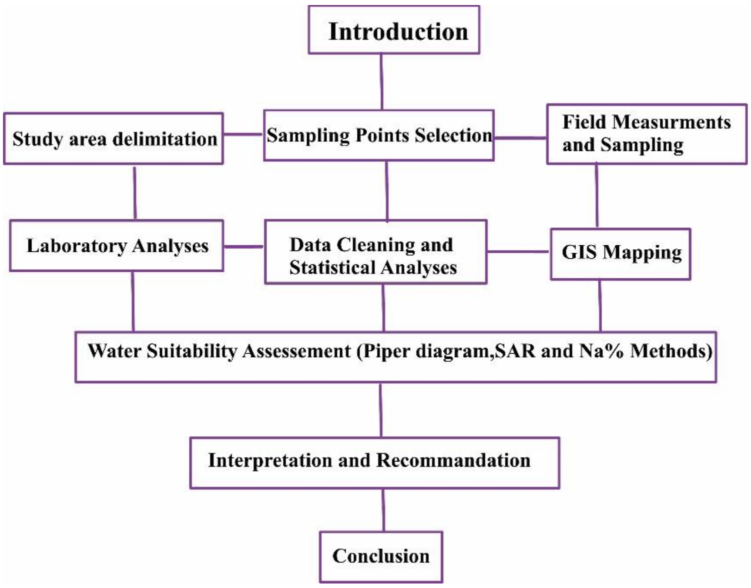


Figure 4. General Diagram presenting the study approaches

2.2 Limitations and sources of uncertainty

While the applied hydrochemical methods provide valuable insights into the groundwater facies and geochemical processes, several limitations and sources of uncertainty should be acknowledged. Firstly, measurement errors associated with field instrumentation (electrical conductivity, pH, and ion-selective electrodes) and laboratory analyses (ion chromatography, titration methods) may affect the accuracy and precision of the chemical data. Additionally, the temporal variability of groundwater chemistry particularly influenced by seasonal changes in recharge, evapotranspiration, and anthropogenic inputs could lead to inconsistencies if the sampling was conducted during a single season or over a short time frame. The spatial coverage of sampling points may also limit the representativeness of the interpreted facies, especially in heterogeneous geological settings where local lithology, permeability, and water-rock interaction can vary significantly. Furthermore, potential mixing of groundwater from multiple sources (deep versus shallow aquifers) could obscure geochemical signatures, complicating facies classification. Lastly, the interpretation of facies is based on the dominant ion composition and does not always account for trace elements, isotopic data, or redox-sensitive species, which can provide critical complementary information for understanding groundwater evolution and contamination processes. Future studies should consider incorporating multitemporal sampling, and modeling approaches to reduce these uncertainties and improve the reliability of hydrochemical interpretations.

2.3 Statistical analysis

Analysis of variance (ANOVA) is a widely used statistical method designed to determine whether the differences observed among the means of multiple groups are statistically significant. It compares the between-group variance, which reflects the effects of explanatory factors (facies type, season), to the within-group variance, associated with natural sample variability (Montgomery, 2017). In hydrogeology, ANOVA is particularly useful for assessing whether variations in physicochemical parameters such as concentrations of major ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-) are significantly influenced by qualitative variables like hydrochemical facies, seasonal changes, or spatial distribution (Helena et al., 2000; Subba Rao, 2006). The null hypothesis (H_0) assumes all group means are equal, while the alternative hypothesis (H_1) suggests at least one group mean differs; a p-value less than 0.05 indicates statistically significant differences unlikely due to random chance (Hair et al., 2014). Valid ANOVA requires assumptions of normality (tested by Shapiro-Wilk), homogeneity of variances (Levene's or Bartlett's test), and independence; violations may necessitate non-parametric alternatives like the Kruskal-Wallis test (Zar, 2010). In this study, ANOVA provides a robust framework to test temporal variability in groundwater chemistry and validate facies classifications from multivariate or classical analyses. Complementing this, Moran's I is a spatial statistic that evaluates whether the values of a variable, such as SAR salinity, exhibit spatial clustering. Ranging from -1 to +1, Moran's I indicates strong positive spatial autocorrelation at +1 (similar values are spatially clustered), zero spatial autocorrelation at 0 (random distribution), and strong negative spatial autocorrelation at -1 (neighboring values differ greatly), helping to reveal geographic clustering patterns in the data.

2.4 Comparison of classes from the Riverside and Wilcox methods

In this comparative study, the Riverside classification method will be the one used as the reference for determining the evaluation of spatial variations in classes. A statistical method will be used to make this comparison: Statistical analysis of class areas. This analysis compares the areas of the different classes produced by the two methods (Riverside and Wilcox), according to a 100 m × 100 m grid. The analysis is based on the two maps and the number of grid cells per class. The evaluation and visualization of the results were carried out using Excel 2010 software, Diagram software, software for the geographic information system GIS (Arc GIS, QGIS) and golden surfer 20 logiciel.

3. RESULTS AND DISCUSSION

The results of physico-chemical analysis of the water of study area, during the observation period, have brought out the parameters usually used for the estimation of the quality of irrigation water. Among these parameters, we count the salinity expressed by the Electrical Conductivity (EC), the %Na, the SAR (Sodium Absorption Ratio) and the toxicity of chlorides. These parameters have been reported in Table 2.

The average value of conductivity between 37,012 and 3,371 (µS/cm) in dry and wet periods.

These values indicate that the groundwater of Bir Chouhada, Souk Namaan and Ouled Zouai is of poor to Unsuitable quality. Nevertheless, several water points are of average quality with an EC below 1050 (µS/cm). However, the average SAR value varies between 15.9 (Dry period) and 17.7 meq/L (Wet period), showing a high risk of sodisation .These results are similar to what was found by (Benmrabet et al., 2025) in the Tebessa region (Algeria). According to the guidelines, there is a problem of toxicity by chlorine if the concentration is between 4 and 10 meq/L, beyond 10 meq/L of Cl^-, the problems become serious. The %Na values of the groundwater samples range from 38 to 40. Most of the groundwater samples are of poor water quality with high mineralization (66%) These results are compatible with those found in the Tebessa region (Algeria) (Benmerabet et al., 2025), with regard to the results found (Table 2) their toxicity is clear, since we find more than half (68.2%) of the wells with contents that greatly exceed 10 meq/L representing the maximum permissible threshold for plants (Ayers and Westcot, 1988; Bremond and Perredon, 1979).

Table 2. Statistical parameters of some groundwater variables in the study area

	CE	Dry			CE	Wet		
		SAR	Cl^-	Na%		SAR	Cl^-	Na%
Unit	µS/cm	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L
Min	1,056	9.44	8.02	26.67	993	8.86	7.61	19.18
Max	9,322	43.60	72.11	61.41	9,000	31.40	68.54	61.06
Mean	3,712.821	15.90	1,796.294	38.43	3,371.923	17.70	17.93555	40.01

3.1 Determination of the Hydrochimique facies of the waters

Analysis of the scatterplots shown in Figures 5(a) and 5(b) does not indicate a clear dominance of either cations (such as calcium, magnesium, sodium, potassium) or anions (such as chloride, sulfate, and bicarbonate). This lack of ion dominance suggests that multiple hydrochemical processes influence the groundwater composition in the study area. However, the classification of hydrochemical facies reveals a relatively dominant calcic chloride facies, representing 46.34% of the analyzed samples. This facies typically reflects more advanced mineralization, likely linked to deeper or longer groundwater circulation through evaporitic formations rich in chlorides. A moderate proportion of calcic sulfate facies (25.15%) is also observed. This indicates a significant contribution from rocks containing gypsum or anhydrite, which is consistent with the presence of gypsiferous marls of Triassic age in the geological substratum. These formations release calcium and sulfate through dissolution, thereby influencing the groundwater chemistry. In addition, two calcic bicarbonate facies are present at lower proportions (18% and 10.5%)**,** suggesting the influence of more recent or less mineralized recharge waters. These facies are generally associated with peripheral zones, where infiltration of rainwater or input from shallow aquifers dilutes major ion concentrations, resulting in less chemically evolved water types (Figures 5(a) and 5(b)). The significant presence of sodium in several samples can be attributed to the Triassic gypsiferous marls that form the aquifer's substratum. These formations contribute sodium through processes such as mineral dissolution or cation exchange, which further complicates the hydrochemical signature of the groundwater. In summary, the distribution of hydrochemical facies reflects a complex interplay of geological substrate, recharge mechanisms, and water-rock interactions. No single ion type (cationic or anionic) clearly dominates across the dataset, underscoring the heterogeneous nature of the groundwater system.

3.2 Water quality status for agricultural use

Potassium (K^+) is not usually included in the traditional SAR because its concentration is low and has less effect on soil sodicity. However, when K^+ is significant, it can be measured in the laboratory and added to the SAR to better assess water quality and its impact on soil. The concentration of sodium ions (Na^+) in the soluble state of the soil plays a crucial role in Base Exchange processes, particularly when sodium levels are high. In such cases, Na^+ ions often replace calcium (Ca^{2+}) ions in the soil's absorbing complex, which can adversely affect soil structure and reduce its permeability to water and air. This phenomenon is particularly common when irrigation water is rich in salts a frequent condition in arid and semi-arid regions where groundwater is the main source for agriculture. To assess this risk, the Sodium Adsorption Ratio (SAR) is commonly used. It is a key agronomic indicator defined by the following equation (1):

$$SAR = \frac{(Na + K)}{\sqrt{(\frac{(Ca + Mg)}{2})}} \tag{1}$$

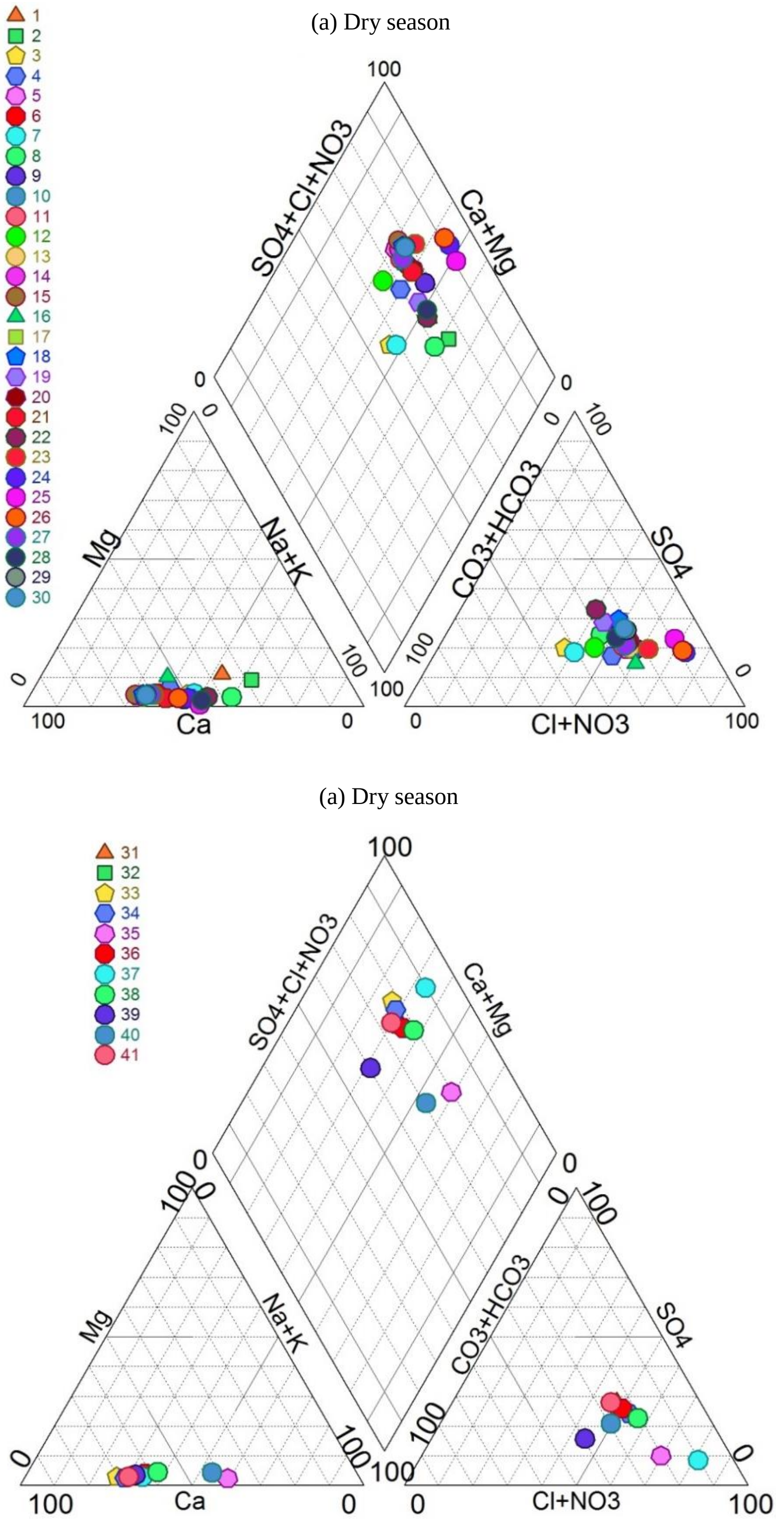
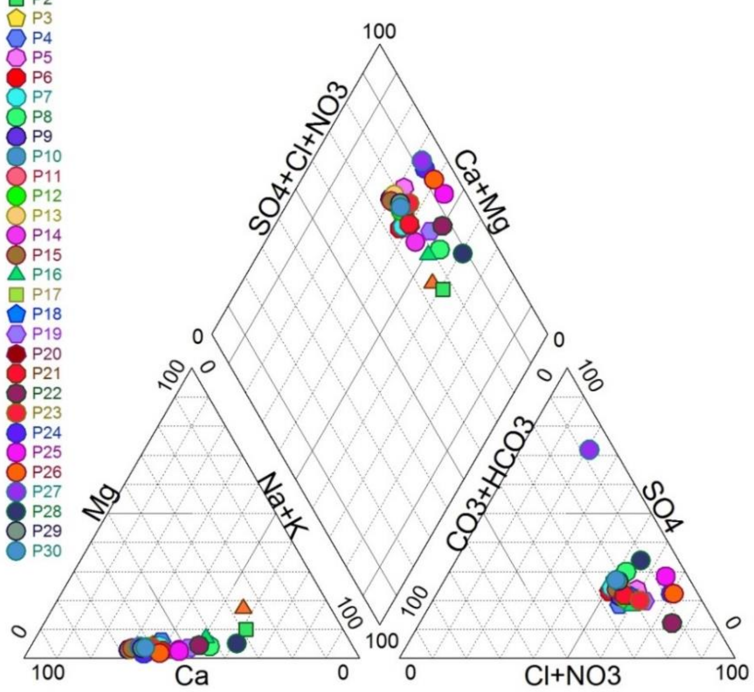


Figure 5. Piper diagram of groundwater in the plain; (a) dry season, (b) wet season

(b) Wet season



(b) Wet season

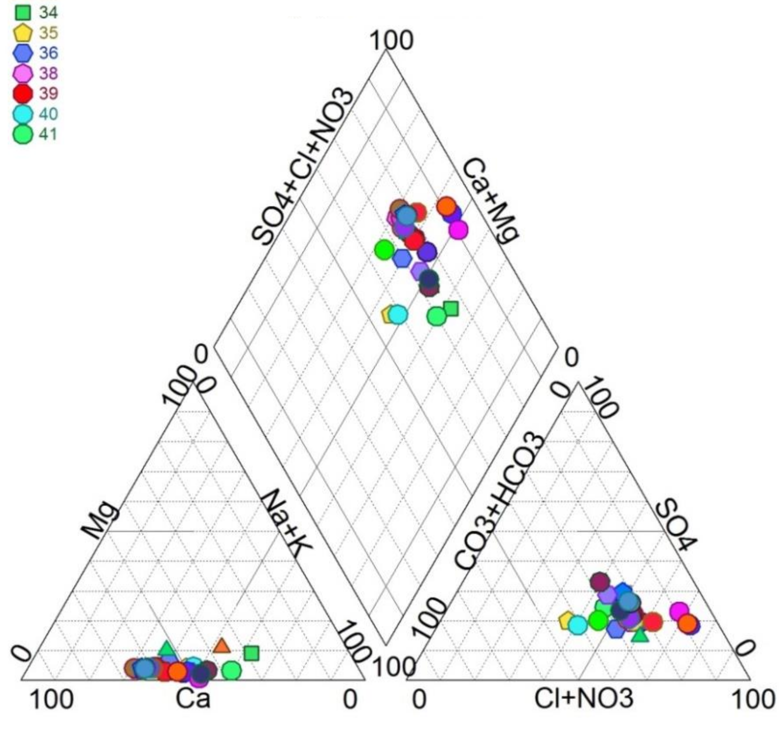


Figure 5. Piper diagram of groundwater in the plain; (a) dry season, (b) wet season (cont.)

In the case study of groundwater from the plains of Bir Chouhada, Souk Naamane, and Ouled Zouai, all water samples from different field campaigns were plotted on the Richards diagram (Figures 6(a) and 6(b)), using their electrical conductivity (EC) and SAR values. This classification allowed for the identification of five water quality classes, ranging from acceptable to poor for irrigation purposes. Classes C3S2 and C3S3 represent water that is acceptable for the irrigation of salt-tolerant crops, provided that the soils are well-drained or exhibit good permeability. Nevertheless, salinity must be regularly monitored to avoid long-term accumulation. Class C3S2 corresponds to wells mainly located in the western part of the plain and the Bir Chouhada area, accounting for 2.43% of the total water points sampled. Class C3S3 accounts for 4.89% and represents a slightly higher salinity level but remains within the acceptable range (Table 3). In contrast, C4S3 and C4S4 represent poor to very poor quality waters, highly mineralized, and only suitable for the irrigation of highly salt-tolerant species on well-drained and frequently leached soils. C4S4 is the most dominant class, making up 58.78% of all sampled water points, mostly located between Souk Naamane and Ouled Zouai (Table 3). This class shows severe salinity and sodicity risks, which could harm agricultural productivity if not properly managed. C4S3, with moderate sodicity compared to C4S4, is found in the central region of Souk Naamane and the southeastern part of the plain. It represents 34.14% of samples in the wet season and rises to 41.46% in the dry season, indicating a relative deterioration in water quality due to seasonal evaporation (Table 3). The comparison of results across the two campaigns indicates that water quality remained relatively stable over time, suggesting no significant short-term changes in the aquifer's composition. However, a slight degradation trend was observed, likely due to the presence of gypsum and clay minerals, which naturally release ions into the water, and evaporation, which increases the concentration of dissolved salts, particularly during the dry season. These waters can only be used for irrigation on permeable soils with good natural drainage. If these soil conditions are not met, there is a significant risk of alkalization, particularly in fine-textured soils such as clays, where sodium accumulation can lead to soil structure deterioration and reduced infiltration. Under such constraints, only salt-tolerant crops should be considered for cultivation. Suitable species include tobacco, cotton, barley, artichoke, and date palms, which have demonstrated resilience under saline or sodic irrigation conditions. The choice of these crops, combined with appropriate soil and water management strategies, is essential to mitigate the long-term impacts of using highly mineralized water for irrigation.

Table 3. Evolution of irrigation classes according to Riverside

	Wet season	Dry season
C3S2	2,43%	2,56%
C3S3	4,89%	4,89%
C4S3	34,14%	41,46%
C4S4	58,78%	51,12%

(a) Dry season

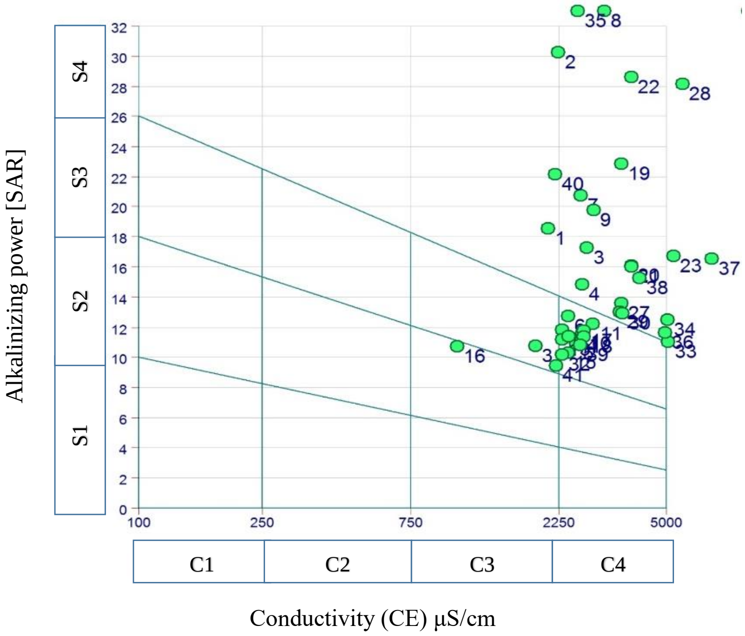


Figure 6. Riverside diagram (a) dry season, (b) wet season

(b) Wet season

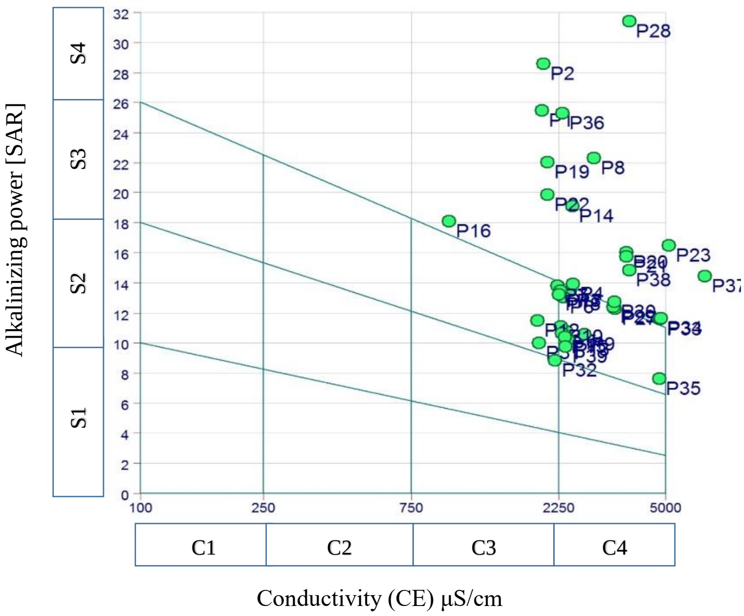


Figure 6. Riverside diagram (a) dry season, (b) wet season (cont.)

The Wilcox classification is based on the electrical conductivity and the sodium content in water expressed in percentage. The representation of the different samples on this diagram allows the characterization of the waters for their suitability for irrigation (Figures 7(a) and 7(b)). The %Na^+ is defined by the relation (2):

$$Na\% = \frac{(Na+K)}{(Ca+Mg+Na+K)} \qquad (2)$$

The classification of irrigation water quality across seasons reveals a concerning trend in the region (Table 4). During the dry season, only 4.87% of the water is classified as good, while the majority falls into the fair/poor (46.34%) and unsuitable (48.78%) categories. In the wet season, water quality shows a slight improvement, with good water increasing to 7.31% and unsuitable water decreasing to 39.02%, likely due to the dilution effect of rainfall (Table 4). However, the overall situation remains problematic, as no water samples fall into the acceptable category in either season, indicating a lack of moderately safe water for irrigation. More than 90% of the water in both seasons is considered either marginal or entirely unsuitable for most crops. This highlights the serious limitations imposed by water quality on agricultural productivity in the region. The dominance of poor and unsuitable water especially during the dry season suggests that evaporation and mineral accumulation significantly worsen water conditions. These findings emphasize the urgent need for integrated management practices, such as improving soil drainage, adopting salt-tolerant crops, and exploring water treatment or blending strategies to ensure the sustainability of irrigated agriculture in this area.

Table 4. Evolution of irrigation classes according to Wilcox (Na%)

	Dry season	Wet season
Good	4,87%	7,31%
Acceptable	00%	00%
Fair/Poor	46,34%	51,41%
Unsuitable	48,78%	39,02%

The analysis of groundwater quality throughout the entire observation period, based on the Wilcox classification (Figures 7(a) and 7(b)), reveals that the waters of Bir Chouhada, Souk Naamane, and Ouled Zouai predominantly fall into three categories: Good**,** Poor, and unsuitable. However, during the dry season, a fourth class acceptable also appears, indicating a slight expansion in water quality variability. Despite this, the majority of water samples across both dry and wet seasons consistently fall within the poor to unsuitable categories, accounting for over 90% of the samples. This widespread degradation in water quality significantly limits its suitability for irrigation. The underlying cause of this poor water quality is primarily natural, linked to the geological composition of the region. The aquifer systems are embedded in

Miocene-aged formations rich in bicarbonate and gypsiferous clays, which contribute high levels of dissolved salts to the groundwater. These geological characteristics, combined with evaporation processes, promote salinity and sodicity, further reducing the irrigation potential of the water.

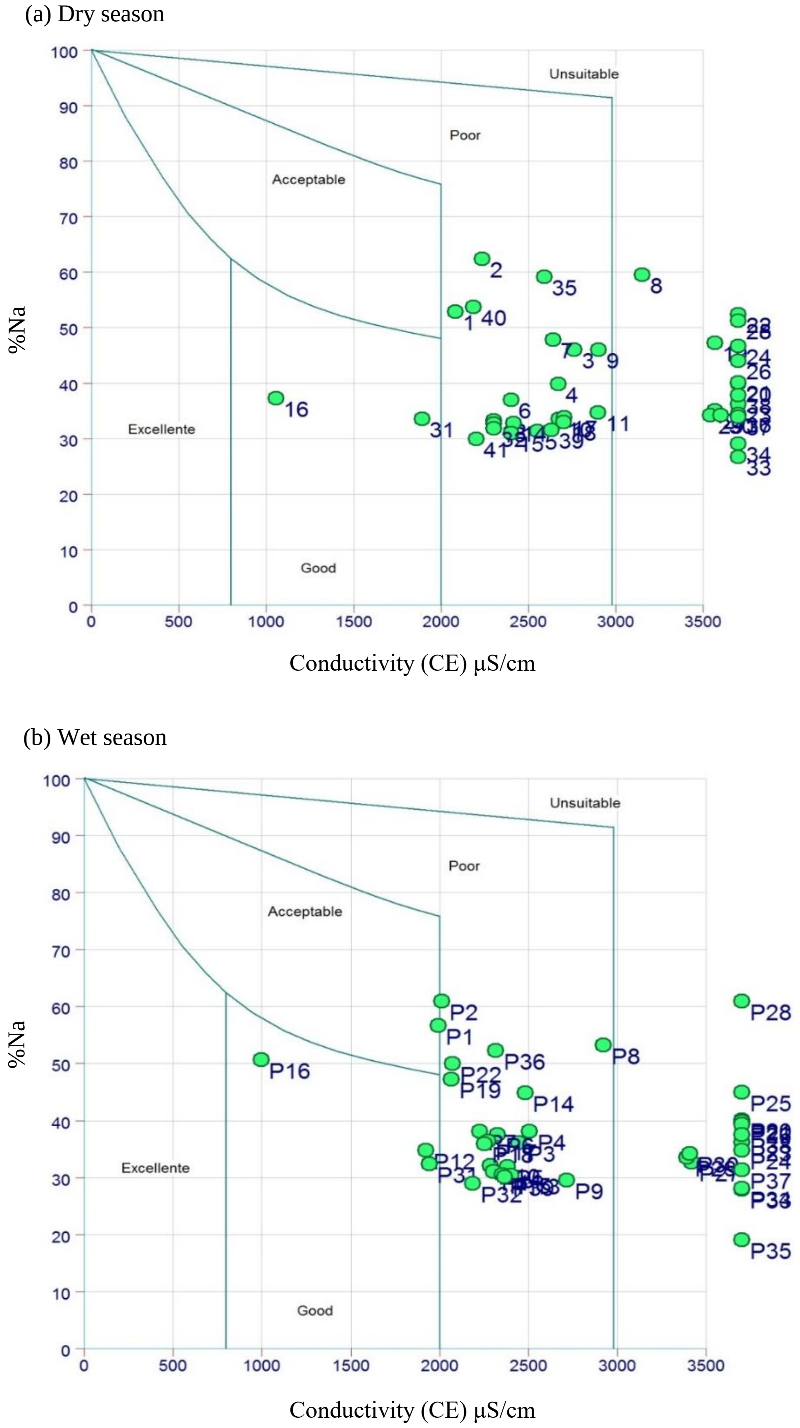


Figure 7. Wilcox diagram (a) dry season, (b) wet season

3.3. Mapping of water suitability classes for irrigation

With the objective of highlighting the effect of lithology on agricultural water quality, we mapped the respective SAR (Riverside) and %Na (Wilcox) values for the dry season, which includes the maximum number of wells (Figures 8(a), 8(b) and Figure 9(a), 9(b)):

3.3.1. Irrigation suitability map based on Richards's classification (dry and wet season)

According to the classification of irrigation water quality during the dry season, two major groups were identified within the study area. The Marginal class (C3S2 and C3S3) is primarily located in the northwest, upstream of the plain (samples 16, 39, 12, 13, 15, 17, 18, and 41), as well as in the southwest portion of the aquifer (wells 30, 32, and 31). These waters are characterized by moderate mineralization and average alkalinity, and are largely derived from the carbonate formations that border the basin (Figure 8(a)). In contrast, the Unsuitable class (C4S3 and C4S4) includes highly mineralized waters that pose serious risks for most crops unless specific irrigation conditions are applied. These waters can only be used with salt-tolerant crops and require well-drained and leached soils to prevent degradation. A similar distribution was observed during the wet season (Figure 8 (b)), with the Marginal class extending across the northwest, the Bir Chouhada zone, the southwest (wells 30, 32, 31, 33, and 29), and parts of the central plain. This group represented 39.02% of the total study area and maintained similar characteristics to those identified in the dry season. However, the Unsuitable class remained dominant, covering approximately 61% of groundwater samples during the wet season. The widespread occurrence of unsuitable water underlines the significant constraints that natural hydrogeological conditions impose on agricultural activities in the region.

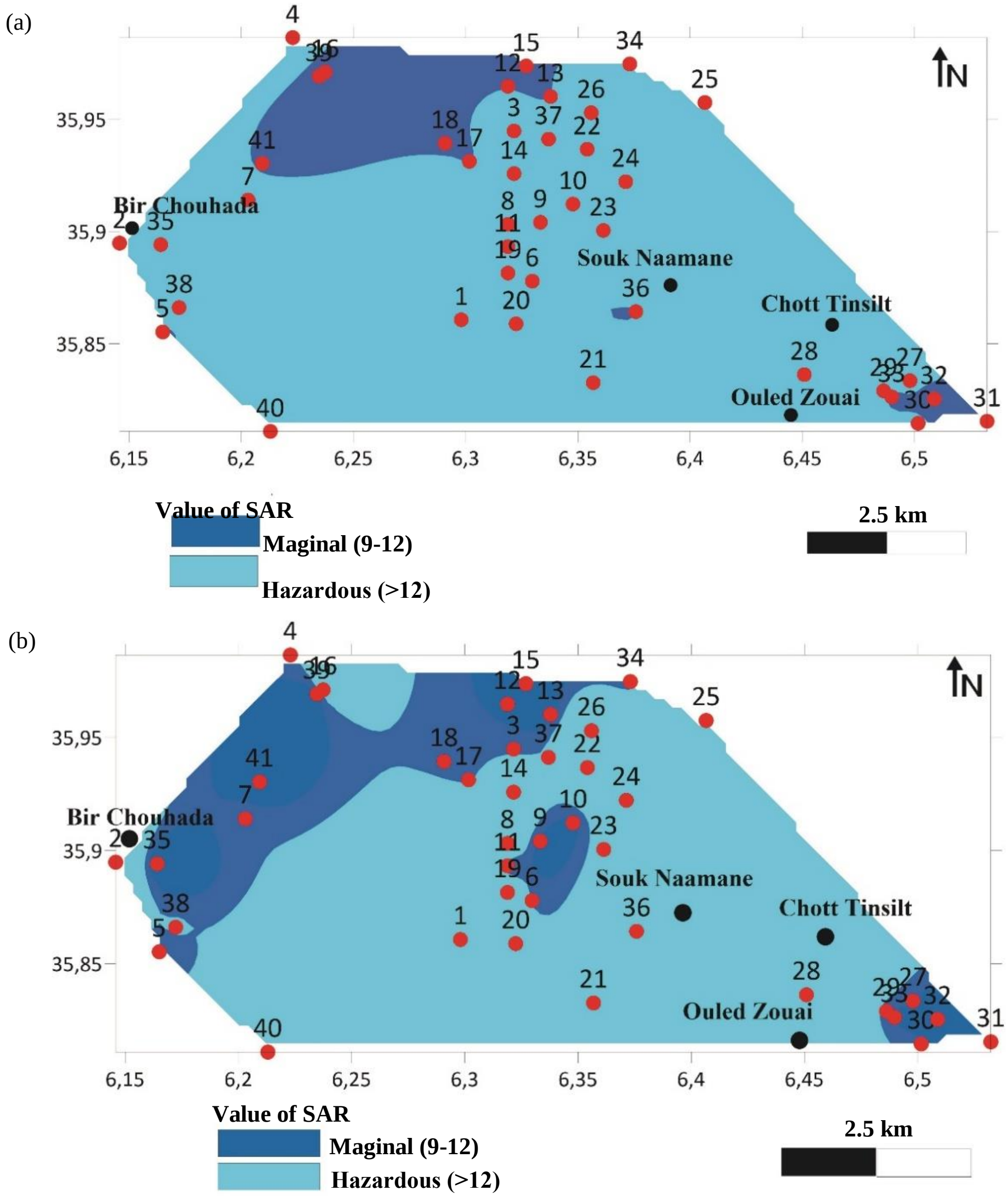


Figure 8. Irrigation suitability map based on Richards classification (a) dry season, (b) wet season

3.3.2 Water suitability map for irrigation in the study area according to Wilcox classification (dry and wet season)

The Wilcox classification applied to groundwater samples from both the dry and wet seasons revealed a predominance of good to poor water quality for irrigation. In the dry season (Figure 9(a)), three classes were identified: Good (58.53%), Poor (36.58%), and Unsuitable (4.87%) of the well sampling. Similarly, in the wet season (Figure 9(b)), the same three classes were observed, although the distribution shifted slightly: Good quality water became the dominant category (65.85%), followed by Poor (31.72%) and Unsuitable (2.43%) of the points water. In both cases, a clear trend of water quality degradation along the direction of groundwater flow was observed, illustrating the influence of lithological factors particularly the interaction with gypsiferous and clay-rich geological formations on mineralization and alkalinity levels. Furthermore, the spatial mapping of irrigation water suitability using both the Riverside and Wilcox methods, applied over a 100 m × 100 m grid, provided a detailed classification of surface areas by water quality classes, as shown in Table 5. The comparison between the Riverside and Wilcox methods for evaluating mesh quality reveals notable differences in classification outcomes. According to the Riverside method, 25% of the meshes fall into the "Good" class, while the remaining 75% are categorized as "Poor," with no meshes classified as "Acceptable" or "Unsuitable." In contrast, the Wilcox method shows a more favorable distribution, with 40.44% of meshes classified as "Good," 58.36% as "Poor," and a small proportion (1.18%) deemed "Unsuitable." Neither method identifies any meshes in the "Acceptable" category. These results suggest that the Wilcox method applies less restrictive criteria than Riverside, resulting in a higher percentage of meshes being considered suitable for use. However, the identification of a small number of "Unsuitable" meshes by Wilcox, which are not detected by Riverside, indicates that it may offer better sensitivity at the lower end of the quality scale. Overall, while both methods highlight significant limitations in mesh quality, Wilcox presents a slightly more optimistic assessment.

Table 5. Percentage of class areas produced by Riverside and Wilcox methods

	Riverside		Wilcox	
	Number of meshes	%	Number of meshes	%
Good class	125	25	200	40,44
Acceptable class	0	0	0	0
Poor class	375	75	294	58,36
Unsuitable class	0	0	6	1,18
Total	500	100	500	100

(a)

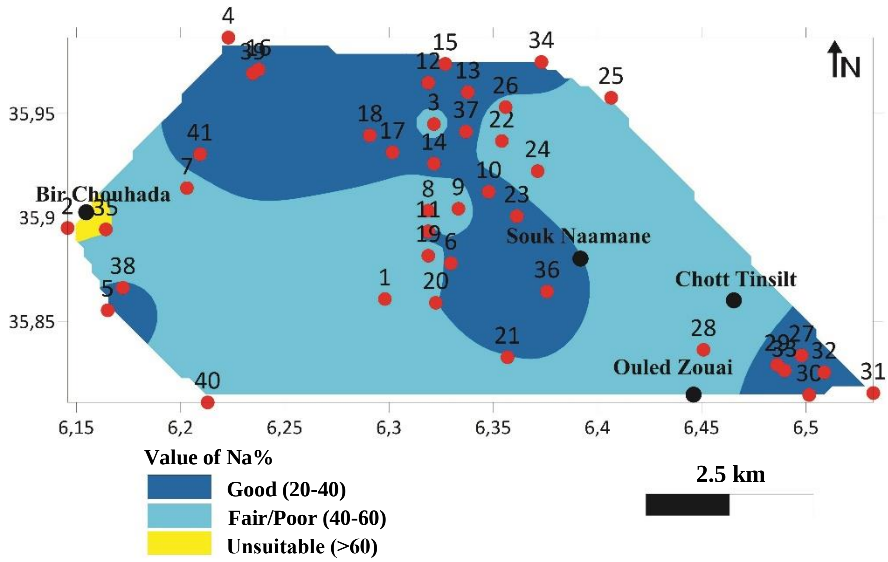


Figure 9. Water suitability map for irrigation in the study area according to Wilcox classification (a) dry season, (b) wet season

(b)

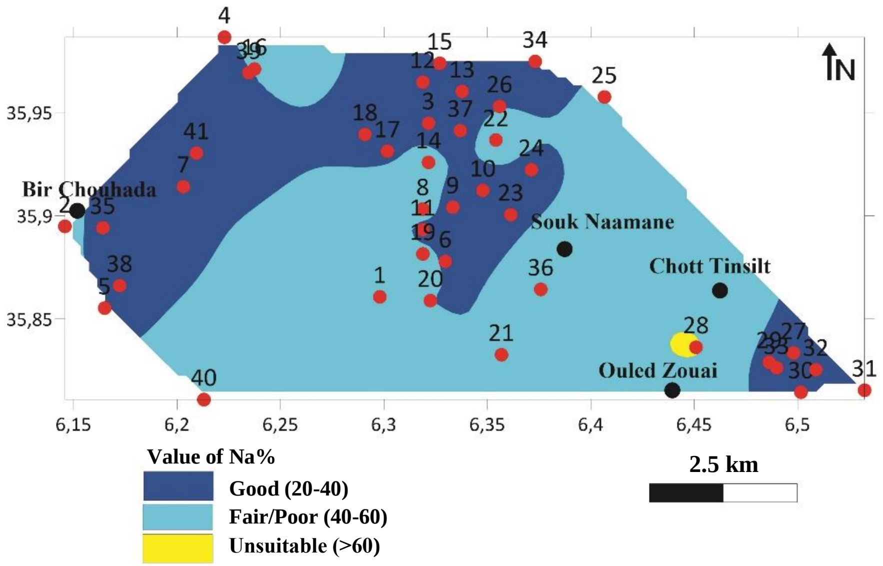


Figure 9. Water suitability map for irrigation in the study area according to Wilcox classification (a) dry season, (b) wet season (cont.)

Table 5. Percentage of class areas produced by Riverside and Wilcox methods

	Riverside		Wilcox	
	Number of meshes	%	Number of meshes	%
Good class	125	25	200	40,44
Acceptable class	0	0	0	0
Poor class	375	75	294	58,36
Unsuitable class	0	0	6	1,18
Total	500	100	500	100

3.3 Statistical analysis

Table 6 shows the analysis of variance (ANOVA) conducted for our simple linear regression model indicates that the model is statistically significant. The F-test, used to assess the contribution of the independent variable, yields an F-statistic of 29.48 with 1 degree of freedom for the regression and 39 degrees of freedom for the residuals. This F-value is associated with a very small p-value ($p \approx 0.000005$), which is far below the conventional significance threshold of 0.05. This means that the likelihood of observing such a result by chance is extremely low. Consequently, we reject the null hypothesis and conclude that the independent variable has a significant effect on the dependent variable. Moreover, the model's coefficient of determination (R^2) is 0.43, indicating that approximately 43% of the total variation in the dependent variable is explained by the predictor. This is considered a moderately strong relationship for a simple regression model, suggesting that the model provides a reasonably good fit to the data. However, it also implies that 57% of the variation remains unexplained, possibly due to other variables not included in the model. In summary, the ANOVA results confirm that the regression model is statistically valid, and the selected independent variable makes a meaningful and significant contribution to explaining the variation in the outcome variable.

Table 6. SAR ANOVA

Source	df	Sum of Square	Mean square	F	p
Regression	1	1,303.75	19.08	29.48	0.000005
Residual	39	1,724.78	44.24	/	/
Total	40	3,027.96	/	/	/

The ANOVA results for the simple linear regression model indicate a highly significant relationship between the independent variable and the dependent variable (Table 7). The regression explains a sum of squares of 1,305.975 with 1 degree of freedom, while the residual variance accounts for 2,498.529 across 39 degrees of freedom, resulting in a total variance of 3,804.504 (Table 7). The mean square for the regression is therefore 1305.975, compared to a residual mean square of 64.06. This yields an F-statistic of 20.38, associated with a p-value of 0.000057, which is well below the conventional significance threshold of 0.05 (Table 7). This strong statistical evidence allows us to reject the null hypothesis that the independent variable has no effect. The model explains approximately 34.3% of the variance in the dependent variable, as indicated by the coefficient of determination (R^2). Overall, these results demonstrate that the predictor variable significantly contributes to explaining the variability of the outcome, making the regression model a valid tool for prediction in this context.

Table 7. Na% ANOVA

Source	df	Sum of Square	Mean square	F	p
Regression	1	1,305.975	69.10	20.38	0.000057
Residual	39	2,498.529	64.06	/	/
Total	40	3,804.504	/	/	/

The spatial autocorrelation analysis based on Moran's I (Table 8) reveals consistent positive spatial clustering patterns in both SAR and Na% values across the dry and wet seasons. Most Moran's I values for SAR range between 0.21 and 0.27 in both seasons, indicating a moderate to strong positive spatial autocorrelation suggesting that wells with similar salinity levels are spatially clustered rather than randomly distributed. The Na% values also show positive autocorrelation, though slightly lower on average, with Moran's I typically ranging from 0.15 to 0.23. The stability of Moran's I across seasons suggest that the spatial distribution of salinity and sodium concentration does not significantly change between wet and dry periods. Notably, the highest Moran's I values for both SAR and Na% are observed in well 41 (0.333-0.351 for SAR and 0.367-0.350 for Na %), indicating particularly strong spatial clustering in that area. These results confirm that spatial processes likely driven by hydrogeological structures or anthropogenic influences govern the distribution of salinity and sodium across the study area.

Table 8. Indice of Moran for SAR and Na% (dry and wet season)

Wells	I Moran's SAR dry season	I Moran's SAR wet season	I Moran's Na% dry season	I Moran's Na% wet season
1	0.214	0.209	0.157	0.155
2	0.216	0.221	0.163	0.171
3	0.234	0.239	0.185	0.195
4	0.234	0.235	0.192	0.193
5	0.240	0.240	0.198	0.197
6	0.232	0.239	0.185	0.193
7	0.213	0.229	0.166	0.179
8	0.219	0.237	0.172	0.191
9	0.240	0.250	0.195	0.211
10	0.247	0.249	0.205	0.209
11	0.246	0.248	0.204	0.206
12	0.248	0.249	0.207	0.207
13	0.248	0.241	0.207	0.198
14	0.249	0.241	0.208	0.198
15	0.246	0.238	0.201	0.189
16	0.243	0.234	0.198	0.183
17	0.245	0.241	0.203	0.198

Table 8. Indice of Moran for SAR and Na% (dry and wet season) (cont.)

Wells	I Moran's SAR dry season	I Moran's SAR wet season	I Moran's Na% dry season	I Moran's Na% wet season
18	0.235	0.234	0.192	0.189
19	0.231	0.232	0.187	0.187
20	0.240	0.240	0.195	0.195
21	0.228	0.237	0.185	0.187
22	0.228	0.237	0.188	0.190
23	0.221	0.236	0.194	0.205
24	0.198	0.225	0.183	0.198
25	0.201	0.220	0.184	0.194
26	0.232	0.240	0.202	0.208
27	0.241	0.239	0.199	0.192
28	0.241	0.238	0.199	0.191
29	0.258	0.259	0.217	0.217
30	0.263	0.264	0.219	0.220
31	0.266	0.268	0.222	0.225
32	0.264	0.264	0.227	0.228
33	0.255	0.256	0.224	0.223
34	0.219	0.246	0.181	0.219
35	0.220	0.233	0.177	0.197
36	0.245	0.233	0.206	0.192
37	0.233	0.213	0.196	0.198
38	0.234	0.196	0.194	0.196
39	0.229	0.183	0.181	0.183
40	0.230	0.182	0.182	0.182
41	0.333	0.351	0.367	0.350

3.4. Recommendation

To reduce the risks associated with high salinity, local farmers can implement several effective strategies. Selecting salt-tolerant crops such as barley, cotton, olive trees, date palms, or sorghum can help maintain productivity despite saline conditions. Crop rotation is also beneficial to prevent excessive salt buildup in the soil. Improving irrigation methods by shifting from traditional flood irrigation to more efficient systems like drip or sprinkler irrigation minimizes salt accumulation near plant roots. Additionally, periodic leaching with excess water can flush salts away if good drainage is available. Soil management techniques, including the use of gypsum to neutralize sodium and the addition of organic matter to enhance soil structure, further mitigate salinity effects. Enhancing drainage through subsurface systems or preserving natural drainage pathways helps prevent waterlogging and salt concentration. Mixing saline groundwater with higher quality water sources and storing rainwater during wet seasons can also reduce irrigation water salinity. Finally, regular monitoring of water quality, especially salinity levels and Sodium Adsorption Ratio (SAR), allows farmers to adapt their irrigation practices and crop selection to current conditions, ensuring more sustainable agricultural production in the face of salinity challenges.

4. CONCLUSION

This study demonstrates that groundwater quality in the Bir Chouhada, Souk Naamane, and Ouled Zouai plains is strongly influenced by geological formations and seasonal variations, significantly affecting its suitability for irrigation in this semi-arid region. According to the Wilcox classification, during the dry season, 58.53% of wells provide good-quality water, 36.58% are poor, and 4.87% are unsuitable for irrigation. In the wet season, water quality improves with 65.85% good, 31.72% poor and only 2.43% unsuitable, reflecting dilution effects from rainfall. Spatial mapping on a 100 m × 100 m grid reveals notable heterogeneity linked to lithology, with 25% of the area classified as good by the Riverside method compared to 40.44% by Wilcox, which also identifies 58.36% poor and 1.18% unsuitable zones. Geological factors, particularly Miocene gypsiferous and clay-rich formations, play a key role in water mineralization and sodicity, causing progressive water quality degradation along groundwater flow paths. Moran's I spatial autocorrelation analysis shows moderate to strong clustering of SAR and sodium percentage (%Na), especially near well 41, indicating geographically concentrated salinity and sodicity likely related to hydrogeological structures or human activities. These conditions pose significant agronomic risks, as elevated SAR and sodium promote clay dispersion, degrading soil structure and permeability, which restricts water and air movement. Consequently, irrigation is sustainable mainly on well-drained soils with salt-tolerant crops such as tobacco, cotton, barley, artichoke, and date palms. Regression and ANOVA analyses confirm the significance of key variables with R^2 values between 34.3% and 43%, indicating moderate explanatory power and suggesting other factors remain to be explored. Despite these insights, the study is limited by the number of analyzed parameters, sampling points, and seasonal coverage, lacking continuous monitoring and detailed consideration of anthropogenic and seasonal influences. Future research should incorporate more comprehensive, year-round monitoring, a broader range of physico-chemical indicators, advanced hydrogeological modeling, and socio-economic data integration to support sustainable groundwater management in this vulnerable semi-arid agricultural zone.

AUTHOR CONTRIBUTIONS

Conceptualization: N. Zair, I. Khater; Methodology: N. Zair; Software: I. Khater; Validation: I. Khater, N. Zair, A. Miloudi; Formal analysis: I. Khater; Investigation: I. Khater, N. Zair; Resources: A. Khechekhouche; Data curation: I. Khater; Writing original Draft: I. Khater, N. Zair; Writing Review and Editing: A. Khechekhouche, B. Attoui; Visualization: I. Khater, N. Zair, A. Miloudi; Supervision: N. Zair; Project administration: N. Zair; Funding acquisition: N. Zair.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have neither conflict nor competing of interests.

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