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INTEGRATED GROUNDWATER SUITABILITY ANALYSIS FOR IRRIGATION PURPOSES: A CASE STUDY FROM THE MIDDLE CHELIFF PLAIN, ALGERIA

Abstract: This study evaluates the quality of shallow groundwater in the Middle Cheliff plain, Algeria, to determine its suitability for agricultural irrigation. Twelve groundwater samples were collected and analyzed for physicochemical properties and key irrigation suitability indices, including SAR, %Na, RSC, KR, and PI. Significant spatial variability was observed, with certain areas suitable for irrigation, while most samples exhibited high salinity and sodium levels, restricting their use. Spatial distribution maps, generated using GIS techniques, revealed a deterioration of water quality in western regions, likely influenced by anthropogenic activities such as excessive fertilizer use. Graphical analyses, including the Richard and Wilcox diagrams, further classified water quality from excellent to unsuitable. The integration of GIS provided a powerful tool for visualizing and interpreting spatial patterns of groundwater quality, enabling the identification of priority areas for intervention. These findings highlight the need for sustainable groundwater management practices to address salinity and sodium risks in arid and semi-arid regions. This study underscores the importance of combining traditional hydrochemical analysis with geospatial tools to develop comprehensive strategies for water resource management in agriculture.

Keywords: groundwater quality, irrigation suitability, salinity, Middle Cheliff plain, water management, Geographic Information System

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Introduction

Groundwater is a vital resource supporting domestic, agricultural, industrial activities, and ecological systems, particularly in arid and semi-arid regions such as North Africa. Its advantages include resistance to drought, superior quality due to natural filtration, and reduced vulnerability to surface contamination, making it more dependable than surface water sources (Sophocleous, 2002; Wang et al., 2023). However, the characteristics of groundwater are increasingly influenced by natural and human-induced factors. Natural determinants include geological formations, rock-water interactions, the quality of recharge water, and climatic conditions, among others (Akhtar et al., 2021). Anthropogenic pressures such as population growth, urban sprawl, industrial development, and poor land-use practices have further exacerbated groundwater quality degradation, particularly in shallow aquifers (Khatri & Tyagi, 2015; Wang et al., 2019).

Assessing groundwater quality for irrigation is essential for sustainable agricultural practices and soil health preservation. High-quality irrigation water is critical for maintaining plant and soil productivity, while poor-quality water can lead to reduced crop yields, soil degradation, and other issues, such as scaling in irrigation systems caused by high calcium and magnesium concentrations (Oster, 1994). Key factors affecting irrigation water quality include salinity, sodium percentage, and the presence of potentially toxic elements like boron (Bhatt et al., 2023; Zaman et al., 2018). Regular evaluation of these parameters, including indices such as electrical conductivity (EC), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC), is necessary to ensure sustainable use of irrigation water (Bouderbala, 2017; Dimple et al., 2022).

This study focuses on evaluating the quality and suitability of shallow groundwater for irrigation in the Middle Cheliff plain, Algeria. It aims to analyze physicochemical properties and derive indices to assess irrigation water quality, providing essential insights for sustainable groundwater management in the region.

Materials and Methods

Study area

The Middle Cheliff Basin, located in the Chlef region of northwestern Algeria, lies about 200 km west of Algiers and 45 km south of the Mediterranean coast (Fig. 1). It covers an area of approximately 321 km². The region's climate is classified as semi-arid Mediterranean, characterized by hot summers and cold winters. Precipitation levels vary significantly, showing a decreasing trend from north to south and east to west. On average, the area receives 365 mm of annual rainfall (Nadjai et al., 2024).

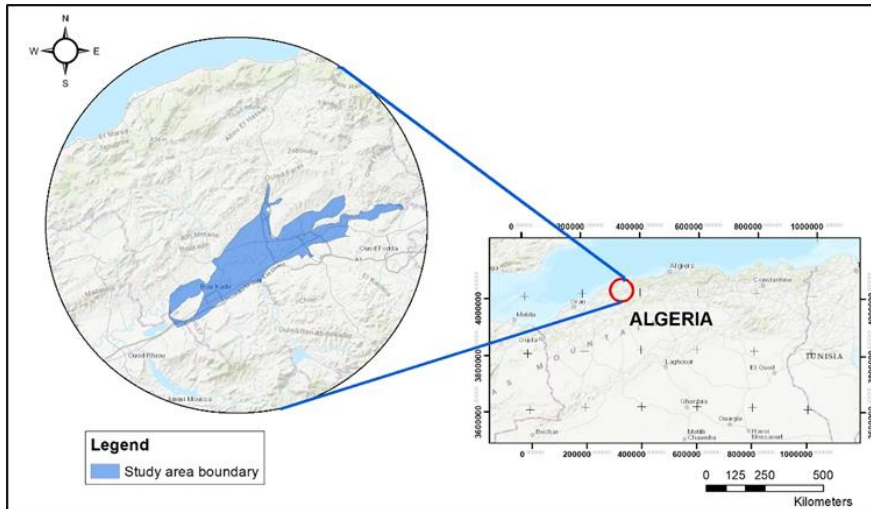


Fig.1. Location map of the study area

As described by Bradai *et al.* (2022), Middle Cheliff watershed as a depression formed during the Mio-Plio-Quaternary period, through which the Cheliff River flows from east to west. The region's hydraulic thresholds are influenced by an impermeable clay-marl substratum that restricts groundwater movement. Over time, the intramountainous depression has accumulated Neogene deposits, including Quaternary, Pliocene, and Miocene sediments. Quaternary deposits mark the onset of Neogene marine formations, with thicknesses reaching up to 3000 meters (Perrodon, 1957). These deposits are prominent in the plains, consisting mainly of coarse alluvium from the early Quaternary and finer silt from the late Quaternary, resting on upper Pliocene sandstone and limestone. The lower Pliocene (Marine Pliocene) is characterized by a marine transgression over the Late Miocene gypsum series, followed by the Astian regression (Fig. 2).

The area contains three distinct aquifers with unique hydrogeological characteristics. The Upper Miocene limestone is located at the southern valley edge, extending beneath alluvial formations. Another aquifer consists of Pliocene sandstone, largely concealed beneath Quaternary deposits. Finally, the Pleistocene–Quaternary alluvial deposits form the valley's embankment, featuring layers of clay and marl mixed with sand, gravel, and conglomerate strata. This study focuses on the last-mentioned aquifer.

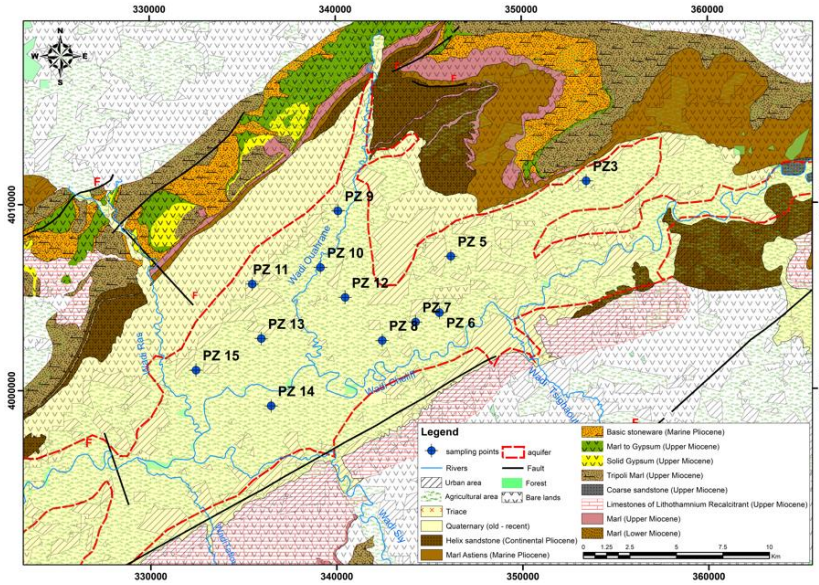


Fig. 2. Hydrogeological and soil occupation map of the study area.

Groundwater sampling and analysis

Twelve samples of groundwater were collected during July 2022 from the Middle Cheliff aquifer. The sampling points are located in Fig. 2. Clean high-density polyethylene (HDPE) bottles of 0.5 dm³ capacity, pre-washed with acid, were used for sample collection. Prior to filling, the bottles were rinsed two to three times with the same water to prevent contamination and sealed tightly to minimize evaporation. Each container was labelled, documented in a datasheet, and transported in an icebox to maintain sample integrity. To ensure cleanliness and avoid cross-contamination, new gloves were worn during each collection process.

Field measurements of physical parameters, including temperature, electrical conductivity (EC), total dissolved solids (TDS), and pH, were performed on-site. Laboratory analysis was conducted at a certified water laboratory of the national agency of hydraulic resources of Blida. This analysis covered parameters such as HCO₃⁻, CO₃²⁻, Cl⁻, SO₄²⁻, NO₃⁻, Na⁺, K⁺, Ca²⁺, Mg²⁺.

To ensure the reliability of the chemical analysis, the ionic balance error (IBE) was calculated to compare the total concentrations of cations (Na⁺, K⁺, Ca²⁺, Mg²⁺) and anions (CO₃²⁻, CO₃⁻, Cl⁻, SO₄²⁻, NO₃⁻), expressed in milliequivalents per liter (meq/L) for each sample. The IBE was determined using the formula (Saikrishna et al., 2023):

$$IBE = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} \times 100 (meq / l) \quad (1)$$

This calculation, performed with Microsoft Excel 2016, confirmed that all samples had IBE values within the acceptable range of ±5%.

Evaluation of Groundwater Suitability for Irrigation

The suitability of groundwater for irrigation was assessed using three distinct approaches:

Assessment Based on Individual Parameters

The evaluation relied on established guidelines for irrigation water quality, including the Food and Agriculture Organization (FAO) standards (Ayers & Westcot, 1985). The physicochemical properties were compared against these benchmarks to determine whether groundwater pollution levels exceeded accepted standards, ensuring reliable conclusions. These parameters are presented in Tab. 1.

Assessment Using Standard Agricultural Indices

Standard indices commonly used to safeguard soil, plants, and the environment were calculated to evaluate irrigation suitability. These indices included the Sodium Adsorption Ratio (SAR), Sodium Percentage (Na%), Residual Sodium Carbonate (RSC), Magnesium Hazard (MH), Kelley Ratio (KR), and Permeability Index (PI). Their computation, based on standard equations, considered the concentrations of key ions such as Na^+ , Mg^{2+} , Ca^{2+} , K^+ , HCO_3^- , and CO_3^{2-} . These indices are also detailed in Tab. 1.

Assessment Using Graphical Approaches

Graphical methods, including those proposed by Richard (1954) and Wilcox (1955), were employed to classify the groundwater samples and assess their quality for irrigation purposes.

The spatial distribution of indicators evaluating the suitability of groundwater from the Middle Cheliff for irrigation is illustrated through graphical representations in the form of iso-concentration maps. The spatial mapping of these parameters was performed using a Geographic Information System (GIS), specifically ArcMap 10.8. The spatial interpolation of these parameters is based on a geostatistical approach, employing the Inverse distance weighting (IDW).

Table 1. Calculation and classes of indices used to classify irrigation water quality.

Type	Parameter	Equation	Range	Class	Reference
Individual	Electrical conductivity (EC)	Measured by instrument	< 250	Excellent	(Wilcox, 1955)
			250-750	Good	
			750-2250	Permissible	
			2250-5000	Doubtful	
			> 5000	Unsuitable	
	Total hardness (TH)		0-75	Soft	(Sawyer <i>et al.</i> , 2003)
		75-150	Moderately hard		
		150-300	Hard		
Standard indices	Sodium absorption ratio (SAR)	$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$	< 10	Excellent	(Richard, 1954)
			10-18	Good	
			18-26	Doubtful	
			> 26	Unsafe	
	Residual sodium carbonate (RSC)	$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+})$	< 1.25	Safe	(Eaton, 1950)
			1.25-2.50	Marginally suitable	
			> 2.50	unsuitable	
	Soluble sodium percentage (SSP)	$SSP = 100 \times \frac{(Na^+ + K^+)}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)}$	< 20	Excellent	(Wilcox, 1955)
			20-40	Good	
			40-60	Permissible	
			60-80	Doubtful	
			> 80	Unsafe	
	Magnesium adsorption ratio (MAR)	$MAR = 100 \times \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}$	< 50	Suitable	(Szabolcs, 1964)
			> 50	Unsuitable	
Kelley ratio (KR)	$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}}$	< 1	Suitable	(Kelley, 1963)	
		> 1	Unsuitable		
Permeability index (PI)	$PI = 100 \times \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+}$	< 25	Unsuitable	(Doneen, 1964)	
		25-75	Suitable		
		> 75	Good		

Results and Discussions

Suitability of water for irrigation use based on individual parameters

The minimum and maximum values, mean, and standard deviation for all analyzed parameters were calculated and are presented in Tab.2. These results were compared with the irrigation water quality guideline values established by the FAO (Ayers & Westcot, 1985) to evaluate their suitability for agricultural use.

To better illustrate the results, Tab.3 provides the classification of the calculated indices for the analyzed samples, as well as the distribution of sample numbers and percentages across the different classes.

Table 2. Comparison of analysed water quality parameters with FAO guidelines

Parameter	Unit	Minimum	Maximum	Mean	Standard deviation	FAO guidelines
pH	-	6,9	8,3	7,69	0,43	6.5 – 8.4
EC	µs/cm	570	8270	4 231	2174,19	0 – 2250
TDS	mg/L	364	4939	2807	1430,80	0 – 2000
Ca ²⁺	mg/L	24	353	166,25	111,87	0 – 400
Mg ²⁺	mg/L	6	259	136,917	99,384	0 – 61
Na ⁺	mg/L	86	875	465,083	245,81	0 – 920
K ⁺	mg/L	1	8	5,25	1,875	0 – 2
Cl ⁻	mg/L	137	2400	827,5	416,75	0 – 1065
NO ₃ ⁻ -N	mg/L	1	280	49,5	83,474	0 – 10
HCO ₃ ⁻	mg/L	46	436	241,167	156,137	0 – 610
SO ₄ ²⁻	mg/L	0	1670	650,917	504,357	0 - 960

Table 3. Quality classification and suitability assessment of groundwater samples for irrigation

Index	Range	Class	Number of samples	Percentage (%)
Electrical conductivity EC (µS/cm)	< 250	Excellent	0	0,00
	250 - 750	Good	1	8,33
	750 - 2250	Permissible	1	8,33
	2250 - 5000	Doubtful	1	8,33
	> 5000	Unsuitable	9	75,00
TH (mg/L CaCO ₃)	0 -75	Soft	6	50,00
	75 - 150	Moderately hard	3	25,00
	150 -300	Hard	3	25,00
SAR (meq/L)	< 10	Excellent	10	83,33
	10 -18	Good	2	16,67
	18 - 26	Doubtful	0	0,00
	> 26	Unsafe	0	0,00
RSC (meq/L)	< 1,25	Safe	12	100,00
	1,25 - 2,50	Marginally suitable	0	0,00
	> 2,50	Unsuitable	0	0,00
SSP (meq/L)	< 20	Excellent	0	0,00
	20 - 40	Good	3	25,00
	40 - 60	Permissible	4	33,33
	60 -80	Doubtful	5	41,67
	> 80	Unsafe	0	0,00
MAR (meq/L)	< 50	Suitable	2	16,67
	> 50	Unsuitable	10	83,33
KR (meq/L)	< 1	Suitable	5	41,67
	> 1	Unsuitable	7	58,33
PI (%)	> 75	Good	3	25,00
	25 -75	Suitable	9	75,00
	< 25	Not suitable	0	0,00

pH

The pH of irrigation water is a critical factor influencing agricultural outcomes, as it affects both soil quality and plant health. According to Ayers and Westcot (1985), the ideal pH range for irrigation water lies between 6.5 and 8.4. Water with a pH below 6 is acidic, which can corrode irrigation systems and reduce pipe longevity (Wojtkowska et al., 2022), and potentially release hazardous substances such as mercury, arsenic, and cadmium. These contaminants can pose risks to soil health, crops, and human safety (Diawara et al., 2006; Custodio et al., 2020; Nwankwo et al., 2023). Conversely, alkaline water with a pH above 8.2 often contains elevated levels of ions like sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonates (HCO_3^-), and carbonates (CO_3^{2-}), which can interfere with nutrient uptake by plants and may lead to soil salinization or alkalinity issues (Qin et al., 2022).

The role of pH in water analysis extends to identifying abnormalities in water quality. Values outside the standard range often signal potential issues that could affect soil conditions or plant growth. In this study, the pH values ranged from 6,9 to 8,3, with an average of 7,63 and a standard deviation of 0,43. These values fall within the recommended range specified by Ayers and Westcot (1985) and align with guidelines suggesting that such waters are suitable for irrigation. Nonetheless, careful monitoring is essential to ensure long-term soil health and optimal crop performance.

Electrical conductivity (EC)

Electrical conductivity (EC) is a crucial parameter for evaluating the quality of irrigation water, as it directly impacts plant growth and soil health (Rafik et al., 2023). Elevated salinity in irrigation water can impair water uptake by plants, leading to soil structural degradation, reduced permeability, and limited aeration, all of which hinder optimal plant development (Prashanthi et al., 2020). High salt concentrations also raise the osmotic potential of the water, making it more difficult for plant roots to absorb moisture, a condition often referred to as physiological drought (Ehtaiwesh, 2022). The EC values measured in this study, presented in Table 2, range from 570 to 8270 $\mu\text{S}/\text{cm}$, with an average of 4 231 $\mu\text{S}/\text{cm}$. Based on the classification proposed by Wilcox (1955), these values indicate moderate suitability for irrigation, suggesting that while the water can be used, monitoring and management practices are advisable to mitigate potential long-term impacts on soil and crop productivity. Furthermore, the spatial distribution of EC in the study area represented in fig. 3 shows that the values of this parameter are elevated in the west of the alluvial aquifer. Thus, this can show a deterioration of groundwater quality in this region due anthropogenic influence as the use of fertilizers in agriculture.

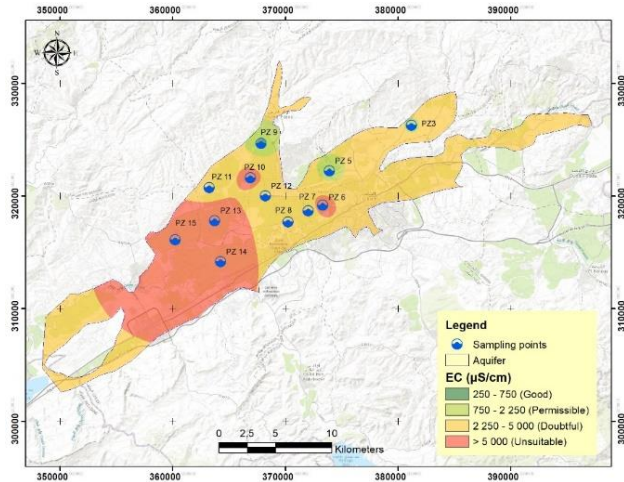


Fig. 3. Spatial distribution of EC for groundwater samples

Beyond evaluating individual parameters, the suitability of groundwater for irrigation is also determined using indices derived from the analyzed parameters. The computed indices, including SAR, Na%, RSC, MH, KR, and PI, are summarized in Tab. 4.

Total Hardness (TH)

The hardness of water is primarily attributed to dissolved calcium and magnesium ions. In our analysis, the total hardness (TH) of the well water samples ranged from 10 to 216 mg/L CaCO_3 , with an average value of 98,58 mg/L CaCO_3 (Table 3). Hard water is generally considered more suitable for irrigation as it tends to soften the soil, whereas soft water can lead to soil hardening over time (Yilmaz et al., 2021). Based on the classification of water hardness given in table 1, 50% of the samples were categorized as soft water, 25% as moderately hard, and the remaining 25% as hard water.

Spatial distribution analysis (Fig. 4) reveals that softer waters are predominantly located in the northern and northeastern parts of the region, whereas water hardness increases progressively towards the western areas. Notably, zones with higher hardness levels are concentrated in two agricultural areas at the center of the alluvial plain. This pattern suggests potential anthropogenic influences, such as agricultural activities and the leaching of fertilizers into groundwater. The continuous use of soft water for irrigation in northern areas may lead to soil compaction over time, while the elevated hardness in central agricultural zones underscores the impact of land use practices on water quality.

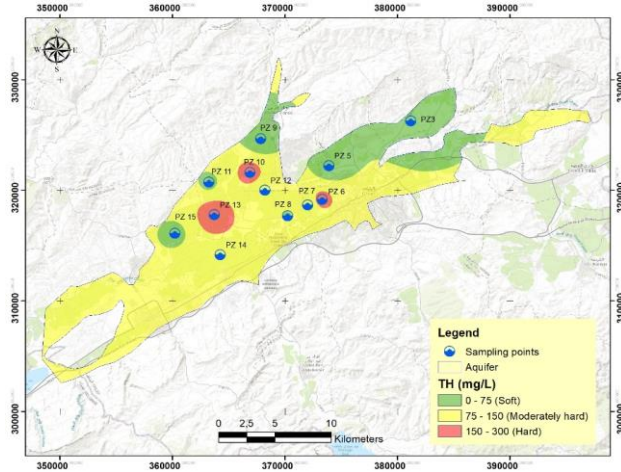


Fig. 4. Spatial distribution of TH for groundwater samples

Suitability of water for irrigation use based on standard indices

Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) is a critical parameter for evaluating the quality of irrigation water, reflecting the balance between sodium and divalent cations such as calcium and magnesium. Elevated SAR levels can lead to soil structural degradation, as excess sodium replaces calcium on the cation exchange complex, causing clay particle dispersion and reduced permeability (Aboukarima et al., 2018). This degradation disrupts water infiltration and the aeration of the root zone, thereby limiting the availability of water and nutrients to plants and impairing their growth (Stavi et al., 2021). Furthermore, excessive sodium concentrations often arise from the weathering of clay minerals and associated rock formations, which can exacerbate sodium-related salinity hazards.

In the study area, the sodium adsorption ratio (SAR) values ranged from 3.79 meq/L to 15.95 meq/L, with an average of 6.95 meq/L. According to the classification in Table 3, 83.33% of the water samples were categorized as excellent for irrigation, suitable for almost all soil types with minimal risk. The remaining samples, located in the western part of the study area, were classified as good for irrigation purposes (Fig.5). However, it is important to note that sodium-sensitive crops, particularly stone fruit trees such as almonds and apricots, may accumulate harmful levels of sodium in their tissues when irrigated with these waters. Water in the good category, characterized by a higher cation exchange capacity (CEC), is better adapted for use on coarse-textured or organic soils with high permeability, reducing the potential impact of sodium accumulation.

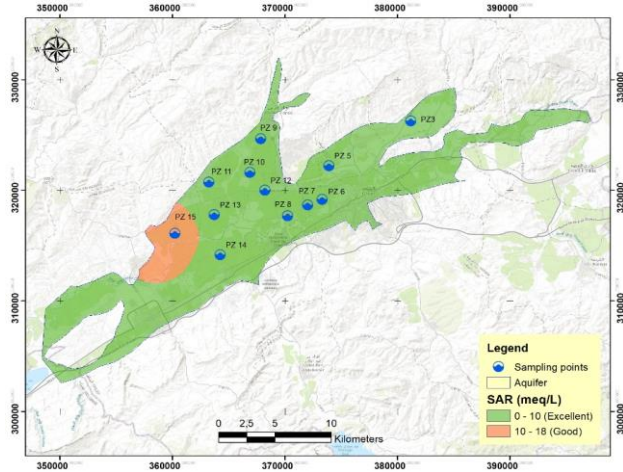


Fig. 5. Spatial distribution of SAR for groundwater samples

Residual Sodium Carbonate (RSC)

Residual Sodium Carbonate (RSC) is a critical parameter used to assess the risk associated with bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) levels in irrigation water. It is calculated as the difference between the concentrations of weak acids (HCO_3^- and CO_3^{2-}) and alkaline earth metals (Ca^{2+} and Mg^{2+}). High RSC values can negatively impact the electrical conductivity (EC), pH, and Sodium Adsorption Ratio (SAR) of irrigation water, potentially leading to adverse effects on soil and crops.

Continuous use of water with elevated RSC levels can result in leaf burn and reduced crop yields. When weak acids exceed alkaline earth metals in the soil, calcium (Ca^{2+}) and magnesium (Mg^{2+}) tend to precipitate, increasing the presence of sodium bicarbonate (NaHCO_3). This process degrades soil permeability and structure, which can severely affect plant growth.

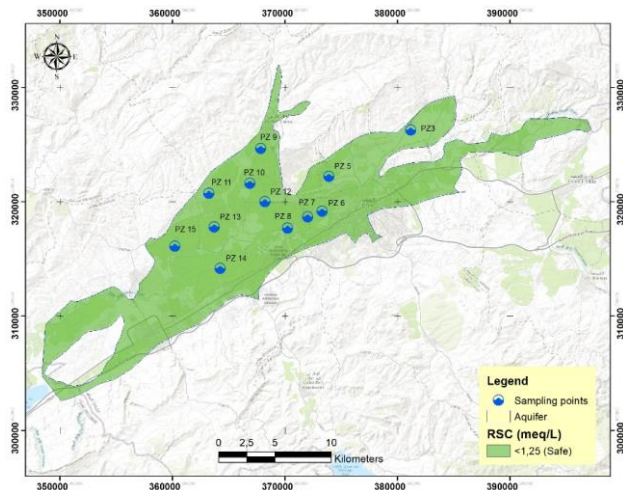


Fig. 6. Spatial distribution of RSC for groundwater samples

In this study, the RSC values range from $-40,05$ to $-0,90$ meq/L, with an average of $-15,77$ meq/L (Table 3). Since the mean RSC value is below the threshold of 1.25 meq/L, the groundwater samples do not pose a significant risk of carbonate or bicarbonate hazards. Thus, the groundwater in the study area is considered suitable for irrigation purposes (Fig. 6).

Soluble Sodium Percentage (SSP)

The magnesium hazard is another important parameter used to evaluate the suitability of groundwater for irrigation, defined as the ratio of calcium (Ca^{2+}) to magnesium (Mg^{2+}) concentrations. It is also known as the magnesium adsorption ratio (MAR), introduced by Szabolcs and Darab in 1964. The soluble sodium percentage (SSP) is a critical parameter for assessing irrigation water quality, particularly in relation to soil permeability. Sodium ions present in irrigation water tend to replace magnesium ions in clay particles, leading to reduced soil permeability, poor internal drainage, and soil hardening. These effects ultimately degrade soil quality and reduce plant growth (Pivić et al., 2022). High sodium levels also encourage the formation of compounds with chloride and carbonate ions, resulting in salinity and alkalinity in soils. While calcium and magnesium are essential nutrients naturally present in soils, elevated levels in irrigation water can increase soil pH, degrade soil quality by causing alkalinity, and reduce crop yields (Ashie et al., 2024).

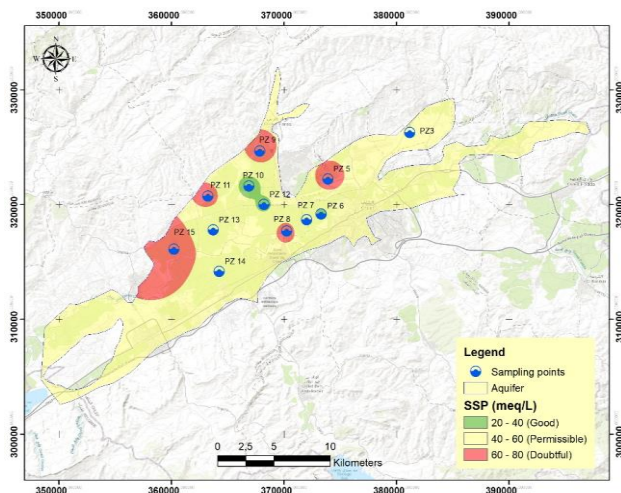


Fig. 7. Spatial distribution of SSP for groundwater samples

In this study, the soluble sodium percentage (SSP) in water ranged from 33.96% to 77.04%, with an average value of 54.08%. According to the Wilcox (1955) classification, the SSP values fall into the categories of "good" (25%), "permissible" (33.33%), and "doubtful" (41.67%) for irrigation purposes, as detailed in Table 3. These results indicate that the water is generally suitable for agricultural use; however, some restrictions may apply in the northern and western parts of the study area, as illustrated in Fig.7.

Magnesium Adsorption Ratio (MAR)

The magnesium concentration in water is a key parameter for evaluating its suitability for irrigation. High magnesium levels are often associated with increased exchangeable sodium

in irrigated soils (Dimple et al., 2022). Chaudhary and Satheeshkumar (2018) noted that high magnesium concentrations in water can negatively impact crop productivity by making soils more alkaline.

The MAR of the well waters ranged from 25.64% to 76.07%, with an average value of 56.01%. According to these findings, only 16.67% of the samples were deemed suitable for irrigation, while the remaining 83.33% were classified as unsuitable (Table 3). The spatial distribution of the magnesium adsorption ratio (MAR), represented in Fig. 8, reveals that only the extreme northern part of the study area is favourable for irrigation without restrictions. In contrast, the majority of the region poses a significant risk due to elevated magnesium levels, which can lead to soil compaction and reduced permeability. These conditions may severely limit the long-term sustainability of agricultural practices in the affected areas. Continuous monitoring and the implementation of targeted soil management strategies are essential to mitigate these risks and preserve soil health.

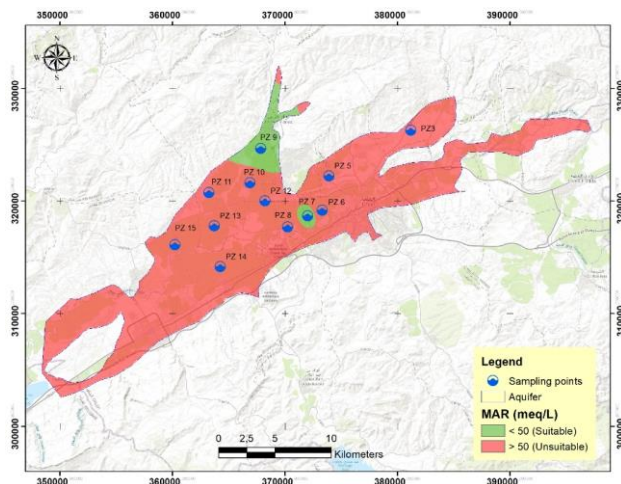


Fig. 8. Spatial distribution of MAR for groundwater samples

The Kelley Ratio (KR)

The Kelley Ratio (KR) is a widely recognized index used to evaluate the suitability of groundwater for irrigation. This ratio assesses the influence of various water quality parameters, including calcium, magnesium, and salinity. It is calculated as the ratio of sodium ions to the combined concentration of calcium and magnesium ions in groundwater. Water with a Kelley Ratio below 1 is deemed suitable for irrigation, while values above 1 indicate water unsuitable for irrigation due to the risks associated with high alkali content.

In this study, Kelley Ratio (KR) values ranged from 0.51 to 3.34, with an average of 1.39. As shown in Table 3, 41.67% of the water samples were classified as suitable for irrigation, while 58.33% were deemed unsuitable. Only three regions, located in the central part of the study area, exhibited KR values below 1, indicating that groundwater in these areas is suitable for irrigation based on Kelley ratio (Fig. 9). This suitability may be linked to intense cation exchange processes elsewhere in the study area, which contribute to an excess of sodium ions (Na^+), thereby reducing water quality for agricultural use.

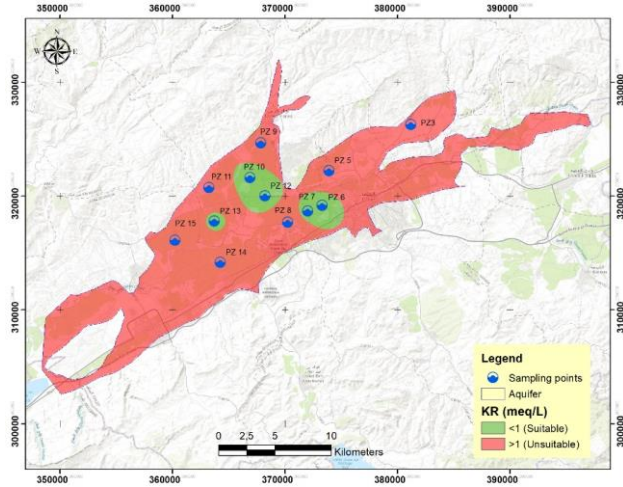


Fig. 9. Spatial distribution of KR for groundwater samples

Permeability Index

Permeability Index (PI) is another important factor in assessing the impact of long-term irrigation on soil permeability. This property is influenced by the presence of sodium, calcium, magnesium, and bicarbonate in the soil. Doneen established a method to evaluate irrigation water suitability based on the permeability index, classifying water into three categories: Good, suitable, and unsuitable (Tab. 1).

In the present study, the Permeability Index (PI) values of the uptaken water samples ranged from a minimum of 35.25% to a maximum of 83.73%, with an average value of 60.59%. These results indicate that 25% of the water samples were classified as "good" and 75% as "suitable" for irrigation purposes (Tab. 3). The spatial distribution map of PI values (Fig.10) demonstrates that the water quality across the study area is predominantly favorable for irrigation.

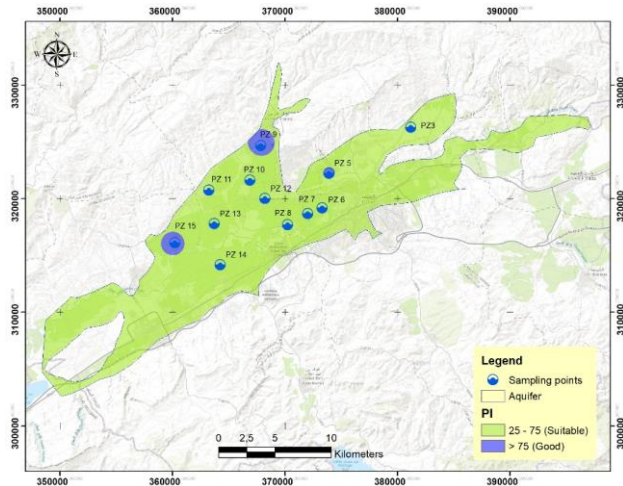


Fig. 10. Spatial distribution of PI for groundwater samples

Regions with higher PI values are concentrated in the central and northern parts of the area, suggesting a strong potential for agricultural use without significant soil permeability concerns. However, continuous monitoring is recommended to assess any long-term changes in water quality that could arise from land use practices, especially in areas where irrigation intensifies.

Suitability based on graphical approaches

Richard's Diagram

The Richard's diagram (1954) (Fig. 11) provides a graphical approach to classify irrigation water by plotting the Sodium Adsorption Ratio (SAR) against electrical conductivity (EC). This diagram categorizes irrigation water based on salinity hazard (EC) and sodium hazard (SAR) into distinct classes: low (C1-S1), medium (C2-S2), high (C3-S3), and very high (C4-S4). Water classified as C1-S1 and C2-S2 is suitable for irrigation without prior treatment. In contrast, water falling into C3-S3 or C4-S4 categories requires treatment to mitigate risks to soil and crops before use (Gevera et al., 2020).

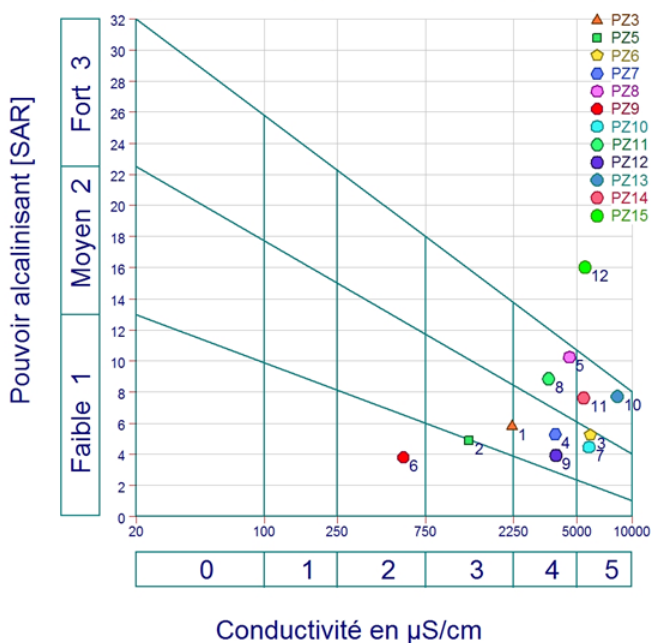


Fig. 11. Plot of Sodium Adsorption Ratio (SAR) Against Electrical Conductivity (EC) for Classifying Irrigation Waters Using Richard's Diagram

In the current study, the plotted SAR and EC values place the groundwater samples into seven categories based on their suitability for irrigation. The water from sampling point PZ9 falls into the C2S1 category, indicating good quality water that can be used without significant restrictions for irrigating plants moderately tolerant to salts in soils. Point PZ5 belongs to the C3S1 class, where water is suitable for irrigating salt-tolerant crops on well-drained soils, though monitoring salinity levels over time is advised. Fig. 11 shows that sampling points PZ3, PZ6, PZ7, PZ11, and PZ12 are classified under C4S2, representing water that can be utilized for irrigating salt-resistant crops on well-drained soils. In contrast,

points PZ8, PZ10, PZ13, and PZ14 fall into the C4S3 category, indicating poor water quality for irrigation. Finally, PZ15 is classified under C4S4, which corresponds to very poor-quality water unsuitable for irrigation purposes. This classification highlights the varying degrees of water quality and their implications for agricultural practices in the study area.

Wilcox Diagram

The Wilcox diagram (1955) (Fig. 12) is a widely used tool to evaluate irrigation water suitability by examining the relationship between sodium percentage (%Na) and electrical conductivity (EC). High values of either parameter can be detrimental to plant growth, as they affect soil structure and permeability. The diagram classifies irrigation water into five categories: excellent to good (Class I), good to permissible (Class II), permissible to doubtful (Class III), doubtful to unsuitable (Class IV), and unsuitable (Class V) (Bhatti et al., 2019).

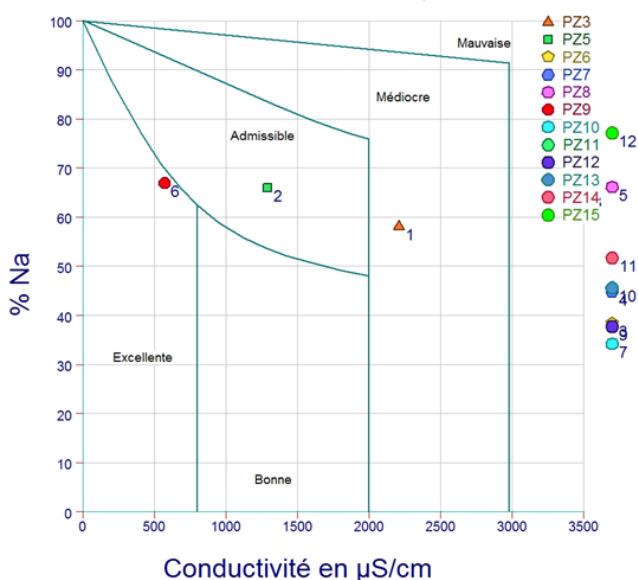


Fig. 12. Plot of Sodium Percentage Versus Electrical Conductivity (EC) for Irrigation Water Classification Using Wilcox Diagram

According to Wilcox (Fig. 12), 8% of the groundwater samples (PZ9) fall into the "excellent" category, 8% (PZ5) are classified as "permissible," 8% (PZ3) are categorized as "poor," and the remaining 75% are considered to have "bad quality" water. This distribution highlights a significant prevalence of low-quality water in the study area, which could pose challenges for agricultural and irrigation purposes. The dominance of poor-quality water is likely influenced by factors such as high salinity levels, the presence of excess sodium, and potentially inadequate drainage systems in certain areas.

Conclusion

This study assessed the irrigation suitability of shallow groundwater in the Middle Cheff plain by analyzing its physicochemical properties and calculating standard water quality indices. The findings reveal that while some regions, particularly in the northern and central parts of the plain, offer water of acceptable quality for irrigation, the majority of the samples exhibit high salinity and sodium concentrations, posing risks to soil structure and crop productivity. Spatial mapping highlights the impact of anthropogenic activities, such as agricultural practices and fertilizer leaching, on groundwater quality. The results obtained from graphical analyses, including the Richard and Wilcox diagrams, align with the spatial classification of water quality indices, confirming the areas identified with varying levels of suitability for irrigation. These results underscore the need for regular monitoring, the adoption of sustainable agricultural practices, and targeted remediation strategies to mitigate these risks and ensure the long-term sustainability of groundwater resources in the study area.

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

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