

Groundwater Suitability for Sustainable Irrigation in the Arid Béni Ounif Syncline, Southwestern Algeria: Salinity Hazards, and Irrigation Water Quality Indices

ARFA Abdellah, BOUSELSAL Boualem

Abstract: Groundwater is a strategic resource for irrigated agriculture in arid regions, where severe water scarcity and high evaporative demand constrain sustainable crop production. This study evaluates the suitability of groundwater in the Béni Ounif syncline, southwestern Algeria, for agricultural irrigation using 46 groundwater samples collected from the shallow and Continental Intercalaire (CI) aquifers. Irrigation quality was assessed through electrical conductivity (EC), sodium adsorption ratio (SAR), soluble sodium percentage (SSP), Kelly's ratio (KR), permeability index (PI), potential salinity (PS), magnesium adsorption ratio (MAR), and the irrigation water quality index (IWQI). Results indicate low sodium hazard, with all samples classified as excellent according to SAR. IWQI classified all CI samples as good, while shallow-aquifer waters were 63.33% good and 36.67% excellent. However, high-salinity conditions occurred in 62.5% of CI and 26.67% of shallow samples, highlighting the need for drainage, leaching, and salt-tolerant crops for sustainable agricultural water management under prevailing local conditions.

Keywords: Béni Ounif; groundwater; irrigation water quality; IWQI; salinity; SAR; sodium hazard; agricultural sustainability.

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ARFA Abdellah (arfa.abdellah@univ-ouargla.dz) Laboratory of underground oil, gas and aquifer reservoirs, Department of Earth and Universe Sciences, University of Kasdi Merbah, Route de Ghardaia, BP 511, 30000, Ouargla, Algeria

BOUSELSAL Boualem, Laboratory of underground oil, gas and aquifer reservoirs, Department of Earth and Universe Sciences, University of Kasdi Merbah, Route de Ghardaia, BP 511, 30000, Ouargla, Algeria

Introduction

Groundwater is a vital strategic resource for socio-economic development and food security, particularly in arid and hyper-arid regions where surface water bodies are virtually absent. In such vulnerable environments, persistent hydrological constraints—governed by hyper-arid climatic conditions, scarce and erratic rainfall, and extremely high potential evapotranspiration rates—severely limit freshwater availability. Consequently, irrigated agriculture relies almost exclusively on subsurface reservoirs to sustain crop production and support expanding oasis agro-ecosystems. However, intensive reliance on groundwater under intensive exploitation regimens frequently induces severe hydraulic and hydrogeochemical imbalances, including progressive piezometric decline, salt mobilization, and water quality deterioration, which threaten the long-term sustainability of agricultural lands.

The suitability of groundwater for agricultural irrigation is dictated by the total concentration of dissolved salts and the relative abundance of specific dissolved ions. Excessive irrigation water salinity (quantified through electrical conductivity, EC, and total dissolved solids, TDS) impairs the osmotic balance of plants by impeding root water uptake, precipitating physiological drought, stunting crop development, and diminishing yields. Simultaneously, elevated sodium concentrations relative to divalent cations (calcium and magnesium)—commonly evaluated via the sodium adsorption ratio (SAR) and soluble sodium percentage (SSP)—foster severe structural degradation of soils. Excessive exchangeable sodium promotes the swelling and dispersion of clay particles, leading to pore clogging, crust formation, diminished aeration, and reduced hydraulic conductivity. Furthermore, elevated magnesium hazards (MAR) and potential salinity (PS) pose continuous risks of secondary soil alkalization and mineral precipitation across sustained cultivation cycles. Therefore, a systematic and multi-index hydrogeochemical assessment is indispensable to decipher salinity–sodicity hazards and establish reliable baselines for agricultural water management.

In the Sahara of southwestern Algeria, securing dependable water supplies for agricultural modernization is an essential challenge. The Béni Ounif syncline, situated in Béchar Province, represents an important agricultural and demographically expanding hub characterized by extreme climatic stress, where annual precipitation rarely exceeds 35 mm and summer temperatures frequently surpass 39 °C. In recent years, demographic growth, agricultural expansion, and inter-basin water transfers (notably the major supply infrastructure transferring ~30,000 m³/day to Béchar city) have imposed substantial pumping pressure on both shallow alluvial and deep artesian aquifers. Hydrogeologically, the region is underlain by two primary interconnected aquifer systems: the deep, confined Lower Cretaceous Continental Intercalaire (CI) aquifer consisting of detrital

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sandstone and gravel formations, and the unconfined Quaternary alluvial aquifer predominantly developed along major ephemeral wadi channels (e.g., Oued Zousfana, Oued Lakhdar, and Oued Namous). These two aquifer units exhibit distinct recharge mechanisms, lithological compositions, and residence times, which inevitably induce contrasting hydrogeochemical signatures and irrigation suitability profiles.

While several studies have explored regional geology and hydrogeology across the Saharan platform, a rigorous comparative evaluation of irrigation quality, sodicity risks, and comprehensive irrigation indexation across the stacked shallow-versus-deep aquifer systems of the Béni Ounif syncline remains unaddressed. Traditional single-parameter classifications often fail to capture the composite geochemical factors governing soil–water–plant interactions. To overcome this limitation, the Irrigation Water Quality Index (IWQI) offers a robust mathematical and predictive framework by integrating multiple chemical variables into a unified rating score.

Materials and methods

2.1 Study area

The study area is situated in Béchar Province, in the southwest of Algeria. Its administrative center, Béni Ounif, lies about 110 km east of the city of Béchar (Fig. 1) and occupies an area of approximately 4,230 km². Geographically, it stretches between 4° W and 3° E longitude and from 30° N to 33° N latitude. According to estimates from 2017, the population was around 13,000 residents. The region experiences a typically Saharan climate, marked by relatively mild winters. Average annual rainfall is very low, not exceeding 32 mm, with monthly values usually below 2 mm. The mean annual temperature is close to 27.4 °C, reaching nearly 39 °C in July and falling to about 13 °C during January ([Arfa A](#)).

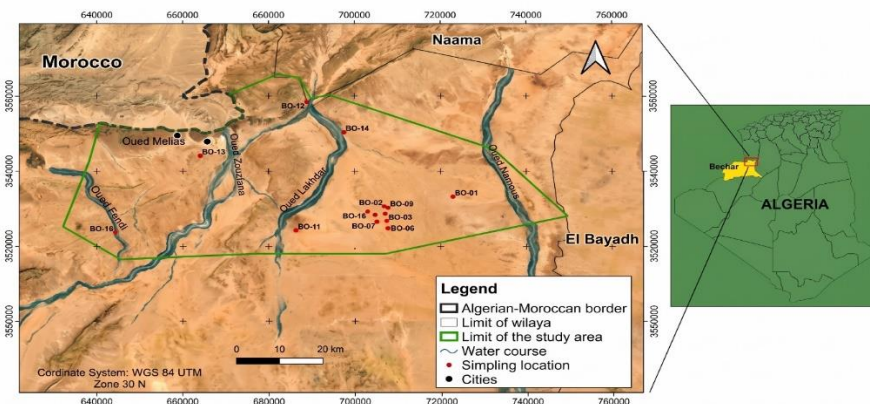


Figure 1. Geographical location of the study region and Positioning of sampled boreholes.

From a geological perspective, the study area is part of a synclinal structure within the extensive Saharan platform, itself belonging to the North African craton. This region features a Precambrian basement overlain unconformably by a thick sedimentary sequence. The Oued Namous basin is particularly notable for its rugged Precambrian bedrock, which is bordered by Paleozoic formations and subsequently overlain by Mesozoic and more recent sedimentary units, including hamadas and ergs.

The hydrogeological framework of the Béni Ounif region reveals the presence of two main aquifer systems. The first is the Lower Cretaceous aquifer, composed of alternating gravelly-sandy and clayey layers. This confined aquifer is primarily recharged through vertical and lateral inflows across the South Atlasic flexure. Its thickness varies between 100 and 300 meters. The second system is a shallow unconfined aquifer consisting of Quaternary alluvial deposits with an average thickness of 5 to 10 meters. This phreatic aquifer, particularly prominent in the Zousfana Valley, plays a vital role in local water supply. It is annually recharged by winter and spring floods, especially during intense flood events from major wadis such as Oued Lakhdar, Oued Zousfana, Oued Namous, and Oued Laouedj.

2.2 Water Quality for Irrigation Uses

Water quality assessment is carried out in several stages to determine its suitability for various uses. It begins with comparing the characteristics of the samples to recognized reference standards, followed by the application of global indices that synthesize the collected data.

For irrigation, quality is evaluated using the **Irrigation Water Quality Index (IWQI)**, based on seven parameters that reflect the influence of salinity and major ions on soils and crops. Finally, for industrial purposes, different indices are employed to assess the potential for corrosion or scaling, helping to anticipate their impact on installations and distribution networks.

The detailed procedures of these assessment methods are illustrated in the flowchart presented in Figure 2, offering a clear and structured overview of the steps involved in analyzing and classifying water quality.

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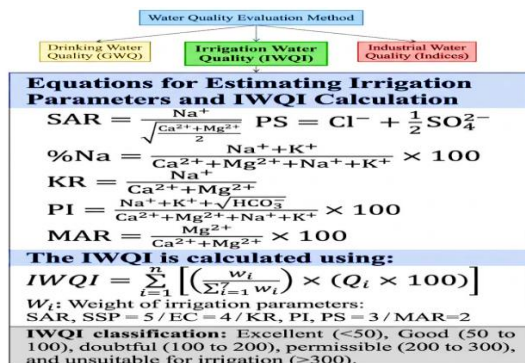


Figure 2. Flowchart showing the methods adopted for water quality assessment. **Suitability of water for agricultural use**

High concentrations of chemical ions in groundwater can adversely affect soil and vegetation, hindering plant development and disrupting their osmotic and metabolic processes. These concentrations also impact soil permeability and aeration, directly influencing plant growth (Bengal and Aznarul, 2021; Eldaw et al. 2021). Therefore, it is crucial to monitor water quality parameters for irrigation such as EC, SAR, SSP, PI, KR, PS, and MAR to ensure healthy and sustainable plant growth.

Water salinity is primarily associated with TDS and EC (Ayers and Westcott, 1985; Todd, 1959). A common method to estimate TDS in ppm or mg/l is to multiply the EC (in $\mu S/cm$) by 0.64, depending on the types of salts present. High levels of TDS and EC can increase soil salinity, adversely affecting plant growth and impacting soil structure, permeability, and aeration. An increase in dissolved solids can also make it more difficult for roots to absorb water and nutrients, leading to stunted growth, reduced yield, discoloration, and leaf burn. EC measurements in the waters of the shallow aquifer range from 500 $\mu S/cm$ to 2067 $\mu S/cm$. According to Wilcox classification (Wilcox 1955) (Table 1), the waters of this aquifer are categorized into three salinity risk categories: low (20%), medium (53.33%), and high (26.67%), while those from the CI aquifer are classified into two risk categories: medium (37.5%) and high (62.5%).

SAR, introduced by Richards (1954), assesses the tendency of Na^+ ions to accumulate in the soil. High SAR levels in irrigation water can increase Na^+ accumulation in the soil, reducing water infiltration due to soil particle dispersion. Excessive SAR may also promote crust formation and reduce soil aeration (Aravinthasamy et al. 2021). A high concentration of sodium (SAR) can also lead to soil alkalization. According to Richards (1954) (Table 1), the groundwater quality in Beni Ounif for irrigation is considered excellent.

According to the USSL diagram (1954) (Fig. 3a), all groundwater samples collected in the study area plot within the S1 class, reflecting a low sodium hazard. Such waters are generally appropriate for irrigation across most soil types, with only a minor risk of accumulating excessive exchangeable sodium. Nevertheless, attention should be given when irrigating sodium-sensitive crops, such as stone fruits or avocados, as these species may absorb sodium to harmful levels.

With respect to salinity, the irrigation suitability of Béni Ounif groundwater can be categorized as follows: Class C1 comprises about 20 % of the shallow-aquifer wells and corresponds to low-salinity water, suitable for nearly all crops and soils, with minimal danger of soil salinization. Some leaching may be necessary, though normal irrigation practices are typically sufficient except in soils with extremely low permeability. Class C2 includes 53.33 % of shallow-aquifer boreholes and 37.5 % of Continental Intercalaire wells; these waters present moderate salinity and can be used safely if adequate leaching is ensured, making them suitable for crops with moderate salt tolerance without the need for intensive salinity-control measures. Finally, Class C3 represents 26.67 % of samples from the shallow aquifer and 62.5 % from the CI aquifer. These high-salinity waters are unsuitable for poorly drained soils, and even in well-drained conditions they require specific management practices, such as selecting salt-tolerant crops and implementing careful salinity control.

The Wilcox classification, which considers electrical conductivity and sodium content in water, ranks the groundwater of Beni Ounif from excellent to good quality, as demonstrated by the distribution of samples on the diagram (Fig. 3b).

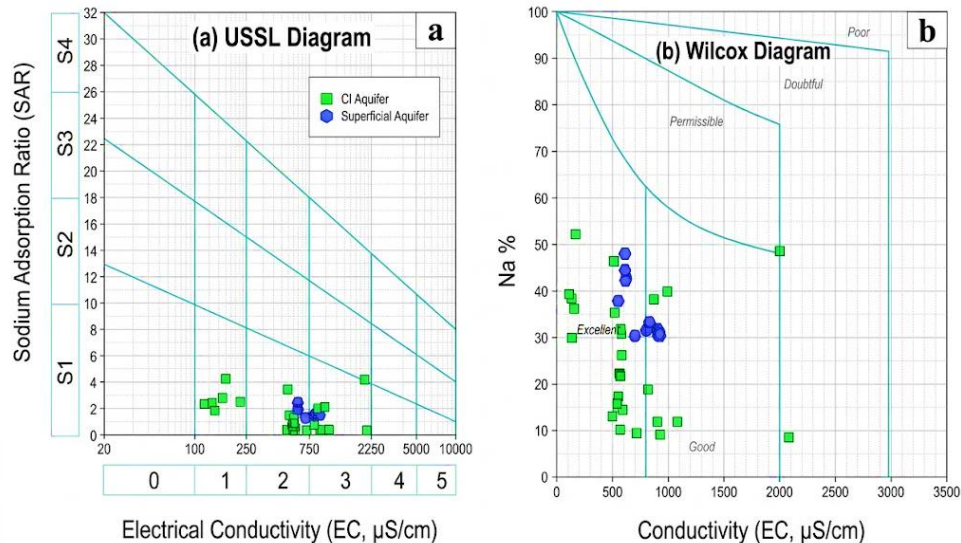


Figure 3. USSL and Wilcox diagram for groundwater in Beni Ounif.

The Soluble Sodium Percentage (SSP) is an important indicator for assessing irrigation water quality and evaluating the potential risks associated with excessive sodium concentrations. It is calculated as the percentage of sodium relative to the combined concentrations of the major cations, particularly calcium and magnesium (Fig. 4). High SSP values indicate that sodium may displace calcium and magnesium from the exchange sites of clay minerals, thereby deteriorating soil structure. These processes can reduce soil permeability and internal drainage, promote soil compaction, and ultimately impair seedling establishment and crop development (Kshitindra Kr et al., 2020). Excessive sodium concentrations can also contribute to soil salinization and alkalization, both of which adversely affect plant growth and agricultural productivity. According to the classification proposed by Todd (1959) (Table 1), irrigation water is categorized into several quality classes based on SSP values: excellent (below 20), good (20–40), fair (40–80), and poor (above 80). In the present study, approximately 40% of the samples from the shallow aquifer fall within the excellent category, while 50% are classified as good and 10% as permissible. In the Continental Intercalaire aquifer, 75% of the analyzed groundwater samples fall within the good category, while the remaining 25% are classified as permissible.

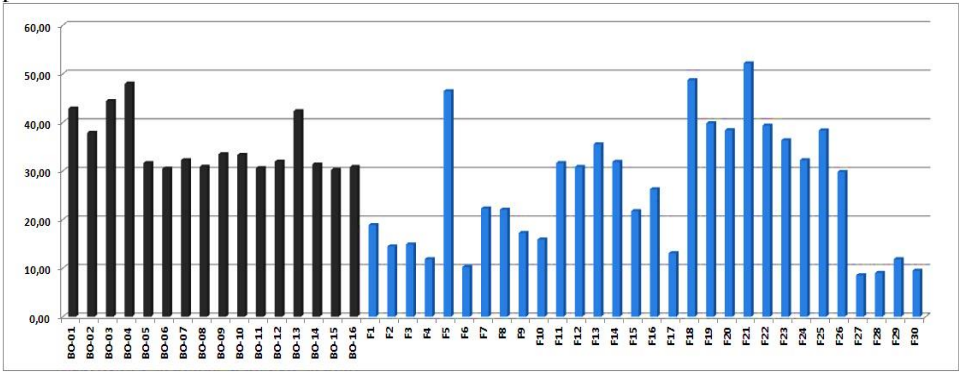


Figure 4. Variation in SSP in groundwater in the study area.

The Kelly Ratio (KR) is an important parameter for judging the suitability of water for agricultural irrigation. It expresses the proportion of sodium in relation to calcium and magnesium concentrations in the water (Kelly, 1940). When the KR exceeds 2, the water contains an excessive amount of sodium and is considered inappropriate for irrigation purposes (Fig. 5). Values between 1 and 2 suggest marginal quality, while a ratio below 1 indicates that the water is acceptable for agricultural use. In the current investigation (Table 1), nearly all sampled wells fell within the acceptable range, with the exception of well F21, which showed a doubtful classification for irrigation.

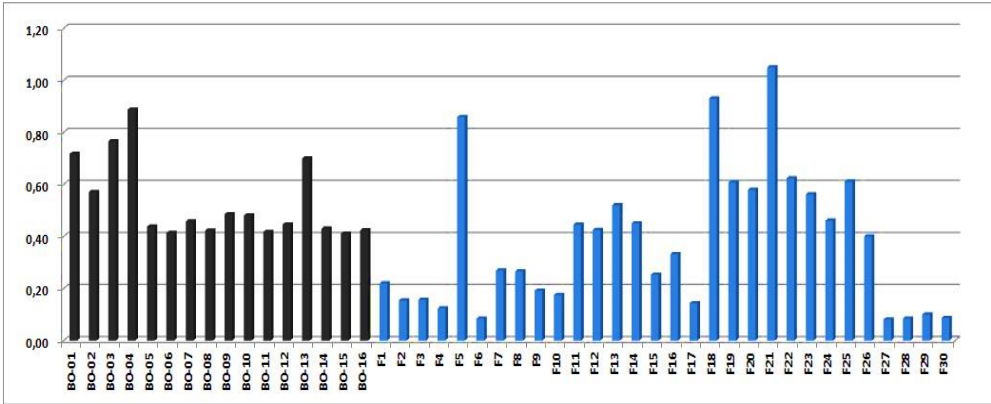


Figure 5 : Variation in KR in groundwater in the study area.

The Permeability Index (PI) provides another useful measure for estimating the effect of irrigation water on soil structure, since infiltration capacity depends largely on the soil’s permeability. The PI is calculated from the concentrations of Na^+ , Ca^{2+} , Mg^{2+} , and HCO_3^- in solution. Following Doneen’s classification (1964) (Table 1), PI values are divided into three groups: Class 1 denotes excellent quality, Class 2 indicates good quality, and Class 3 represents waters that are unsuitable for irrigation. In this study, all samples were placed in Classes 1 or 2, meaning that the groundwater can be safely used for irrigation with an effective permeability of 75% or higher.

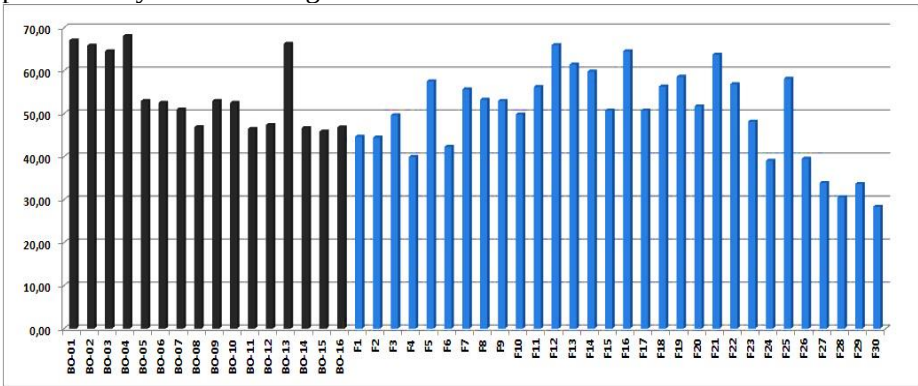


Figure 6 : Variation in PI in groundwater in the study area.

Another key indicator is the Salinity Potential (PS), which assesses the likelihood of salt accumulation in soils due to the presence of sulfate and chloride in irrigation water. If these salts precipitate and build up after successive cropping cycles, they can impair soil productivity and crop yields. Maintaining PS within an optimal range is therefore crucial for the long-term sustainability of irrigated lands. As summarized in Table 1, PS values in the study area range from 0.43 to 12.80 meq/L in the shallow aquifer (average 3.98 meq/L) and between 1.34 and 2.49

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meq/L in the Continental Intercalaire (average 1.68 meq/L). Based on these values, 86.67% of the shallow-aquifer samples are classified as ranging from “Good” to “Detrimental,” whereas 13.33% fall within the “Injurious to Unsatisfactory” category. All samples from the deeper aquifer belong to the “Good to Detrimental” class.

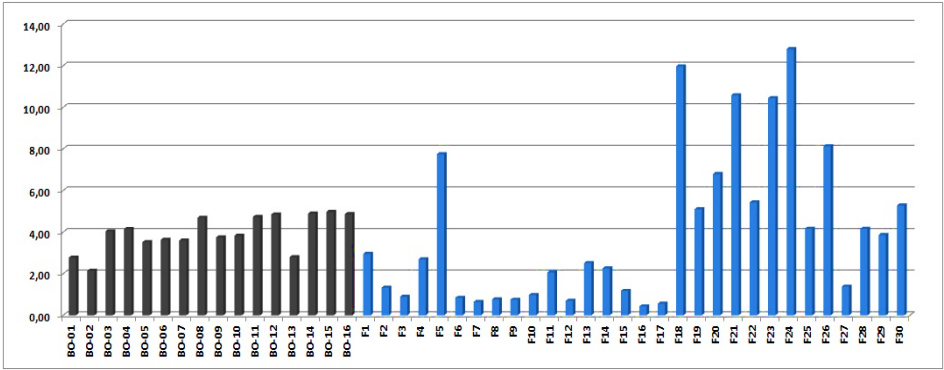


Figure 7. Variation in PS in groundwater in the study area.

Finally, the balance between magnesium and calcium is also relevant when determining water quality for irrigation. Because magnesium often has a stronger influence than calcium on soil chemistry, the Magnesium Adsorption Ratio (MAR) is applied to assess its impact. According to Ragnath (1987), irrigation water is considered safe when MAR values are below 50. Levels above this threshold can contribute to soil alkalinity, increase sodium adsorption, and reduce permeability, leading to lower crop productivity (Kshitindra Kr et al., 2020). As presented in Table 1, 80% of samples from the shallow aquifer and 37.5% from the Continental Intercalaire aquifer meet the recommended MAR limit, while the remaining waters may pose a risk to soil quality and agricultural yields.

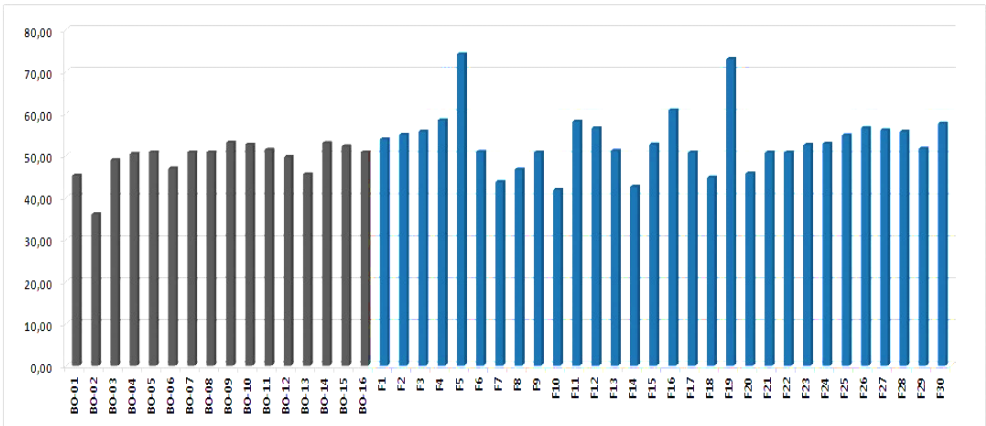


Figure 8. Variation in MAR in groundwater in the study area.

The quality of water for agricultural use can be assessed using the Irrigation Water Quality Index (IWQI), which aggregates seven predetermined water quality

parameters into a single value that indicates the suitability of the water for irrigation purposes.

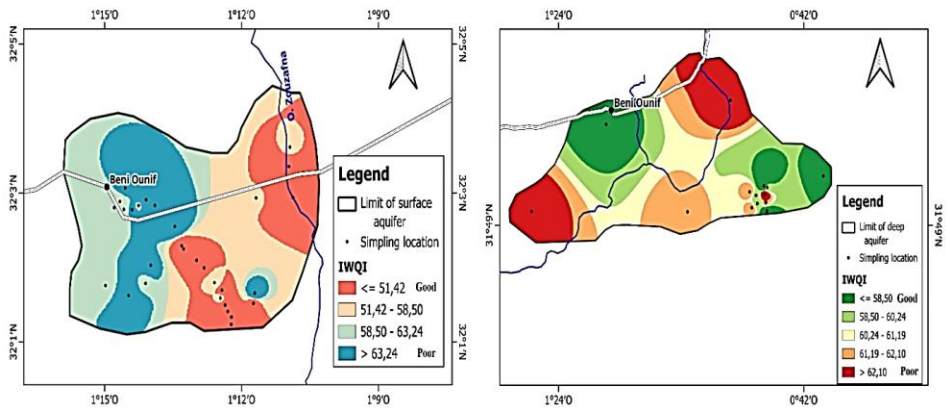


Figure 9. Variation in IWQI in groundwater in the study area.

In the Beni Ounif region, the IWQI values for waters from the Continental Intercalary (CI) aquifer range from 51 to 64, as shown in Table 1. For the shallow aquifer, IWQI values vary between 40 and 88 (Fig. 9).

Approximately 63.33% of the groundwater samples from the shallow aquifer and 100% of the samples from the CI aquifer are categorized as "good," while 36.67% of samples from the shallow aquifer are rated as "excellent." The lower IWQI values are attributed to the relatively modest mineralization of the groundwater compared to the arid climatic conditions prevailing in the study area. The reduced concentration of minerals in the groundwater is due to the low evaporation rates in the study area.

Table 1. Classification of groundwater samples for irrigation.

Parameter	Scale	Groundwater r classes	CI Aquifer		superficial Aquifer	
			No. sample	% sample	No. sample	% sample
EC (µS/cm) (Wilcox 1955)	<250	Salinity risks: weak (good)	00	00	06	20
	250-750	medium (moderate)	06	37.5	16	53.33
	750-2250	high (low)	10	62.5	08	26.67
	>2250	very high	00	00	00	00
	0	(very low)				

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SAR (meq/l) (Richards 1954)	0-10	Excellent	16	100	30	100
	10-18	GOOD	00	00	00	00
	18-26	Doubtful	00	00	00	00
	> 26	Inappropriate	00	00	00	00
SSP (Todd 1959)	0-20	Excellent	00	00	12	40
	20-40	GOOD	12	75	15	50
	40-60	Permissible	04	25	03	10
	60-80	Doubtful	00	00	00	00
	> 80	Inappropriate	00	00	00	00
KR (Kelley 1963)	< 1	Good	16	100	29	96.67
	1-2	Doubtful	00	00	01	3.33
	> 2	Inappropriate	00	00	00	00
IP (%) (Doneen 1964)	>75	Permeability: 100%	00	00	00	00
	75-25	75%	16	100	16	100
	< 25	25%	00	00	00	00
SP (Doneen 1954)	>5	Excellent to	16	100	26	86.67
	5-10	Good	00	00	04	13.33
	< 10	Good to harmful Detrimental to unsatisfactory	00	00	00	00
MAR (%) (Ragunat h 1987)	< 50%	Appropriate	06	37.5	24	80
	> 50%	Inappropriate	10	62.5	06	20
	> 50%					
IWQI	0-50	Excellent	00	00	11	36.67
	50-100	Good	16	100	19	63.33
	100-200	Permissible	00	00	00	00
	200-300	Doubtful	00	00	00	00
	> 300	Inappropriate	00	00	00	00

Conclusion

In the Beni Ounif region, groundwater is predominantly utilized to satisfy domestic, agricultural, and industrial needs. This study focuses on the hydrochemical characterization of these waters, assessing their quality for various

applications and examining mineralization mechanisms. Hydrochemical data from 16 boreholes tapping the Continental Intercalaire (CI) aquifer and 30 boreholes accessing the shallow aquifer were analyzed.

This study evaluated the hydrogeochemical suitability of groundwater for agricultural irrigation in the arid region of Beni Ounif, targeting both the shallow and Continental Intercalaire (CI) aquifers. Overall, the integrated assessment reveals favorable irrigation potential across the study area. Indices targeting sodium and permeability hazards—specifically SAR, USSL diagram (S1 class), Wilcox classification, SSP, KR, and Doneen's PI (Classes 1 and 2)—consistently demonstrate minimal sodicity risks and safe soil infiltration properties. Furthermore, the Irrigation Water Quality Index (IWQI) corroborates these findings, classifying 100% of CI samples and 63.33% of shallow aquifer waters as "good," with the remaining 36.67% of shallow groundwater categorized as "excellent."

However, sustainable agricultural development remains constrained by localized salinity and magnesium hazards. Salinity-induced risks are evidenced by the prevalence of high-salinity water (Class C3) in 26.67% of shallow aquifer and 62.5% of CI aquifer samples, compounded by elevated magnesium adsorption ratio (MAR) values exceeding the permissible threshold (50%) in 62.5% of CI waters.

These conditions pose potential risks of secondary soil salinization and structural degradation under prolonged irrigation. Consequently, sustainable water resource management in this arid setting necessitates the selection of salt-tolerant crops, adequate leaching fractions, efficient drainage systems, and regular hydrochemical monitoring to preserve soil quality and ensure agricultural sustainability.

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