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Groundwater quality assessment of the Boudinar Basin (Morocco) for drinking and irrigation purpose

Valutazione della qualità delle acque sotterranee del Bacino di Boudinar (Marocco) per uso potabile e irriguo

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Abstract

This study evaluates groundwater quality in the Boudinar Basin, northeastern Morocco, for irrigation and drinking purposes. In April 2024, sixteen GPS-referenced tap water samples directly supplied from local groundwater wells were collected across the Boudinar Basin. Major ions and physico-chemical parameters were analyzed using HI83399 and DR 3900 photometers, and a multiparameter probe, while hydrochemical facies and water suitability were evaluated using Piper, Stiff, Stabler, and Wilcox diagrams. Water Quality Index was calculated from twelve parameters. Hydrochemical diagrams indicate that the water is predominantly of the $Ca–HCO_3$ *type, with calcium as the dominant cation and bicarbonate as the dominant anion. Magnesium, sodium, potassium, and chloride are present in lower proportions, reflecting water–rock interactions and potential anthropogenic influences. While pH levels are safe for drinking, salinity exceeds World Health Organization and Moroccan standards in several samples. High calcium concentrations affect water hardness, and aluminum contamination is found in five samples. Other parameters like sodium, nitrates, chloride, and potassium are within acceptable limits. While 37.5% of the samples are suitable for irrigation, 56.25% are poor and require soil drainage and periodic leaching to prevent the accumulation of salts within the root zone. The Water Quality Index shows 11 samples as "Excellent," one as "Good," but three are "Very Poor," and one is "Unfit for all uses." The northern and central regions generally have good water quality, while the southern areas face localized contamination. Sustainable water management strategies, including salinity control and agricultural runoff reduction, are recommended.*

Riassunto

Questo studio analizza la qualità delle acque sotterranee nel Bacino di Boudinar, nel nord-est del Marocco, per usi irrigui e potabili. Nell'aprile 2024 sono stati raccolti sedici campioni di acqua di rubinetto, prelevati direttamente dai pozzi locali nel bacino, e georeferenziati tramite GPS. Gli ioni principali e i parametri fisico-chimici sono stati analizzati utilizzando i fotometri HI83399 e DR 3900 e una sonda multiparametrica, mentre le facies idrochimiche e la qualità dell'acqua sono state valutate mediante i diagrammi di Piper, Stiff, Stabler e Wilcox. L'Indice di Qualità dell'Acqua è stato calcolato considerando dodici parametri. I diagrammi idrochimici indicano che l'acqua è prevalentemente di tipo $Ca–HCO_3$, con il calcio come catione dominante e il bicarbonato come anione principale. Magnesio, sodio, potassio e cloruro sono presenti in proporzioni minori, riflettendo le interazioni acqua-roccia e possibili influenze antropiche. Sebbene i valori di pH siano sicuri per il consumo umano, la salinità supera i limiti stabiliti dall'Organizzazione Mondiale della Sanità e dagli standard fissati dal Marocco in diversi campioni. Alte concentrazioni di calcio aumentano la durezza dell'acqua e la contaminazione da alluminio è stata rilevata in cinque campioni. Altri parametri, come sodio, nitrati, cloruro e potassio, rientrano nei limiti accettabili. Per quanto riguarda la qualità per l'irrigazione, il 37,5% dei campioni è adatto, mentre il 56,25% presenta limitazioni legate alla salinità. Di conseguenza, il loro utilizzo richiede adeguati sistemi di drenaggio del suolo per migliorare la qualità dell'acqua e prevenire l'accumulo di sali nella zona delle radici. L'Indice di Qualità dell'Acqua classifica 11 campioni in stato "Eccellente", uno in stato "Buono", tre in stato "Molto Scarso" e uno in stato "Non idoneo a qualsiasi uso". Dal punto di vista spaziale, le aree settentrionali e centrali mostrano generalmente una buona qualità delle acque sotterranee, mentre nel sud si osservano contaminazioni localizzate. I risultati sottolineano l'importanza di strategie sostenibili di gestione delle acque, comprendenti il controllo della salinità e la riduzione del deflusso superficiale nelle zone agricole.

Introduction

Groundwater quality in Morocco is of critical concern due to its significant role in providing drinking water and supporting agricultural activities. Various studies have been conducted to assess and predict the Water Quality Index (WQI) of groundwater in different regions of Morocco, employing diverse methodologies and focusing on different parameters. Yousfi et al. (2022) focused on the Ghiss-Nekkor aquifer in northeastern Morocco, utilizing statistical analysis and multilayer perceptron approaches to predict groundwater quality. The study analyzed 50 groundwater samples for major anions and cations, calculating the entropy-weighted groundwater quality index from parameters such as Total Dissolved Solids (TDS), pH, Electrical Conductivity (EC), Na, K, Ca, Mg, HCO_3, NO_3, Br, SO_4, and Cl. The WQI values ranged from 90.98 to 337.28, indicating varying levels of water quality, with some samples deemed unsuitable for drinking due to seawater intrusion resulting from overexploitation of the groundwater resources. Heiß et al. (2020) conducted a study in the arid region of Tata city (Morocco), where the DRASTIC model (Aller et al., 1987) was implemented to assess groundwater vulnerability and quality. The study identified areas at great risk potential for groundwater contamination based on geological, hydrogeological, and human impact parameters. A new WQI was developed, focusing on specific electrical conductivity, chloride, nitrate, and ammonia, revealing that nitrate was a significant pollutant, particularly in urban areas. Said et al. (2023) evaluated the Tinejdad-Touroug aquifer in southeastern Morocco for domestic and irrigation purposes. The study found that groundwater quality varied significantly, with many samples exceeding World health organization (WHO) and Moroccan standards (MN) for drinking water. Elevated salinity levels were noted, attributed to natural mechanisms such as evaporation and geological factors. Azzirgue et al. (2022) conducted an exploratory study In the Jouamaa Hakama region, comparing groundwater quality using in situ measurements, WQIs, and a fuzzy logic method. The study found that all wells tested were of poor quality according to both WQIs and fuzzy logic, highlighting the need for improved monitoring and decision-making tools. Mountassir et al. (2022) assessed groundwater quality in the Essaouira basin over several years, revealing that a significant portion of the groundwater was unsuitable for drinking due to contamination by nitrates and other pollutants. The study emphasized the need for treatment before use and highlighted the impact of evaporation and seawater intrusion on groundwater quality. Bouaissa et al. (2021) applied groundwater quality indices for drinking and irrigation purposes in the Bokoya Massif. The study found that a significant number of samples were not suitable for drinking, although many were suitable for irrigation, underscoring the need for targeted water management strategies. Azirar et al. (2023) evaluated the Tafilalet region's groundwater using the weighted arithmetic WQI, showing an overall improvement in water quality over a 15-year period. However, nitrate and sulfate concentrations increased, indicating ongoing pollution challenges. Sarti et al. (2021) studied the rural area of R'mel to assess the impact of anthropogenic activities on groundwater quality. The study found high concentrations of nitrates and some heavy metals, with agricultural activities identified as a major pollution source. The combined use of WQI and multivariate statistical analysis provided a comprehensive understanding of groundwater quality. Malki et al. (2017) examined the Chtouka-Massa region, where intensive agricultural practices impacted groundwater quality, with nitrate concentrations exceeding WHO limits in some areas. The study highlighted the benefits of improved irrigation practices and the need for sustainable groundwater management. Mountassir et al. (2021) assessed groundwater contamination with nitrate in the Essaouira basin using the nitrate pollution index and groundwater pollution index. The study found significant nitrate pollution in certain areas, primarily due to agricultural activities, and emphasized the need for better management practices to protect groundwater resources. These studies collectively underscore the importance of continuous monitoring, sustainable management practices, and the development of effective water quality indices to ensure the safe and sustainable use of groundwater resources in Morocco.

For irrigation purposes, hydrophysical parameters like EC and the sodium adsorption ratio (SAR) are crucial in assessing water's impact on soil health. High SAR values can lead to soil sodicity, which reduces permeability and affects plant growth, while elevated EC indicates saline water that can cause crop stress and reduce yields (Ayers & Westcot, 1985). The integration of hydrochemical diagrams, such as Piper, Wilcox, and Richards diagrams, allows for the classification of water types and the identification of potential risks related to salinity and sodicity (Todd & Mays, 2004). These tools are widely used in arid and semi-arid regions, where water scarcity necessitates careful monitoring of water quality for sustainable irrigation practices (Rahman et al., 2021). In this regard, comprehensive hydrophysico-chemical analysis remains indispensable for the sustainable management of water resources in regions facing agricultural and domestic water quality challenges.

The Boudinar Basin in the Rif belt of Morocco (350 km^2), home to over 60,000 residents according to the Moroccan High Commission for Planning, was selected for this study due to its reliance on groundwater as the exclusive source for drinking and irrigation water supply (Taher et al., 2023). Several hydrochemical studies have focused on the Rif belt, including Ghiss-Nekor (Bouhout et al., 2024; Bourjila et al., 2024a), Bokoya massif (Benaissa et al., 2024; Errahmouni et al., 2024), Kert aquifer (Gueddari et al., 2023). However, no detailed hydrochemical and spatial assessment has yet been conducted in the Boudinar Basin.

This study aims to comprehensively evaluate the groundwater quality of the Boudinar Basin by analyzing its hydrochemical and hydrophysical characteristics. Specifically, it seeks to (i) assess the concentrations of major ions and determine the overall qualitative status of groundwater using the WQI, (ii) classify hydrochemical facies and identify dominant geochemical processes through Piper, Stiff, and Stabler diagrams, and (iii) evaluate irrigation suitability and potential salinity and sodium hazards using the Wilcox diagram. The study provides a multidimensional assessment of groundwater quality for both drinking and agricultural purposes. This work represents the first systematic hydrogeochemical assessment of the Boudinar Basin, generating original data to support sustainable water resource management in the region.

Materials and methods

Case study description

The Boudinar Basin is located in Driouch province, within the Oriental region of northeastern Morocco, and covers an area of approximately 35,000 hectares. It extends between latitudes 34.99°–35.22° N and longitudes 3.52°–3.77° W. The main hydrographic feature of the basin is the 40-km-long Amakran river (Fig. 1a), which flows from south to north and discharges into the Mediterranean Sea (Taher et al., 2023). The study area is characterized by a mountainous landscape with marked spatial variability in precipitation. Elevation ranges from 49 m to 1,612 m above sea level (Fig. 1a). Over a 12-year period, the average annual rainfall varied between 394 and 441 mm, showing a gradual decrease toward the northeastern part of the basin (Taher et al., 2025). Agriculture constitutes the principal economic activity in the region.

Geologically (Fig. 1b), the basin consists of sedimentary formations, primarily limestone, marls, and clays, which play a significant role in shaping the region's hydrogeology. The aquifer system of the Boudinar basin is primarily controlled by its lithological heterogeneity, with the main groundwater reservoir formed by permeable alluvial and sandy deposits distributed along the central valley (Temsaman–Boudinar axis). These unconsolidated materials constitute a predominantly unconfined aquifer with relatively high porosity and permeability, ensuring good groundwater storage and flow. Fractured limestone units in the eastern sector locally act as a secondary aquifer where permeability is enhanced by structural discontinuities. In contrast, marl and sericite gray shale formations behave as low-permeability aquitards that limit vertical flow and compartmentalize the system, while conglomerates show variable hydraulic behavior depending on their degree of cementation, and dolerites generally act as impermeable barriers except where fractured. In general, the basin represents an alluvial–sandy aquifer system hydraulically constrained by surrounding low-permeability formations and structurally controlled groundwater circulation. The basin faces increasing pressures from human activities, such as intensive agriculture, urban expansion, and groundwater over-extraction. These factors, coupled with climate variability, have impacted both the quantity and quality of the water resources.

Sample collection

In the study area, tap water is directly supplied from local groundwater wells that exploit the same aquifers investigated in this research. Therefore, tap water represents pumped groundwater that has undergone only distribution through the supply network, without significant chemical treatment that could alter its hydrochemical composition. During a field mission in April 2024, sixteen tap water samples were carefully selected, and the geographic coordinates of each sampling point were recorded using a portable GPS. This selection considered the spatial distribution to optimize coverage of the Boudinar Basin, informed by population density and agricultural activities. We stored all water samples in a cooler at approximately 4 °C to preserve their properties and maintain their integrity. We excluded the southern area of the basin from sampling due to several factors. The rugged

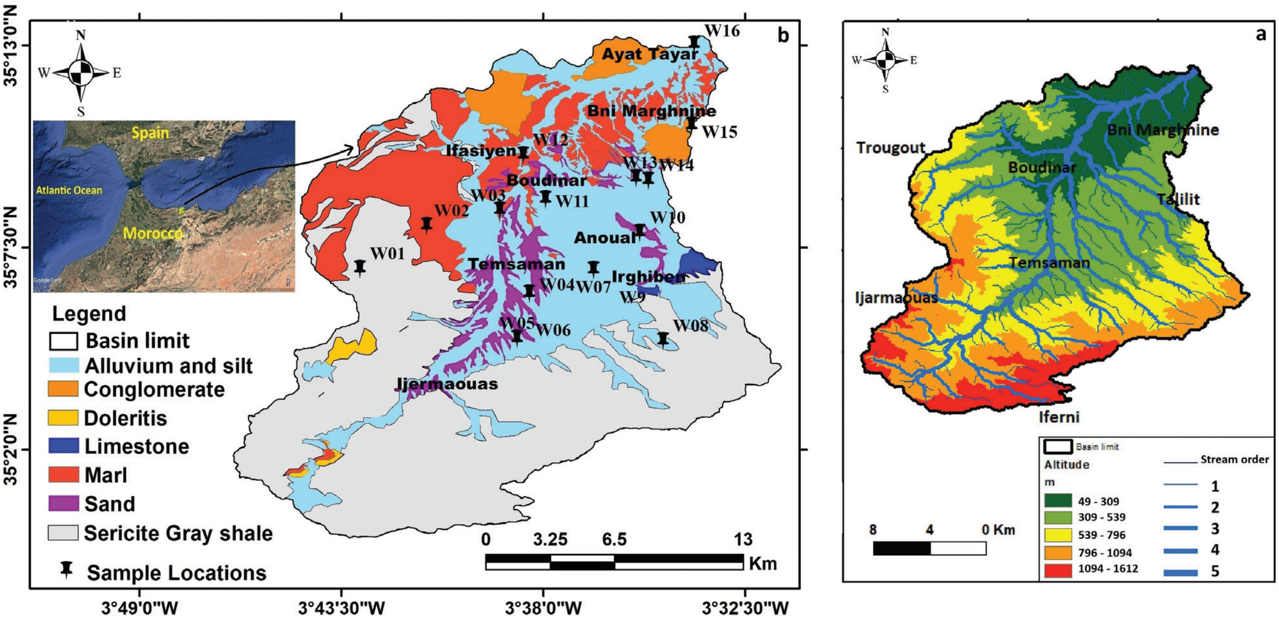

Fig. 1 - Geological and morphological setting and sample points location in the Boudinar basin.

Fig. 1 - Geologia, morfologia e posizione dei punti di campionamento nel bacino di Boudinar.

topography of this region presents significant challenges for accessibility and sampling. Moreover, the low population density in this area restricts the access to water sources, a situation further exacerbated by the absence of tap water infrastructure. These factors collectively hindered our ability to conduct a thorough assessment of groundwater quality in the southern basin.

The hydrogeochemical characteristics of water reflect various influences, including lithology of watersheds (Zineb & Meriem, 2024). To further investigate the influence of lithology on the hydrogeochemical characteristics of water in the Boudinar Basin, the locations of the water samples were superimposed on a detailed geological map of the area (Table 1). This analysis aimed to identify potential correlations between the geological formations present and the variations observed in water quality parameters.

Tab. 1 - Distribution of water samples according to geological units in the Boudinar basin.

Tab. 1 - Distribuzione dei campioni d'acqua in base alle unità geologiche nel bacino del Boudinar.

Water sample	Geological Units
W01	Sericite gray shale
W02	Marl
W03	Alluvium and silt
W04	Alluvium and silt
W05	Alluvium and silt
W06	Alluvium and silt
W07	Alluvium and silt
W08	Sericite gray shale
W09	Alluvium and silt
W10	Alluvium and silt
W11	Alluvium and silt
W12	Marl
W13	Alluvium and silt
W14	Alluvium and silt
W15	Conglomerate
W16	Alluvium and silt

Sample analysis

For the hydrochemical analysis, multiple methods and instruments were employed to quantify various ions in water samples:

- a multiparameter photometer HI83399 (Hanna Instruments) was used for the analysis of K^+, Al^{3+}, and Ca^{2+}. This device is equipped to provide high-precision measurements across a range of parameters, ensuring accurate readings of these essential ions.
- concentrations of Cl^-, SO_4^{2-}, Mg^{2+}, NO_3^-, and Fe were measured using the Hach DR 3900 photometer, with all analyses carried out using the pre-prepared reagent kits provided with the instrument.
- bicarbonate and sodium ion concentrations in water samples were determined using traditional titration methods based on conventional acid-base titration techniques, known for their reliability and accuracy.

The hydrophysical parameters of the water samples were measured using the multiparameter Orion (Thermo Fisher Scientific). This instrument allows for the simultaneous assessment of various physical properties of water, including temperature, pH, EC, and dissolved oxygen (DO), among others. The data collected provides essential insights into the overall water quality and complements the chemical analysis.

Hydrochemical diagram

Piper, Stiff, and Stabler diagrams were employed to identify hydrochemical facies, dominant ion associations, and spatial variations in groundwater composition, which are essential for understanding the hydrogeochemical processes controlling water chemistry. Wilcox's diagram was specifically selected to evaluate irrigation suitability by assessing salinity and sodicity hazards, directly supporting the agricultural water-use objective.

To analyze and classify the water samples, various hydrochemical diagrams were generated using the free software Diagramme (Simler, 2023). This software was selected for its ease of use, versatility, and ability to produce high-quality plots suitable for scientific analysis. It enabled efficient data processing and visualization, contributing to the detailed interpretation of the hydrochemical characteristics of the study area. The following diagrams were produced.

The Piper diagram was employed to display the relative proportions of major cations (calcium, magnesium, sodium, and potassium) and anions (chloride, sulfate, bicarbonate, and carbonate) (Piper, 1944). This trilinear plot helps in identifying the hydrochemical facies and classifying the water types present in the study area (Aly et al., 2024; Chafouq et al., 2018; Hendrayana et al., 2024; Landar et al., 2024).

Stiff diagrams were used to represent the ionic composition of the water samples (Stiff Jr, 1951). These polygonal plots visually compare the chemical makeup of different samples, allowing for the detection of similarities or variations (Bourjila et al., 2023).

The Stabler diagram was applied to provide a quick visual comparison of the major ions in the water (Hoyt & Stabler, 1935). This method highlights the dominant cations and anions, facilitating the assessment of water chemistry patterns (Remmani et al., 2021).

To classify the suitability of water for irrigation, Wilcox's diagram (sodium percentage vs. electrical conductivity) was employed (Wilcox, 1955). These diagrams are critical for evaluating the risk of salinity and sodicity in soils, ensuring that irrigation practices remain sustainable.

Water Quality Index

The development of WQI is essential for accurately defining the qualitative status of groundwater resources within the study area (Table 2), making it a valuable tool for the preliminary assessment of water quality conditions (Bouhout et al., 2024; Naz et al., 2024). The WQI is derived from various parameters that influence the overall water quality. These parameters include ionic groups, as well as physical and chemical factors (Nazif, 2024). The WQI approach assumes that groundwater quality can be effectively represented through the weighted aggregation of key physico-chemical parameters, an assumption widely adopted for preliminary and regional-scale groundwater quality evaluations. Twelve key physico-chemical parameters were used to calculate the WQI for the study area to evaluate drinking water quality (Table 3). These parameters were compared against WHO permissible limits for drinking water, following the WQI calculation formula (Brown et al., 1972):

$$W_i = K / S_n \tag{1}$$

$$K = 1 / \left(\sum 1 / S_n \right) \tag{2}$$

$$Q_i = \left(\left(V - V_i \right) / \left(S_n - V_i \right) \right) \cdot 100 \tag{3}$$

$$WQ_i = \left(\left(\sum n_i = 1 W_i \cdot Q_i \right) / \left(\sum n_i = 1 W_i \right) \right) \tag{4}$$

Where:

W_i = relative weight of the physicochemical standards of water.

K = proportionality constant

S_n = maximum permissible value for standards (mg/L)

Q_i = sub-coefficient of n standards

V = analyzed value (mg/L)

V_i = ideal values (equal to zero for each physiochemical criterion, except pH equal to 7).

Tab. 2 - Water quality classification (Brown et al., 1972).

Tab. 2 - Classificazione della qualità dell'acqua (Brown et al., 1972).

WQI	Water quality classification
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
More than 100	Unfit and unsuitable for drinking

Tab. 3 - The parameters used for WQI index calculations.

Tab. 3 - Parametri usati per il calcolo dell'indice WQI.

Parameters	WHO
pH	8.5
EC (μs/cm)	1500
TDS (ppm)	1000
Cl^- (mg/L)	250
K^+ (mg/L)	12
Al^{3+} (mg/L)	0.2
Ca^{2+} (mg/L)	75
Na^+ (mg/L)	200
SO_4^{-2} (mg/L)	250
Mg^{2+} (mg/L)	50
NO^{3-} (mg/L)	50
Fe^{2+} (mg/L)	0.3

Results and discussion

Physico-chemical parameters analysis

Table 4 presents the results of the chemical and physical analysis of the water samples, providing detailed data on various water quality parameters. Table 5 offers a summary of these chemical and physical parameters, comparing them to the standards set by the WHO (WHO, 2022) and MN regulations (MN 03.7.001, 2006). Additionally, Table 5 highlights the number of samples that exceed the permissible limits established by these standards.

- The physico-chemical analysis of groundwater in the Boudinar Basin revealed that pH values ranged between 7.70 and 8.15, indicating that the water is mostly neutral to slightly alkaline and suitable for drinking (WHO & MN limits: 6.5–8.5), consistent with previous studies in the Rif belt (Bourjila et al., 2024b; Errahmouni et al., 2024).
- EC, which measures water's ability to conduct electricity due to dissolved salts, ranged from 1226 to 3245 μS/cm. Thirteen samples (W02, W03, W04, W07, W08, W09, W10, W11, W12, W13, W14, W15, and W16) exceeded the WHO standard, and three samples (W03, W12, and W13) exceeded the MN standard, highlighting salinity issues in some areas, similar to observations in the Bokoya Massif and the Ghis-Nekor Basin to the west (Bouhout et al., 2024; Bourjila et al., 2024a; Errahmouni et al., 2024).
- TDS varied from 617 to 1629 mg/L, with ten samples exceeding the WHO recommended limit of 1000 mg/L, reflecting wide variability in water quality. Elevated TDS may affect taste and suitability for consumption and could originate from geogenic sources or human activities (Al-Bahathy et al., 2024; Xiao et al., 2023).
- Chloride concentrations ranged from 18 to 158 mg/L, remaining below WHO (250 mg/L) and MN (750 mg/L) limits, suggesting minimal saltwater intrusion or pollution (Yang et al., 2023). Sodium levels were acceptable (43–71 mg/L), well below the WHO limit of 200 mg/L. Nitrate concentrations (0.2–9 mg/L) were within WHO and MN limits of 50 mg/L, indicating limited influence from agricultural runoff (Thayalakumaran et al., 2008). Iron concentrations ranged from 0.02 to 0.13 mg/L, remaining below both WHO and MN limits (0.3 mg/L).
- Calcium concentrations varied significantly, from 56 to 227 mg/L, with most samples exceeding the WHO guideline of 75 mg/L, potentially affecting water hardness and taste (Kozisek, 2020). Aluminum levels ranged from 0 to 0.34 mg/L, with five samples (W01, W04, W06, W07, and W08) exceeding the guideline, which could pose health risks, including a potential link to Alzheimer's disease (Rondeau et al., 2000). Magnesium concentrations (31.1–52.3 mg/L) were close to the WHO guideline of 50 mg/L, with several samples (W04, W08, W12, and W16) slightly exceeding this limit. Potassium, sulfate, and bicarbonate concentrations were all within acceptable limits set by both WHO and Moroccan standards.

As shown in Table 1, most groundwater samples are associated with alluvium and silt deposits, which are characterized by high porosity and permeability, allowing active groundwater circulation and making them more vulnerable to surface influences such as agricultural activities and dissolved salts. Two samples (W01 and W08) occur in sericite gray shale, a low-permeability formation where groundwater chemistry is mainly controlled by water–rock interactions. Samples W02 and W12 are located in marl formations, whose carbonate content can influence groundwater composition through dissolution processes, particularly increasing calcium and bicarbonate concentrations.

Tab. 4 - Results of chemical and physical analysis of groundwater samples.

Tab. 4 - Risultati dell'analisi chimica e fisica dei campioni d'acqua sotterranea.

Sample ID	Chemical parameters (mg/L)										Physical parameters			
	Cl^-	K^+	Al^{3+}	Ca^{2+}	HCO_3^-	Na^+	SO_4^{2-}	Mg^{2+}	NO_3^-	Fe^{2+}	pH	DO %	EC (µS/cm)	TDS (ppm)
W01	45.7	3.4	0.30	131	360	55.17	49	49.4	0.50	0.074	8.03	22.1	1445	730
W02	120.4	1.3	0.00	130	434	45.98	55	48.9	2.02	0.067	7.82	22.8	2419	1220
W03	210.0	2.9	0.00	227	502	57.47	62	38.1	1.46	0.092	7.89	22.2	3245	1629
W04	141.0	0.9	0.27	163	346	71.26	53	52.3	4.88	0.090	7.70	22.1	2327	1166
W05	18.7	2.6	0.01	182	588	45.98	45	31.8	0.20	0.133	7.90	21.9	1238	617
W06	53.2	1.3	0.34	163	475	43.68	25	39.6	6.87	0.061	7.97	21.2	1226	813
W07	158.9	2.7	0.28	154	678	62.07	45	40.5	3.53	0.054	7.99	21.9	2604	1311
W08	131.8	1.7	0.31	131	360	50.57	44	51.7	5.45	0.031	7.76	21.6	2251	1092
W09	134.2	1.7	0.00	178	561	50.57	42	50.0	6.51	0.026	7.81	21.9	2383	1194
W10	107.6	5.8	0.07	99	817	68.97	34	31.4	3.57	0.048	8.15	21.5	2137	1048
W11	61.1	8.8	0.04	56	927	55.17	36	32.9	13.40	0.056	8.13	21.5	2410	1222
W12	139.3	5.8	0.00	131	410	85.06	66	50.2	1.56	0.087	7.90	21.6	2726	1374
W13	77.7	3.7	0.00	68	534	55.17	19	35.0	9.13	0.053	8.06	21.3	1750	877
W14	78.2	4.3	0.02	114	549	57.47	17	31.1	6.78	0.072	7.97	21.3	1669	943
W15	34.7	3.7	0.00	97	432	45.98	15	34.0	9.05	0.062	7.95	21.3	1520	740
W16	134.7	1.2	0.00	127	556	45.98	62	50.6	0.86	0.097	7.85	21.7	2774	1393

Tab. 5 - Summary of chemical and physical parameters of groundwater samples compared to WHO and MN standard, and summary of samples that exceed standard.

Tab. 5 - Riepilogo dei parametri chimici e fisici dei campioni d'acqua sotterranea rispetto agli standard WHO e MN e riepilogo dei campioni che superano lo standard.

Parameters	Minimum	Maximum	Means	WHO	Number of samples exceeding WHO	MN	Number of samples exceeding MN	MN limit for Irrigation
pH	7.70	8.15	7.93	6.5 – 8.5	0	6.5-8.5	0	6.5-8.4
Conductivity (µs/cm)	1226	3245	2132	1500	13	2700	3	12000
TDS (ppm)	617	1629	1085	1000	10	2000	0	7680
Cl^- (mg/L)	18.7	210.2	102.0	250.0	0	750.0	0	-----
K^+ (mg/L)	0.9	8.8	3.2	12.0	0	-----	-----	-----
Al^{3+}(mg/L)	0.00	0.30	0.10	0.20	5	0.20	5	5.00
Ca^{2+}(mg/L)	56	277	134	75	14	-----	-----	-----
HCO_3^-(mg/L)	346	927	533	-----	-----	-----	-----	-----
Na^+(mg/L)	43.68	71.26	56.47	200.00	0	-----	-----	-----
SO_4^{2-}(mg/L)	15	66	41	250	0	400	0	250
Mg^{2+}(mg/L)	31.1	51.7	41.4	50.0	4	-----	-----	-----
NO_3^-(mg/L)	0.20	9.13	4.16	50.00	0	50.00	0	-----
Fe^{2+}(mg/L)	0.026	0.133	0.079	0.300	0	0.300	0	5.000

Diagram analysis

Piper diagram

The Piper diagram (Fig. 2) shows that the water samples are characterized by low relative proportions of Mg^{2+} and Cl^-, as evidenced by their proximity to the zero end of the respective axes. In the cation triangle, Ca^{2+} is the dominant cation, while $Na^+ + K^+$ contents are higher than those of Mg^{2+}. In the anion triangle, $HCO_3^- + CO_3^{2-}$ clearly dominate over $Cl^- + NO_3^-$ and SO_4^{2-}. The dominant hydrochemical facies identified in the study area is the $Ca–HCO_3$ type. This facies is typically associated with groundwater circulating through carbonate-rich geological formations, where the dissolution of calcite and dolomite minerals controls the chemical composition of the water (Errahmouni et al., 2022; Greiserman et al., 2016).

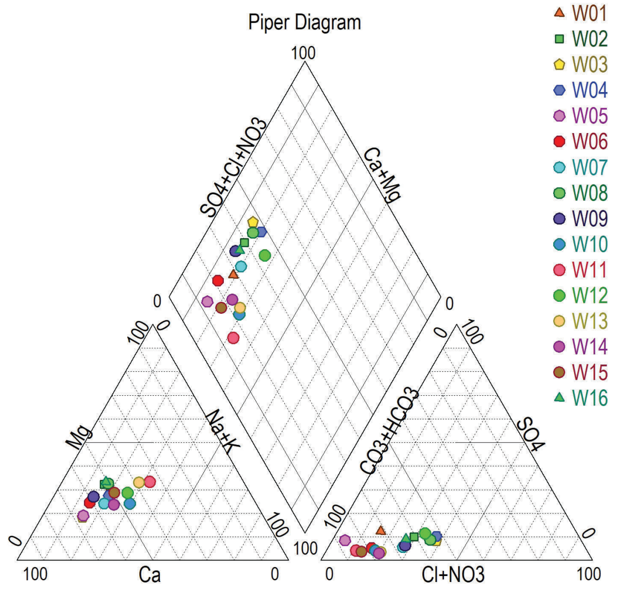

Fig. 2 - Piper diagram of groundwater in the Boudinar basin.

Fig. 2 - Diagramma di Piper delle acque sotterranee nel bacino di Boudinar.

Stabler diagram

The stabler diagram (Fig. 3) shows that the tendency of the cations in all wells follows the order $Ca^{2+} > Mg^{2+} > Na^+ > K^+$, with calcium being the dominant cation, while the anions follow the order $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$, with bicarbonate as the dominant anion. The dominance of calcium (Ca^{2+}) and bicarbonate (HCO_3^-) in all wells suggests that the groundwater in the Boudinar watershed is influenced by the dissolution of carbonate minerals, such as limestone or dolomite (Greiserman et al., 2016).

Stiff diagrams

Based on the Stiff diagrams in Figure 4, which were compared to those described by (Hounslow, 2018), most of the samples exhibit characteristics typical of water influenced by calcium carbonate-rich rocks, such as limestone or dolomite, with notable concentrations of Ca^{2+} and HCO_3^-. Samples W03, W05, W06, W07, W09, W10, W11, W13, W14, and W16, drawn from alluvium and silt deposits, show a broader range of ion concentrations. The remaining samples (W01, W02, W04, W08, W12, and W15) do not exhibit particularly distinctive hydrochemical characteristics. These diagrams reflect a mixture of ions, possibly due to interactions with limestone, dolomite, or gypsum present in the alluvial deposits. The heterogeneity in ion content suggests varied sources, including dissolved salts from nearby formations.

Fig. 3 - Stabler diagrams of groundwater in the Boudinar basin.

Fig. 3 - Diagramma di Stabler delle acque sotterranee nel bacino di Boudinar.

Wilcox diagram

A Wilcox diagram was generated using two parameters: (1) conductivity (µS/cm) and (2) Na% (Fig. 5). The analysis revealed that six samples (37.5%) fell into the good category, suitable for all irrigation purposes. Meanwhile, nine samples (56.25%) were classified as poor, and one sample (6%) was categorized as bad. Although water in the poor category is not ideal for irrigation, it may still be used under controlled conditions. Specifically, appropriate surface and subsurface drainage systems are required to prevent salt accumulation in the root zone. In addition, selecting salt-tolerant crops, applying periodic leaching practices, and carefully managing irrigation scheduling can help mitigate the adverse effects of salinity. Without these management strategies, prolonged use of such water may lead to soil salinization, reduced soil permeability, and decreased agricultural productivity. (Landar et al., 2024). According to Moroccan irrigation standards, as shown in Table 5, all recorded values of chemical and physical parameters of water samples fall within the acceptable limits established by Moroccan national guideline (Secrétariat d'Etat auprès du Ministère de l'Energie, des Mines, 2007).

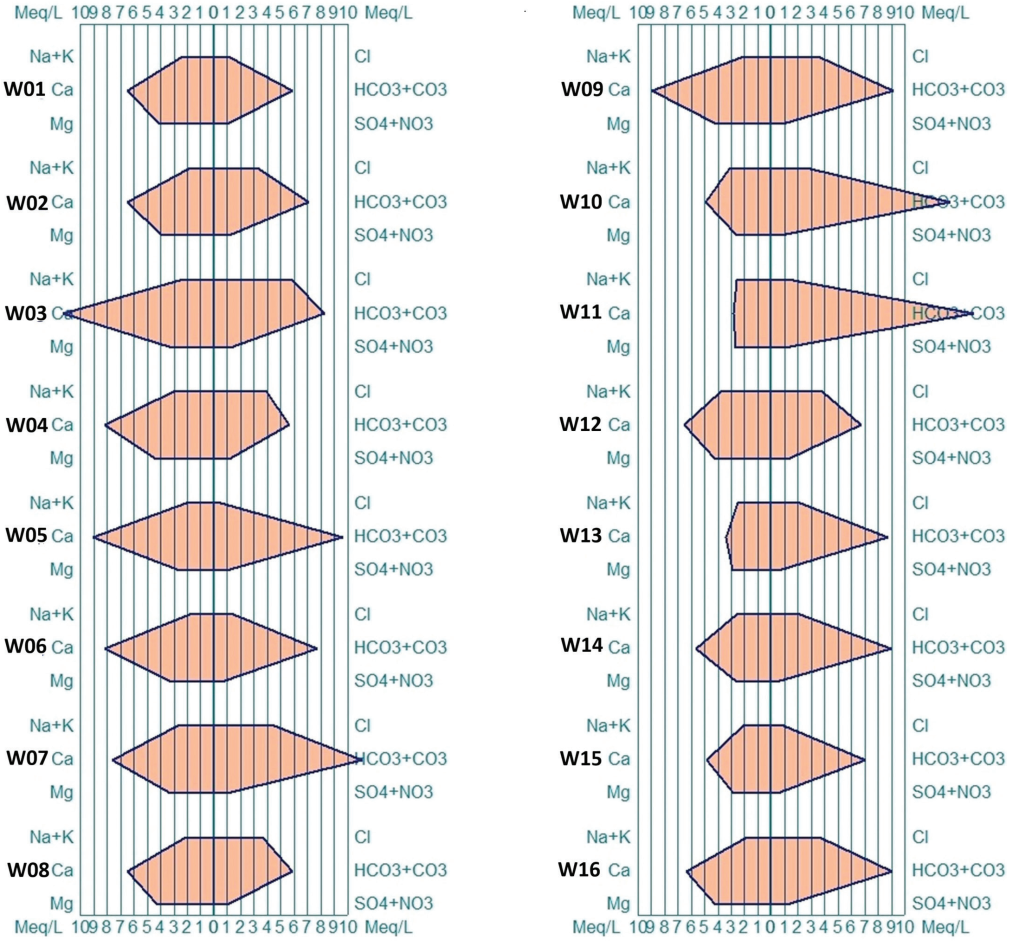

Fig. 4 - Stiff diagrams of groundwater in the Boudinar basin.

Fig. 4 - Diagramma di Stiff delle acque sotterranee nel bacino di Boudinar.

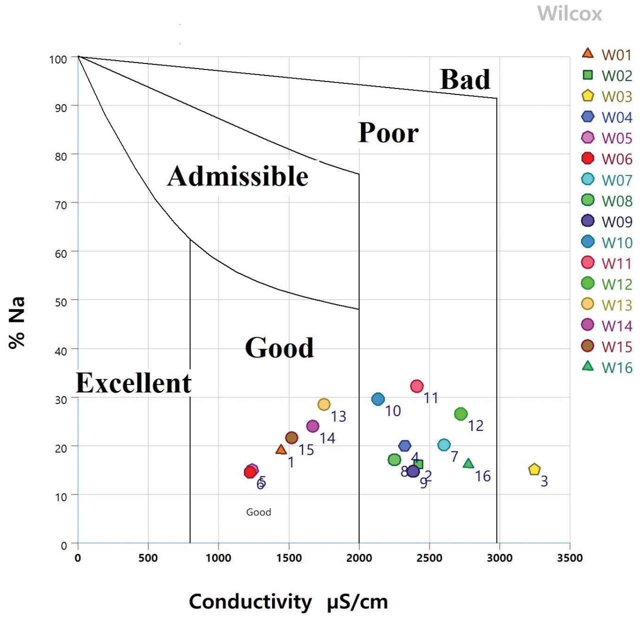

Fig. 5 - Wilcox diagram of groundwater analysis in the Boudinar basin.

Fig. 5 - Diagramma di Wilcox delle acque sotterranee nel bacino di Boudinar.

Water Quality Index analysis

WQI results for the 16 groundwater samples from the Boudinar basin (Table 6) show a wide range of water quality, with WQI values spanning from 4 to 108. Most samples W02, W03, W05, W07, W09, W11, W12, W13, W14, W15, W16) are classified as excellent (WQI 4–21), while one sample (W10, WQI 28) is good. Samples W01, W04, and W08 fall into the very Poor category (WQI 91–98), and W06, with the highest WQI of 108, is unfit for all uses. Overall, 75% of the sampled water is suitable for drinking or other purposes, whereas 25% require attention due to poor quality. Compared to other regional studies, water quality in the Boudinar Basin is relatively favorable. For instance, 60% of water in the Bokoya Massif was found to be excellent, good, or permissible (Benaissa et al., 2022), 44.79% in Bouaissa et al. (2021), and only 6% in the Ghis Nekor basin (Yousfi et al., 2022). Spatially, the WQI-based classification (Figure 6) highlights excellent water quality in the northern and central regions, particularly near Ayat Tayar, Boudinar, Ifasiyen, and Anoual, indicating relatively clean groundwater in these areas. Good water quality is observed at one central site near Anoual, suggesting minor local concerns. Conversely, several sites in the central and southern regions, including W01, W04, and W08, show very poor water quality, while W06 near Temsaman is unfit for drinking, reflecting localized contamination or significant water quality degradation. These results indicate that groundwater in the northern part of the basin is generally favorable, while the central and southern zones face more serious water quality challenges requiring targeted management.

Tab. 6 - WQI index of groundwater samples of the Boudinar basin.

Tab. 6 - Indice WQI dei campioni di acqua sotterranea del bacino di Boudinar.

Sample	WQI level	Water Quality status
W01	98	Very poor
W02	10	Excellent
W03	13	Excellent
W04	91	Very poor
W05	21	Excellent
W06	108	Unfit for all uses
W07	4	Excellent
W08	95	Very poor
W09	5	Excellent
W10	28	Good
W11	20	Excellent
W12	13	Excellent
W13	8	Excellent
W14	16	Excellent
W15	9	Excellent
W16	13	Excellent

Conclusions

This study represents the first integrated hydrogeochemical assessment of groundwater quality in the Boudinar Basin, combining field sampling, hydrochemical diagrams (Piper, Stiff, Stabler, and Wilcox), and the WQI. The results demonstrate that groundwater chemistry is predominantly controlled by natural geogenic processes, particularly the dissolution of carbonate rocks, which gives rise to the Ca–HCO_3 hydrochemical facies in 12 out of 16 sampled wells (75%). The predominance of high calcium concentrations suggests that carbonate mineral weathering plays a significant role in controlling groundwater chemistry, contributing to increased hardness in many samples. In addition, the detection of elevated aluminum and magnesium levels in a limited number of wells indicates localized geochemical anomalies that may require periodic monitoring due to potential health implications.

From an agricultural perspective, groundwater remains largely suitable for irrigation according to Moroccan standards. The Wilcox diagram reveals moderate salinity and sodium hazards in several locations. This suggests that long-term irrigation using these waters may require appropriate soil and water management practices to prevent salinization.

The WQI highlights spatial variability in groundwater quality, with most wells classified as suitable for drinking, while a few wells exhibit poor to unsuitable quality. These degraded conditions correspond to areas where higher mineralization and trace element concentrations were detected, confirming the reliability of the WQI as an integrated assessment tool.

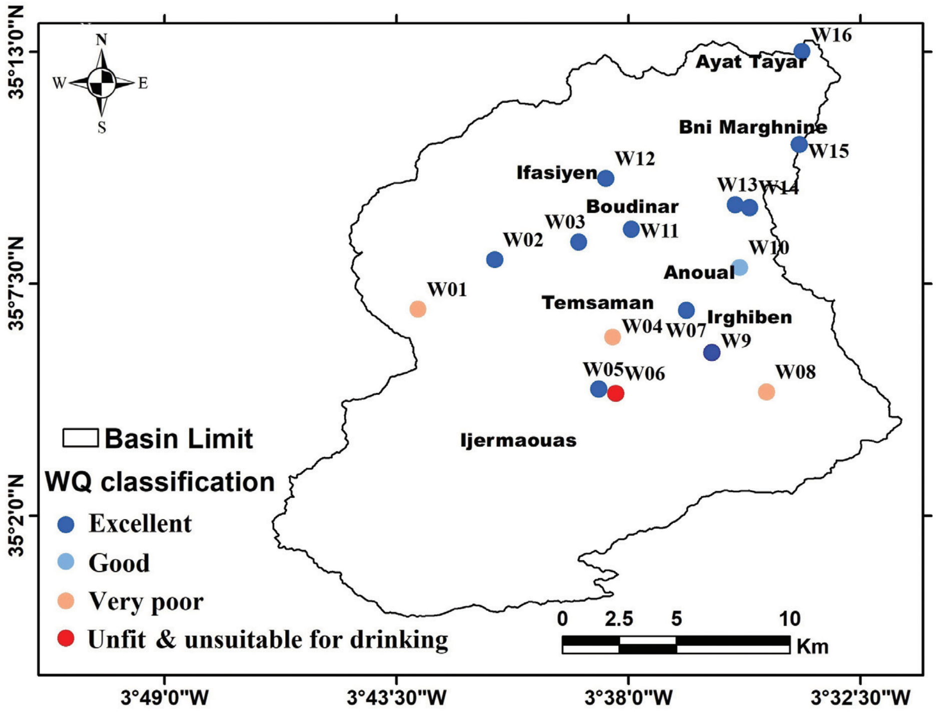

Fig. 6 - Spatial distribution of water quality in the Boudinar basin.

Fig. 6 - Distribuzione spaziale della qualità dell'acqua nel bacino del Boudinar.

Groundwater in the Boudinar Basin is generally suitable for domestic and agricultural use, but localized anomalies in EC, TDS, calcium, magnesium, and aluminum highlight areas of concern. The integrated use of hydrochemical diagrams, WQI, and spatial mapping provides a robust framework for understanding the geogenic and anthropogenic factors controlling water quality. Future work should focus on establishing a detailed hydrogeological framework, including piezometric monitoring, isotopic tracing, and geochemical modeling, to refine the understanding of aquifer dynamics, solute transport, and vulnerability, thereby supporting sustainable management of groundwater resources in the basin.

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Competing interest

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AI Use Declaration Statement

The authors used ChatGPT during the writing process to improve readability, grammar, and clarity of the manuscript. All AI-generated suggestions were carefully reviewed and verified for accuracy by the authors. The authors confirm that the AI tool is not listed as a co-author.

Author contributions

TM: field work, data processing, interpretation of results, writing original draft preparation. HCD: visualization. ie: review and editing. NZ: data processing. ab: writing draft preparation, data processing.ma: data processing. AE: data processing. AM: writing-review and editing. All authors have read and agreed to the final version of the manuscript.

Additional information

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