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The contribution of water quality index and principal component analysis to groundwater quality assessment: A case study of the Wadi Moulay Bouchta catchment, northern Morocco

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ABSTRACT

This study focuses on contributing to hydrogeochemical knowledge and enhancing groundwater quality within the hydrogeological catchment area of the western zone of Talassemtan National Park, Northern Morocco, employing classical hydrogeochemical and bacteriological methods, water quality index calculations, and descriptive statistical analysis. The research examines hydrogeological, hydrogeochemical, and bacteriological data from groundwater flowing through detrital and carbonate sedimentary rocks. Geographically situated within the Flysch zone and the Rif calcareous chain in Northern Morocco, the area features springs predominantly located along principal abnormal contacts linking aquifer formations with aquiclude formations. The region encompasses three aquifer systems: the Beni Ider flysch aquifer system/Tangier unit, the Quaternary aquifer system/Tangier unit, and the calcareous-dorsal aquifer system/Tangier unit, with the calcareous-dolomitic and detrital geomorphological units serving as the primary reservoir. Natural aquifer recharge correlates closely with direct rainfall. Physical parameters were measured in situ, while laboratory analyses determined chemical and bacteriological characteristics. Chemical analyses utilized spectrophotometry, titration, and inductively coupled plasma atomic emission spectroscopy (ICP-AES). In contrast, bacteriological analyses employed the membrane filtration technique on twenty groundwater samples sourced from springs, boreholes, and traditional wells. These analyses identified key factors influencing water mineralization. The study assessed water quality by examining physico-chemical and bacteriological parameters, finding that the aquifer systems generally contained nitrate-free water of excellent to bad quality. The water quality index (WQI) and principal component analysis (PCA) confirmed these findings. The prevalent water type in the area was characterized as bicarbonate-calcium. Electrical conductivity (EC) and percentage sodium classification (%Na) classified all water samples as good or relatively good quality for irrigation. However, when considering electrical conductivity and percentage sodium classification (%Na), 95% and 5% of groundwater samples were classified as excellent and good water quality, respectively.

Keywords: aquifer-system, groundwater, water quality index, principal component analysis, irrigation, hydrogeochemistry, Talassemtan national park, sustainable rural development.

INTRODUCTION

Water is a vital and intricate resource essential for human existence. Access to this crucial resource has become a strategic and sovereign concern. The demand for drinking water is expected to significantly increase in the coming years, primarily due to population growth and irrigated agriculture. Consequently, groundwater resources are being depleted and contaminated at an alarming rate, posing a threat to water security (Blanco and Donoso, 2021).

According to the latest data from the World Resources Institute (August 2023), Morocco is experiencing a severe water shortage crisis and is classified among the most affected by drought. Morocco must substantially mitigate a potential water shortage crisis in the upcoming decade. Numerous studies have been conducted, all highlighting the scarcity of water resources, excessive usage, deterioration in quality, and inadequate management (Analy and Laftouhi, 2021; Beny-oussef and al., 2024). To this is added water scarcity, distribution remains uneven geographically and temporally (Ait Dhmane et al., 2024).

The groundwater issue holds significant importance in Morocco's political and economic spheres. The country's water challenges, particularly in rural areas, have been exacerbated due to recent droughts and climate change (El Mountassir et al., 2022). Uncontrolled exploitation has also degraded water quality: nitrates and coliforms often exceed health standards (Elbarghmi et al., 2024), with increasing salinisation due to intensive agricultural activities and marine intrusion (Sanad et al., 2024). Furthermore, in strategic planning, water quality monitoring is crucial. The link between water quality and public health is strong, and even if a water source or borehole can provide a substantial quantity, the water itself may be unsuitable for consumption. Therefore, conducting research, promoting development, and valuing every cubic meter of this vital resource is imperative.

This study represents the first of its kind in the region. It employs traditional hydrogeological methods, the water quality index, and a descriptive statistical approach. The objective is to analyze and process groundwater hydrogeochemical and bacteriological data from geological formations (detrital and carbonate).

The study area lies in northern Morocco, within the northern Rif region. It covers part of the Flysch aquifer and extends into the Calcareous Dorsal northwest of Talassemtane National Park. The Quaternary deposits of the limestone-dolomitic and detrital geomorphological unit act as a major groundwater reservoir in this area. Natural recharge of these aquifers is directly linked to precipitation. The Talassemtane and Bouhachem National Parks, recognized by UNESCO as part of Morocco's exceptional heritage, are known for their outstanding biodiversity and belong to the Mediterranean Intercontinental Biosphere Reserve (El Karmoudi et al., 2025). While decision-makers have shown strong commitment to conserving biodiversity, hydrogeological heritage continues to receive much less attention.

This study therefore seeks to advance hydrogeochemical and bacteriological understanding of groundwater in the Moulay Bouchta Wadi hydrogeological basin. The focus lies on evaluating water quality using the water quality index (WQI), identifying recharge mechanisms, and exploring potential uses. Located at the interface of two UNESCO-listed national parks and increasingly shaped by demographic growth, rising ecotourism, and recent infrastructure development, the area represents a strategic setting where the promotion and sustainable management of groundwater resources and hydrogeological heritage are critically important (Dawood et al., 2022; Krishan et al., 2023).

Geographical and socio-economic characteristics of the study area

Covering an area of 1865 hectares, the study area is situated in the northern region of Morocco, specifically within the north of Rif, delineated by the following Lambert coordinates: X_{Min} = 497500 m, X_{Max} = 510000 m, Y_{Min} = 517500 m, and Y_{Max} = 527500 m (refer to Figure 1). Renowned for its rich biodiversity, the area is recognized as one of the national parks most frequented by tourists (Aoulad-Sidi-Mhend et al., 2020). From a geological perspective, it falls within the flysch nappes and calcareous dorsal domain, which are integral components of the Rifian chain located west of Chefchaouen City.

It is worth mentioning that the socio-economic background of the area under study was rural and of a mixed economy type including small holder agriculture with advancing trends of rural tourism due to the high proximity of the Talassemtan and Bouhachem national parks. The better quality of groundwater which is applicable for irrigation purpose improves both productivity and sustainability of agro-ecotourism project. Climate threats, including climate change, add to the necessity to preserve water quality especially for irrigation facilities and soil conservation (Boubou et al., 2025).

Groundwater plays a crucial role in the socio-economic development of most rural Mediterranean regions, serving as the main source for meeting human drinking water needs, irrigation, and small-scale artisanal and industrial uses. Its strategic importance is further heightened by increasing demographic pressure (High Commission for Planning, 2015), the impacts of climate change, and the expansion of tourism, all of which contribute to a growing demand for groundwater resources (WWAP, 2022).

Geological and hydrogeological context

Geological context

The area is in part in the internal domain (calcareous dorsal), in part in the external one (unit of Tanger) and in the flysch nappes of the Riffian chain (Saidi et al., 2002; Wildi, 1983) (Figure 1). This latter is known for its significant structural complexity and multiple thrust contacts within the geological units (Durand-Delga, 1972).

- The calcareous dorsal represents the internal domain of the Riffian chain. It is composed of several units, including: (i) the unit of Bettara (sandstone, conglomerates, and marls of Oligocene age overlying lower early limestones at the base), (ii) the unit of Arifane (with at the top an Oligocene terrigenous formation made by sandstone, conglomerate and marl, lying over thick basal Triassic – early massive carbonated formation, (iii) El Babat nappe (Triassic – early formation made by red detrital formation, dolostone and white massive limestone with at the top Paleogene formation made by polygenic conglomerates), (iv) Hafa Ferkennix nappe; with at top Oligocene formation made by sandstones, conglomerates and marls, and Triassic-Hettangian massive dolostone and Sinemurian massive white Limestones partially dolomitized (Didon et al., 1973).
- The Tanger unit represents the external domain and is characterized by an upper Cretaceous succession. At the top, there is a marl interbedded with micro-breccias, while at the bottom, there are the clay, siltstone, and some thick-layered siliceous calcilutite grading into flint (silex). The Tanger unit has been extensively affected by the flysch nappes and the inner domain. (Didon et al., 1973; Didon and Hoyez, 1978).
- The flysch nappe formations, including the Beni Ider nappe with Eocene calcarenites and Oligocene micaceous sandstones, and the Melloussa nappe characterized by schisto-quartzite flysch of Albian-Aptian age, phthanites of Cenomanian age, and upper Cretaceous "marl-schist", overthrust the external zones (Durand-Delga et al., 1960; Gimeno-Vives et al., 2020).
- The Predorsalian unit consists of marls with thin-bedded sandstones, a flysch sequence, and Numidian-like sandstone from the Oligocene age. It also includes marl-limestone with Saccocoma from the Malm age. These outcrops are found between the internal and external zones of the Rif and the Betic Cordilleras (Durand-Delga, 1972).
- The main southwest slopes of the calcareous dorsal exhibit glacis, which is a paved slope.

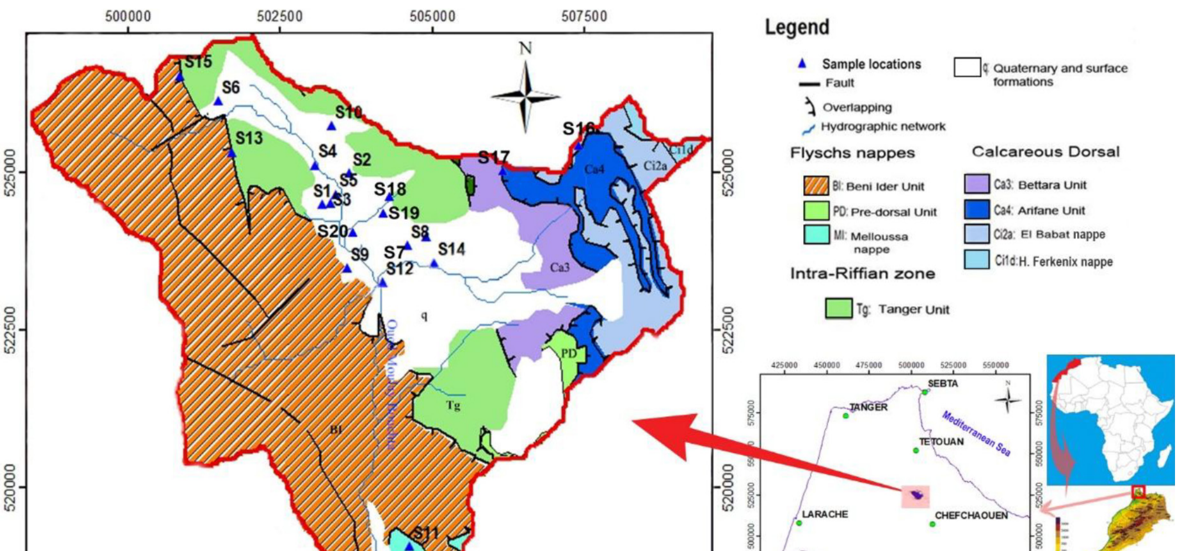

Figure 1. Structural map of water supply points in the Wadi Moulay Bouchta catchment area

The rock peaks in this area are partially covered by dwarf vegetation.

Hydroclimatic characteristics and hydrogeological context

The western zone of Talassemtane National Park includes a large catchment area comprising the Wadi Moulay-Bouchta catchment area, as well as other sub-basins and small temporary or torrential streams. These watercourses carry substantial amounts of water towards infiltration zones that are essential for recharging the park's aquifers. Moreover, there are lakes and ponds situated at the peak of the Calcareous-Dorsal (Figure 1). The climate in this region, known as the Rif, is of the Mediterranean type, characterized by hot and dry summers, and cold and moderately humid winters, with annual precipitation surpassing 1.600 mm per year, so it's considered one of the rainiest zones in Morocco (Figure 2).

The study area contains two types of aquifers: cracked aquifers and porous aquifers (Figure 2). The area's hydrogeological watershed is marked by aquifer units of varying lithological composition. Typically, the lower boundary of these subterranean water layers is defined by an impermeable layer known as the Bni-Ider nappe, along with the upper Cretaceous succession of the Tanger unit. The materials found in the Flyschs units, consisting of sandstone and clay, exhibit limited plasticity, yet ground instabilities are frequent. The existence of an extensive network of fractures allows for the formation of perched water sheets during the wet season, even within initially impermeable formations. The study area contains two types of aquifers: cracked aquifers and porous aquifers (Figure 2).

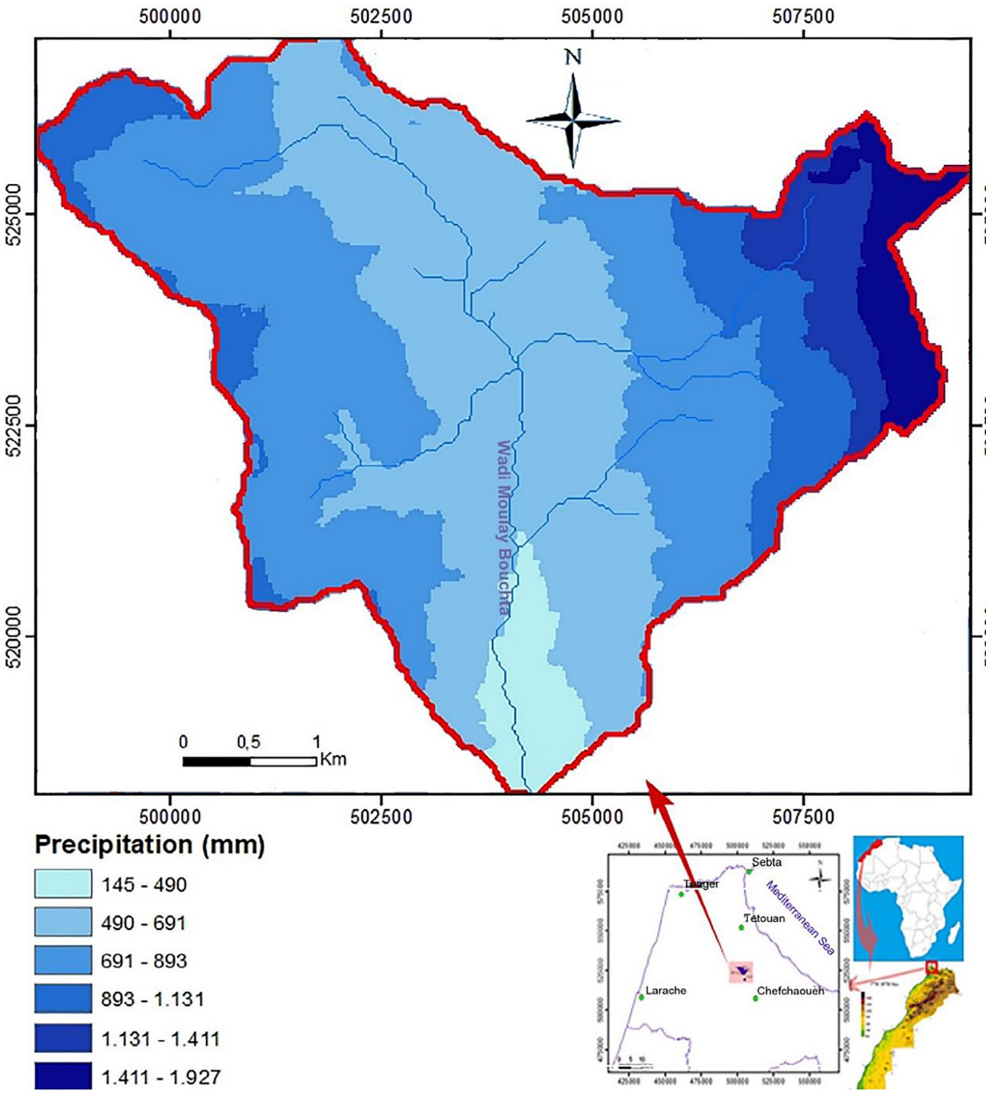

Figure 2. Spatial distribution of average annual precipitation in the Wadi Moulay Bouchta catchment area

MATERIALS AND METHODS

Data and materials

To investigate the area, we used a topographic map sourced from the Ministry of Agriculture with a scale of 1:50,000. Additionally, we consulted one geological map from the Ministry of Energy and Mines with scales of 1:500,000 and 1:50,000, and a structural map at a scale of 1:500,000 from the Ministry of Energy and Mines (Durand-Delga et al., 1960). To collect climatological data, we obtained information and contact details of weather stations from the Loukkous Hydraulic Basin Agency in Tetouan City.

Methods

Systematic sampling, measurements, and analyses were undertaken during a dry season (2022–2023) and a wet season (2022–2023). Water samples for chemical analysis were kept in plastic bottles. Two bottles were utilized: the primary 125 ml bottle for cations, acidified with 3 drops of concentrated HNO_3 (Acidification stabilizes the medium and prevents metal ion loss through precipitation or adsorption, preserving cation concentrations until analysis), and the secondary 125 ml bottle untreated for other analyses. When samples contained sediment, filtration was performed to ensure clarity. Prior to filling, sampling bottles were rinsed three times with the collected water. To ensure representative sampling, groundwater was pumped for more than three minutes, taking into account flow rate, pump capacity, and the piezometric level of the aquifer. For bacteriological analyses, clean and sterile plastic containers were used. The samples were kept under refrigerated conditions. All sampled water was immediately stored in a portable refrigerator maintained at 4 °C in situ.

In situ measurements included electrical conductivity (EC), temperature (°C), and pH. Temperature was measured with a digital thermometer equipped with a remote probe (CHECKTEMPR1 precision thermometer). pH was determined using a waterproof portable pH meter with an electrode (CONSORT C933) and verified with indicator strips (pH-Quick® roll, pH 1–11). Conductivity was measured with a waterproof portable multi-range conductivity meter with automatic temperature compensation.

Laboratory analyses included the quantification of major ions and selected physicochemical parameters. Calcium (Ca^{2+}) concentrations were determined by atomic absorption spectrometry, nitrate (NO_3^-) by UV spectrophotometry, sodium (Na^+) and potassium (K^+) by flame photometry, chloride (Cl^-) and bicarbonate (HCO_3^-) by titrimetric methods, and sulfate (SO_4^{2-}) by a colorimetric method. A maximum delay of 48 hours was observed for the analysis of major ions.

To ensure accuracy and comparability, chemical and bacteriological analyses were performed in three laboratories: the Chouaib Doukkali University analytical platform (El Jadida), the Chefchaouen Water Laboratory (Chefchaouen), and the Loukouss Hydraulic Basin Laboratory (Tetouan). All procedures followed the standardized Rodier protocol (Rodier et al., 2009).

Trace metal analyses were performed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-AES), model Perkin Elmer Optima 8000 DV (Norwalk, CT, USA), equipped with a cross-flow nebulizer and an AS 93-plus autosampler. High-purity argon (C-45, >99.995%) was used as the plasma, auxiliary, and carrier gas. The instrument operating conditions were as follows: RF power = 1.3 kW; plasma gas flow rate = 15 L/min; auxiliary gas flow rate = 2.0 L/min; nebulizer gas flow rate = 0.8 L/min; and sample uptake rate = 1.1 mL/min. Calibration was carried out using certified single-element standards (Perkin Elmer Pure) for each target element in a 2–5% HNO_3 matrix. Stock solutions (1000 µg/mL) were diluted with ultrapure water (18.2 MΩ·cm, Millipore Milli-Q) to prepare the calibration ranges. The calibration curves exhibited excellent linearity ($R^2 = 0.999$), demonstrating the robustness and reliability of the analytical measurements.

Quality assurance (QA) and quality control (QC) procedures were systematically applied. Certified standards, analytical blanks, and sample duplicates were analyzed to verify accuracy. Reproducibility was confirmed through repeated measurements, with relative standard deviations (RSD) below 5%. Detection limits (LOD) and quantification limits (LOQ) were calculated based on blank variance according to the 3σ and 10σ criteria, respectively (Armbruster and Pry, 2008).

The water quality was assessed based on classical techniques in hydrogeochemistry and bacteriology, PCA, and the WQI. WQI was calculated using the weighted arithmetic Water quality range as per (WAWQI) mean approach (Krishan et al., 2023). The whole process may seem complicated at first, but it can be broken down into important steps (Kadam et al., 2021):

a) Choosing the parameters – the methodology is predicated on the examination of the subsequent elements: major elements; the study encompassed various physicochemical parameters, including pH, calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), nitrates (NO_3^-), chlorides (Cl^-), sulfates (SO_4^{2-}), total hardness (TH), total alkalinity (TA), and total dissolved solids (TDS), All of these measurements together give a picture of the aquifer system's chemical signature (Chorol and Gupta, 2025). The study has broadened its analytical scope to encompass trace metal elements, which are typically regarded as secondary yet are essential for evaluating water safety. This level of testing looked for lead (Pb), chromium (Cr), zinc (Zn), copper (Cu), iron (Fe), cadmium (Cd), and aluminum (Al). These elements are known to be bad for you, even in small amounts. These metals are a sign of hydrochemical deterioration and long-term physical damage, whether they come from natural rock formations through geological processes or from human activities like industrial discharges or agricultural runoff. Counting them makes groundwater assessment models more accurate and fits with the new safety limits suggested by the WHO (2022). This makes for a stronger and more health-focused framework for water quality governance. The selection of these parameters is predicated on their acknowledged health implications (WHO, 2022), their prevalence in exploited aquifers, and their function as indicators of geochemical processes, including weathering, dissolution, or anthropogenic contamination.

b) Assigning weight (wi) – after that, we gave each of these water quality parameters a certain weight, which we called wi. Not all pollutants have the same effect on the quality of water. Some are just more dangerous than others. Table 1 shows how much each parameter is worth based on how important it is for health and the environment.

- Highest weight (4–5) – for parameters that pose a considerable health risk even at minimal doses (e.g., Pb, Cd, Cr, NO_3^-).
- Moderate weight (2–3) – for important factors that could be dangerous at high levels (like Fe, Na, and SO_4^{-2}).
- Lowest weight (1) – for elements that are usually not very harmful or toxic (e.g., Zn, Cu, and K).

c) Finding the relative weight (*Wi*) – to find the relative weight (*Wi*) of each parameter, use the formula (1):

Table 1. Comparative values of WHO and Moroccan standards, assigned weight (wi), and computed relative weight (Wi) for each physicochemical parameter

Parameter	WHO 2022 standard (Si, mg/L)	Moroccan standards (Si, mg/L)	Initial weight (wi)	Relative weight (Wi)
pH	6.5 – 8.5 (no units)	6.5 – 8.5 (no units)	4	0.052
TDS	1000	2000	4	0.071
TAC(F⁰)	200 (F⁰)	Not specified	3	0.09
Th (F⁰)	300 (F⁰)	Not specified	3	0,06
Ca^{2+}	120	Not specified	3	0.053
Mg^{2+}	50	Not specified	3	0.053
Na^+	200	300	3	0.053
K^+	12	Not specified	2	0.035
HCO_3^-	500	Not specified	2	0.087
Cl^-	250	750	5	0.053
SO_4^{2-}	250	500	5	0.071
NO_3^-	50	50	5	0.086
Pb	0.01	0.01	5	0.088
Cd	0.003	0.003	5	0.088
Cr	0.05	0.05	5	0.088
Zn	3	4	3	0.053
Cu	1	2	3	0.053
Fe	0.3	0.3	3	0.052
Al	0.2	0.2	3	0.053

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \quad (1)$$

where: wi – the weight of the *i-th* parameter, n – total number of parameters considered.

d) Quality assessment for each parameter (qi). To get the quality score (qi) for each parameter, do the following:

$$qi = (\frac{Ci}{Si}) \times 100 \quad (2)$$

where: Ci – the measured concentration of the *i-th* parameter in the sample, Si – the standard permissible limit of that parameter (WHO, 2022).

Sub-index calculation (SIi). The Sub-index for each parameter is:

$$SIi = Wi \times qi \quad (3)$$

The last step in figuring out the WQI. To get the overall index, add up all the SIi values:

$$WQI = \sum_{i=1}^{n} SIi \quad (4)$$

RESULTS AND DISCUSSION

Geochemical facies and parentage

The results of an in-depth hydrogeochemical study of twenty (20) groundwater samples taken from the different aquifer systems in the study area are summarized in Table 2. In situ temperature measurements of twenty groundwater samples from the three aquifer systems in the study area (Table 2) ranged from 13 to 16 °C, showing

Table 2. Synthesis of the statistical analysis of the physical-chemical parameters

Aquifer systeme	Physical-chemical parameters		T °C	pH	EC (25C°) (µs/cm)	TDS (mg/L)	Th (°F)	TAC (°F)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^- (mg/L)
	Sample	WHO standards	<25	6.5-8.5	<1500	< 500			< 120	< 50	< 200	< 12	< 500	< 250	< 250	< 50
Flysch	S13		14.8	7.2	558	374	2.9	20.92	89	16.51	20.12	1.4	255.2	58.8	15.04	0.09
	S15		14.7	7.7	479	321	2.6	21.86	64.13	25.51	3.5	0.6	266.71	25.08	18.63	0.05
	S6		15.9	7.32	536	359	2.7	21.79	83	15.31	21.13	1.5	265.8	37.8	20.11	0
	S11		13	7.21	763	511	3	18.77	108.21	7.29	9.5	0.4	228.94	108.52	11.75	0.02
	Max		15.9	7.7	763	511	3	21.86	108.21	25.51	21.13	1.5	266.71	108.52	20.11	0.09
	Mean		13.55	7.36	584	391.28	2.81	20.83	86.09	16.16	13.56	0.98	254.16	57.55	16.38	0.04
	Min		13	7.2	479	321	2.65	18.77	64.13	7.29	3.5	0.4	228.94	25.08	11.75	0
Calcareaus-Dorsal	S12		16	7.7	607	407	3.9	31.50	112.22	26.94	11	0.4	384.3	25.23	16.38	0
	S14		15.3	7.4	507	340	3	21.83	71.54	29.09	10.4	0.2	266.32	29.2	21	0
	S16		15.6	7.8	638	427	3.5	25.71	96.26	26.31	2.5	0.1	313.71	28.28	10.63	0
	S17		15.9	7.85	685	459	3.8	28.69	116.23	21.51	3.2	0.5	350.1	32.9	12.13	0
	Max		16	7.85	685	459	3.9	31.50	116.23	29.09	11	0.5	384.3	32.9	21	0
	Mean		15.7	7.69	609.25	408	3.5	26.93	99.06	25.96	6.8	0.3	328.6	28.9	15.04	0
	Min		15.3	7.4	507	340	3	21.83	71.54	21.51	2.5	0.1	266.32	25.23	10.63	0
Quaternary	S1		15.6	7.44	644	431	2.7	23.66	84.17	15.79	28.2	1.7	288.66	35.08	49.75	0
	S2		15	7.9	575	385	2.5	23.84	80.16	10.94	22.4	1.2	290.79	22.35	17.63	0
	S3		14.3	7.41	615	412	2.5	23.36	78.16	14.58	19.8	1.8	285	29.11	20.2	0
	S4		13.2	7.23	617	413	2.3	19.29	71	12.84	19.4	1.5	235.3	29.61	21.3	0
	S5		14	7.13	613	411	2.2	17.65	60	18.3	19.7	1.2	215.3	28.69	33.27	0
	S9		15.1	7.98	576	386	2.8	22.04	89.21	13.29	19.5	1.4	268.94	39.62	32.75	0
	S10		15.5	7.8	709	475	2.8	23.76	91.21	11.73	21.92	1.6	289.85	29.83	19.57	0
	S7		13.2	6.89	772	517	3.3	29.60	114	10.28	11.8	1.2	361.16	29.6	21.49	0.15
	S8		15.2	6.62	768	515	3.3	28.08	115	10.89	11.4	1.7	342.6	29.7	22	0.14
	S18		14	7.4	913	612	3.0	28.06	101.35	12.51	35.5	3.4	342.32	92.86	50.38	0.7
	S19		14	7.57	798	535	3.1	27.95	94.12	17.68	24.7	2.3	341	62.6	22	0.8
	S20		14.8	7.88	645	432	2.8	19.07	92.17	13.23	10.5	0.9	232.67	69.99	21	0.9
	Max		15.6	7.98	913	612	3.32	29.60	115	18.3	35.5	3.4	361.16	92.86	50.38	0.9
	Mean		14.5	7.44	687.08	460.35	2.78	23.86	89.21	13.51	20.4	1.66	291.13	41.59	27.61	0.22
	Min		13.2	6.62	575	385	2.25	17.65	60	10.28	10.5	0.9	215.3	22.35	17.63	0

that the groundwater temperatures were mostly low and stable. This thermal stability is due to the buffering effect of the aquifer's depth and matrix, which lessens the impact of changes in the climate on the surface. The values are in line with the idea that local rainwater is recharging the area and that there is active circulation through permeable formations (Kurylyk et al., 2013) keeping the thermal regime close to the average annual air temperature. These results show how the hydrogeological setting and regional climate affect the temperature of groundwater in Mediterranean areas.

The pH analysis indicates that the values vary from place to place, ranging from 6.62 to 7.98. This means that the aquifers usually have a chemical regime that changes slightly acidic and moderately basic conditions. This range shows how geochemical equilibria are affected by interactions between rock and water and localized mineralization processes.

In the study area, the electrical conductivity (EC) varies considerably between sampling sites, ranging from 479 µS/cm, typical of a well capturing the flysch aquifer system, to 913 µS/cm, recorded at a water point in the Quaternary aquifer. The maintenance of EC values below 1500 µS/cm is due to the slow dissolution of mineral phases in the aquifer matrix and the still low infiltration of anthropogenic pollutants (diffuse pollution). The combined action of these processes controls the balanced and high-quality ionic enrichment observed locally in the three aquifer systems.

The TDS of the area ranges from 321 to 612 mg/L, which corresponds to soft waters according to classical classifications. Total hardness values ranging from 2.25 to 3.9 confirm this observation, indicating the dominance of calcium and magnesium ions in the solution. The spatial variations in EC and TDS values are due to the geochemistry of the subsurface environment, under the influence of ion exchange, evaporation, sediment dissolution, and rainwater infiltration in the three systems. The analysis of anion concentrations shows a dominance of bicarbonate (HCO_3^-), with calcium bicarbonate being the dominant chemical species. The bicarbonate concentration values range from 215 mg/L (minimum level in the quaternary aquifer) to 384.3 mg/L (maximum level in a well capturing groundwater from the calcareous-dorsal aquifer) with an average of 291.29 mg/L for all samples. Among the cations, the calcium ion (Ca^{2+}) is the predominant species. The measured values range from 60 mg/L, the minimum level recorded in a well of the quaternary aquifer system, to 116 mg/L, the maximum level typical of a well of the Calcareous-Dorsal aquifer system. The average calcium content for all analyzed samples is 91.45 mg/L. This distribution of major ions shows the dominant impact of aquifer lithologies on the hydrogeochemical composition of groundwater in the study area.

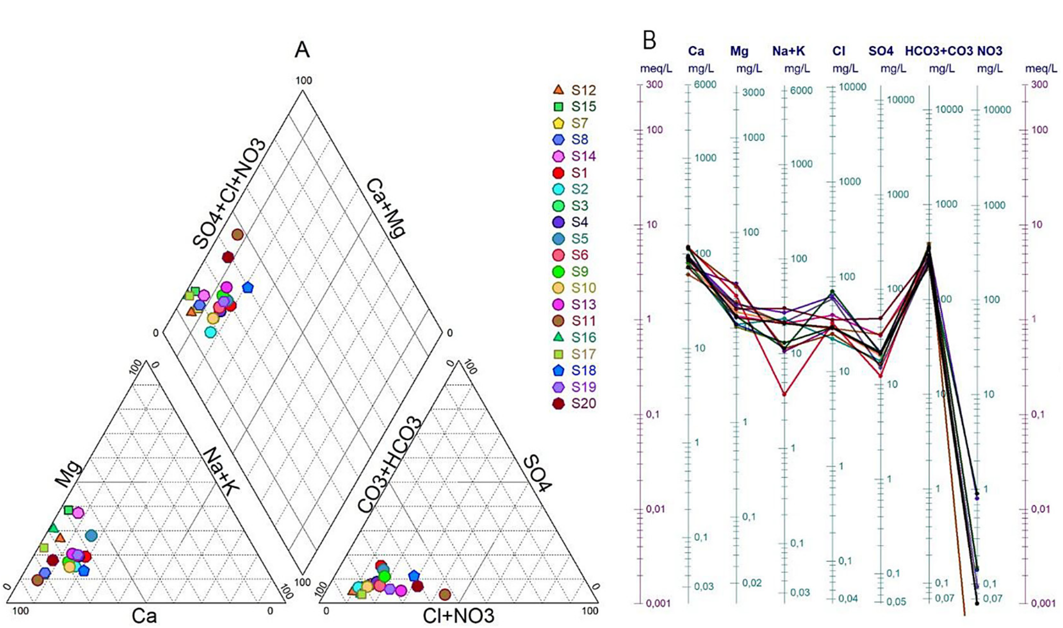

Figure 3. Semi-logarithmic and triangular diagrams, respectively designed by Schöeller-Berkaloff (B) and Piper(A), illustrate the water facies of the sources within the study area

We used semi-logarithmic (Schöeller–Berkaloff) and trilinear (Piper) diagrams (Figures 3 A and B) to show the hydrogeochemical facies of the groundwater we looked at. These graphical tools regularly reveal a calcic-bicarbonate facies (Figure 3), a pattern that aligns with the lithological and geological framework of the research area. The hydrogeochemical signs point to interactions with the Flysch formations (Beni Ider), the Calcareous-Dorsal units, and the Quaternary detrital deposits (Figure 2). These findings highlight the primary role of water–rock interactions, particularly dissolution and ion exchange processes involving carbonate and detrital lithologies, in controlling groundwater chemistry. A comparison between the high- and low-water periods reveals no significant differences in hydrogeochemical characteristics. The analyzed parameters remain generally stable, indicating a natural mineral water that retains the same hydrochemical facies throughout the year, except in the event of future modifications driven by hydrogeological, hydrodynamic, or structural changes in the study area. Comparable outcomes have been recorded in other Mediterranean aquifers. Calcic–bicarbonate facies are common in carbonate-dominated areas of southern Spain (Pulido-Velazquez et al., 2015), central Italy (Celico et al., 2010), and northern Tunisia (Hamed et al., 2010). In these places, the dissolution of carbonate and the recharge from local rainwater have similar effects. Investigations in the Rif and Atlas regions of Morocco have identified

Table 3. Trace metal elements characteristics of groundwater in the study area

Aquifer systeme	Sample	Trace metal elements						
	WHO standards	Al (µg/l)	Cu (µg/l)	Zn (µg/l)	Cd (µg/l)	Cr (µg/l)	Pb (µg/l)	Fe (µg/l)
		< 200	< 2000	<3000	< 3	< 50	< 10	< 300
Flysch	S13	33.15	0	12.35	0	0	0	0
	S15	32.05	0	11.35	0	0	0	0
	S6	54.28	0	19.78	0	0	0	0
	S11	52.18	0.13	18.78	0	0	0	0
	Max	54.28	0	19.78				
	Min	32	0	11.35				
	Mean	42.91	0	15.56				
Calcareaus-Dorsal	S12	145.71	0.34	0	0	0	0	0
	S14	123.54	0.37	0	0	0	0	0
	S16	100.23	0.27	0	0	0	0	0
	S17	101.22	0.26	0	0	0	0	0
	Max	146	0.37					
	Min	100	0.27					
	Mean	118	0.32					
Quaternary	S1	53.58	0	15.35	0	0	0	0
	S2	33.63	0	14.17	0	0	0	0
	S3	53.16	0	13.57	0	0	0	0
	S4	52.48	0	14.25	0	0	0	0
	S5	53.13	0	14.32	0	0	0	0
	S9	31.25	0	18.86	0	0	0	0
	S10	51.36	0	16.48	0	0	0	0
	S7	97.81	0.28	8.17	0	0	0	0
	S8	95.63	0.21	8.42	0	0	0	0
	S18	18.35	0	10.73	0	0	0	0
	S19	17.53	0	10.14	0	0	0	0
	S20	48.7	0	13.33	0	0	0	0
	Max	97.81	0.28	18.86				
	Min	17.53	0	8.17				
	Mean	50.55	0.04	13.15				

Note: LOD and LOQ were calculated for the studied elements; calibration curves exhibited $R^2 = 0.999$; analyses reproducible with RSD < 5%."

analogous hydrogeochemical signatures linked to carbonate deposits (Bouchaou et al., 2009). The concordance of these results indicates that Mediterranean rural aquifers are distinctive due to the interplay of lithological management and meteoric recharge in maintaining a calcic–bicarbonate signature.

Water quality

We did a full examination of the physico-chemical and bacteriological parameters, which are shown in Tables 3–5, to find out how good the groundwater was.

Trace metals

Results indicate (Table 3) that the concentrations of lead (Pb), cadmium (Cd), chromium (Cr), and iron (Fe) are far below the detection limits of the measuring equipment used, this is likely because their actual concentrations were below the instrument's detection limits. It is worth emphasizing that the use of certified standards, the nearly ideal calibration curves (R^2 = 0.999), and the low variability among replicates together ensured the high reliability and reproducibility of the results. This observation reflects the relatively high quality of groundwater in the study area. meaning no contamination by these elements is detected. The man concentrations of copper (Cu), zinc (Zn), and aluminum (Al) are measurable but remain under the WHO drinking water guidelines (Yu et al., 2023). For copper (Cu), the guideline value is <2 mg/L; for zinc (Zn), <3 mg/L; and for aluminum (Al), <0.2 mg/L. The analyses (Table 3) indicate that, within the flysch aquifer system, Cu concentrations ranged from 32.05 to 54.28 µg/L, with an average of 42,91 µg/L. In the dorsal-calcareous aquifer system, values ranged from 117.67 to 145.71 µg/L, with a mean of 100.23 µg/L. For the Quaternary aquifer system, concentrations varied between 17.53 and 97.81 µg/L, with an average of 50.55 µg/L. All recorded values are well below international guideline limits for drinking water quality. These findings confirm that groundwater in the study area does not pose a public health risk and that there is no evidence of chronic exposure to

Table 4. Distribution of groundwater quality classes for the three aquifer systems in the study area according to the WAWQI

Aquifer systeme	Water quality status	Excellent	Good	Poor	Very poor	Unfit for consumption	Water type
	Suitability for drinking	Safe	Acceptible	Unsafe, required treatment	Unsuitable	Dangerous	
	WQI value range	[0–25]	[26–50]	[51–75]	[76–100]	>100	
	Sample	Calculated WQI					
Flysch	S13	25					Excellent /safe
	S15	23					Excellent /safe
	S6	25					Excellent /safe
	S11	29					Good /acceptble
Calcareaus-Dorsal	S12	26					Good /acceptble
	S14	23					Excellent /safe
	S16	25					Excellent /safe
	S17	27					Good /acceptble
Quaternary	S1	28					Good /acceptble
	S2	25					Excellent /safe
	S3	25					Excellent /safe
	S4	25					Excellent /safe
	S5	25					Excellent /safe
	S9	27					Good /acceptble
	S10	27					Good /acceptble
	S7	28					Good /acceptble
	S8	28					Good /acceptble
	S18	36					Good /acceptble
	S19	31					Good /acceptble
	S20	28					Good /acceptble

potentially toxic elements (PTEs), particularly in children, who constitute a vulnerable subgroup. Including trace metal analysis in the evaluation enhances its robustness, as these metals are seldom featured in regional indices yet may indicate initial signs of contamination (Khan et al., 2023). The consistently low levels observed here support the idea that there is little geogenic or anthropogenic influence. These analyses highlight the good quality of groundwater resources in the region northwest of Talassemtan National Park, a rural area with significant ecotourism potential, currently experiencing infrastructure development along the main road linking Tetouan to Chefchaouen.

Water quality index

The water quality index (WQI) was calculated for twelve essential physicochemical parameters: pH, Ca^{2+}, Mg^{2+}, K^+, HCO_3^-, SO_4^{2-}, Cl^-, NO_3^-, Na^+, Th(f_0), TAC(f_0), and TDS, in accordance with the approach established by Chorol and Gupta (2025), and the weighted arithmetic mean approach (Krishan et al., 2023, Patel et al., 2025). This method gave each parameter a weight based on how important it was to groundwater quality (2–5).

The regional distribution of WQI values (Table 3) shows that the groundwater in the area studied is heterogeneous. The WQI shows that three sampling points in the flysch aquifer have excellent quality (WQI < 25), and one point has good quality (25 < WQI < 50). The distribution for the calcareous-dorsal aquifer system is uniform, with 50% of the sampling points being of excellent quality and the other 50% being of good quality, according to the WQI thresholds. Four (4) of the groundwater points in the Quaternary aquifer system are of excellent quality and meet drinking water standards; the other eight (8) points are of good quality and are considered safe for human consumption. This criterion puts the waters in the "excellent to good" quality category (Voudouris and Kazakis, 2021).

This interpretation is based only on data from in-depth chemical analyses, which demonstrate that groundwater quality varies from excellent to good and is not evenly distributed in the three primary aquifers. This variability is because each aquifer system has its own lithological and hydrogeological properties, anthropogenic actions have very little effect on them, and they are in a rural, low-intensity land use setting (Reberski et al., 2022). Similar rural aquifers in North Africa

Table 5. Standard water quality for three aquifers of the study zone based on microorganisms (CFU/100 ml) in the studied water

Aquifer systeme	Sample	Micro-organisme (CFU/100ml)				Quality Classe
	WHO standards	Health limit	Low-risk	Moderate risk	A high risk	
		0	[1–10]	[11–100]	[101–1000]	
Flysch	S13	0				Excellent
	S15	0				Excellent
	S6	0				Excellent
	S11	7				Good
Calcareaus-Dorsal	S12	0				Excellent
	S14	0				Excellent
	S16	0				Excellent
	S17	0				Excellent
Quaternary	S1	81				Bad
	S2	35				Bad
	S3	76				Bad
	S4	0				Excellent
	S5	0				Excellent
	S9	0				Excellent
	S10	0				Excellent
	S7	43				Bad
	S8	22				Bad
	S18	378				Bad
	S19	287				Bad
	S20	219				Bad

and southern Europe have reported greater heterogeneity and localized degradation, particularly regarding nitrate and chloride contamination (Alqarawy et al., 2023), highlighting the relative preservation of groundwater integrity in our study area.

Bacteriological characteristics

The analysis of bacteriological data (Table 5) indicates anthropogenic contamination originating from septic tanks and fecal discharges from avian species residing in inadequately maintained wells, particularly at water points proximal to abandoned wells no longer utilized by local inhabitants, situated within the Quaternary aquifer (S1, S2, S3, S7, S8, S18, S19, S20) and the well (S11) of the Flysch aquifer system. This means, from a bacteriological quality perspective, that there are three types of groundwater. About 55% of the water is of excellent quality, with a fecal coliform content of 0 CFU/100 mL (the WHO recommended health limit). About 5% of the water is of good quality, with a concentration of 10 CFU/100 mL or less. This means it is not harmful to one's health. It is a well (S11) that captures water from the flysch aquifer system. The other 40% of water sources are of bad quality; they capture groundwater from the Quaternary aquifer system. They have a bacterial concentration that is higher than the WHO limit of 10 CFU/100 mL (WHO, 2022). Three of the water points (S18, S19 and S20) have a concentration that is higher than the limit of 101 CFU/100 mL, which means that they are among the groundwater extraction points that can be very dangerous to health, the other five water points (S1,S2,S3, S7 and S8) from the Quaternary aquifer system have a moderate risk, which is common in areas with separate sanitation systems (Verlicchi and Grillini, 2020) and in undeveloped water points mainly occupied by avian species.

The analysis of the physicochemical and bacteriological data revealed that the water from the three aquifer systems in the study area was predominantly devoid of nitrates (NO_3^-) and exhibited quality ranging from excellent, good to bad.

The coexistence of low nitrate concentrations (NO_3^-) and high microbial contamination can be attributed to two well-known mechanisms: (i) denitrification in suboxic aquifers, which reduces nitrate concentrations independently of the nitrogen load (Rivett et al., 2008) and (ii) dilution and dispersion in highly permeable environments (Foster and Chilton, 2003).

The gradual population increase in the study area, the extensive utilization of septic tanks and

Table 6. A matrix of correlations between several groundwater parameters in the study area

Variables	T	pH	EC	TDS	Th	TAC	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	FC	WQI	Al	Cu	Zn
T	1																		
pH	0.45	1																	
EC	-0.40	-0.30	1																
TDS	-0.40	-0.30	1	1															
Th	0.38	0.07	0.32	0.32	1														
TAC	-0.11	-0.21	0.34	0.34	0.11	1													
Ca^{2+}	0.09	-0.12	0.64	0.64	0.83	0.13	1												
Mg^{2+}	0.50	0.31	-0.50	-0.50	0.37	-0.03	-0.22	1											
Na^+	-0.17	-0.10	0.32	0.32	-0.46	0.33	-0.21	-0.46	1										
K^+	-0.27	-0.23	0.56	0.56	-0.30	0.40	0.00	-0.52	0.86	1									
HCO_3^-	0.28	-0.01	0.46	0.46	0.77	0.31	0.70	0.18	-0.04	0.16	1								
Cl^-	-0.45	-0.08	0.55	0.55	0.05	0.05	0.30	-0.41	0.25	0.30	-0.18	1							
SO_4^{2-}	-0.08	-0.11	0.30	0.30	-0.29	0.31	-0.18	-0.21	0.72	0.67	0	0.16	1						
NO_3^-	-0.25	0.09	0.53	0.53	0.08	0.08	0.19	-0.18	0.27	0.48	0.13	0.57	0.26	1					
FC	-0.27	0.07	0.64	0.64	0.02	0.33	0.15	-0.22	0.53	0.69	0.24	0.58	0.51	0.9	1				
WQI	-0.23	-0.01	0.89	0.89	0.28	0.34	0.55	-0.42	0.51	0.66	0.41	0.68	0.51	0.65	0.81	1			
Al	0.38	-0.14	-0.12	-0.12	0.67	-0.04	0.39	0.51	-0.60	-0.61	0.44	-0.42	-0.36	-0.37	-0.45	-0.30	1		
Cu	0.23	-0.15	0.04	0.04	0.77	-0.04	0.51	0.49	-0.63	-0.59	0.52	-0.23	-0.39	-0.25	-0.32	-0.14	0.93	1	
Zn	-0.33	-0.08	-0.02	-0.02	-0.74	-0.16	-0.34	-0.72	0.53	0.43	-0.60	0.30	0.30	0.02	0.05	0.08	-0.76	-0.82	1

Table 7. Correlation values of the parameters studied with the two factorial axes F1 and F2

Parameters	T	pH	EC	TDS	Th	TAC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	FC	WQI	Al	Cu	Zn
Axe F1	-0.50	-0.19	0.73	0.73	-0.26	0.34	0.13	-0.67	0.76	0.87	0.02	0.65	0.61	0.65	0.80	0.83	-0.68	-0.58	0.50
Axe F2	0.15	-0.10	0.60	0.60	0.93	0.26	0.86	0.18	-0.28	-0.07	0.84	0.14	-0.13	0.24	0.25	0.49	0.60	0.73	-0.72

latrines, coupled with inadequate maintenance and safeguarding of water sources, as well as the lack of communal sanitation in the study area, contribute to the deterioration of the microbiological quality of groundwater. Therefore, it is mainly about strengthening the monitoring systems for groundwater quality and promoting integrated management methods. This makes it imperative and urgent to improve sanitation infrastructure and raise awareness among users about the risks of contamination in order to preserve the sustainability of this vital resource in the Wadi Moulay Bouchta region.

Principal component analysis (PCA) and correlation structure

A19 hydrogeochemical and bacteriological variables, PCA isolates two components (eigenvalues > 1) explaining 63.01% of total variance (F1 = 36.58%, F2 = 26.43%). The F1 axis expresses a mineralization–contamination gradient (Figure 4A): EC, TDS, Na^+, K^+, WQI, and FC load strongly and positively, whereas Mg^{2+}, Cu, and Al load negatively. The F2 axis is a carbonate-hardness control with positive loadings of TH, HCO_3^-, Ca^{2+}, Cu and a strong negative loading of Zn (Table 7). These structural patterns reflect (i) a global mineralization (EC, TDS), commonly co-driven by Na^+ and K^+, and (ii) a "carbonate-hardness" pole (Ca^{2+}, HCO_3^-, Th), which highlights the water–carbonate rock interaction processes (Figure 4A). Pearson correlations (Table 6) corroborate the PCA: EC correlates strongly with TDS, Ca^{2+}, WQI, FC and moderately with NO_3^-, Cl^-, Mg^{2+}, K^+, HCO_3^-; the dominant cation, Ca^{2+} is strongly tied to HCO_3^-/TH/EC/TDS. Meanwhile, the dominant anion, HCO_3^- is strongly related to TH/Ca^{2+}, moderately to EC/TDS/Cu, and negatively to Zn. Microbiologically, FC aligns strongly with NO_3^-, WQI, K^+, TDS, EC and moderately with Cl^-, SO_4^{2-}, Na^+, while showing a moderate negative association with Al. The WQI is well correlated, or in other words, it tracks EC, TDS, FC most closely, then Cl^-, NO_3^-, Ca^{2+} and SO_4^{2-}. These patterns are frequently reported in Moroccan and Mediterranean aquifers, attesting that salinity (EC/TDS) and anthropogenic inputs (NO_3^-, FC) co-determine WQI in rural tourist aquifer systems. In comparable contexts in Morocco and elsewhere, recent studies document high EC-TDS correlations and NO_3^-/FC contributions to WQI and PCA axes (Safo-Adu, 2022).

For trace metals, the positive Cu–Al and Cu–Th associations indicate co-mobilization via acidity/organic complexation or aluminosilicate weathering; the negative relations of Zn with Cu, Al, Th, Mg^{2+} and HCO_3^- suggest distinct sources and/or

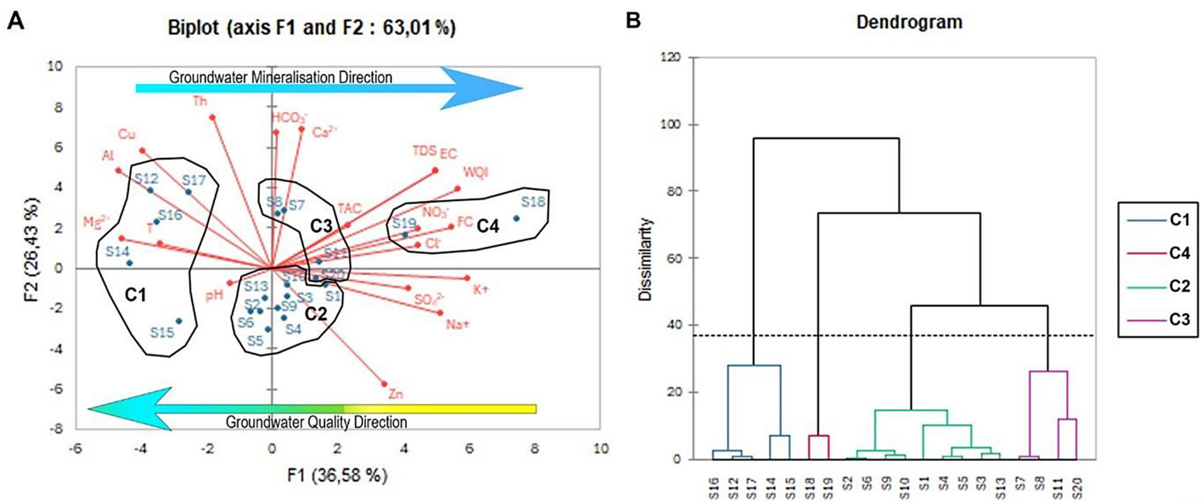

Figure 4. Factor analysis-conceptual structure map (A) and dendrogram (B) of the study area

contrasting adsorption/precipitation behavior (pH–carbonate controlled). Recent studies in alluvial and karst settings similarly group Cu/Al on lithogenic factors, with Zn more redox-sensitive, explaining local anti-correlations (Msengi et al., 2024).

Spatial typology (HCA/dendrogram)

The factor map and dendrogram resolve four clusters (Figure 4B):

- Cluster 1 (S14, S15, S12, S16, S17): lowest mineralization (negative F1), short residence time, and weak water–rock interaction; excellent (S14, S15 et S16) to good-quality (S12 et S17) sources needing strict protection.
- Cluster 2 (S1, S2, S4, S5, S9, S10, S13): transition between G1 and G3–G4 with moderate mineralization and susceptibility to diffuse inputs (variable recharge, preferential flow, localized anthropogenic loads). Dynamic hydrogeological processes, such as recharge variability, preferential flow paths, and localized anthropogenic inputs (Wang et al., 2024), explain this mixing from a hydrogeochemical and bacteriological perspective, with water quality ranging from excellent (S4, S5 et S13), Good (S9 et S10) to bad (S1 et S2). The discovery of this cluster highlights the complexity of the groundwater history in the region and suggests a susceptibility to both natural geochemical enrichment and initial pollution, which requires meticulous monitoring.
- Cluster 3 (S7, S8, S11, S20): positively related to F1, higher mineralization but patchy quality (good to bad), indicating heterogeneous pressures.
- Cluster 4 (S18, S19): highest mineralization and fecal load (high F1); TDS/EC and ionic ratios point to longer residence/dissolution of soluble carbonates compounded by agricultural runoff and wastewater infiltration (bad water quality and a heightened risk).

Discussion and implications

The F1 axis correlates salinity with anthropogenic influence: EC/TDS reflect bulk ionic load, while NO_3^-/FC trace agriculture and sanitation deficits. The close alignment of WQI with EC/TDS/FC mirrors recent findings where WQI rises with mineralization and pollution markers(Safo-Adu, 2022). The axis F2 captures carbonate hardness (Ca^{2+}, HCO_3^-, TH) opposed to Zn, consistent with pH/redox-dependent Zn mobility and carbonate/oxide sorption. Regional studies document similar carbonate vs. trace-metal factor contrasts. The FC–NO_3^- association supports mixed fecal and agricultural sources, aligning with drinking-water health concerns (tolerance 0 CFU/100 mL for fecal coliforms (WHO, 2022).

Given the area's tourism footprint, safeguarding Cluster1 sources via protection perimeters, seasonal monitoring, and targeted WASH (Water, Assanitation, Sanitation, Hygiene) interventions upstream of C3-C4 is warranted. Mediterranean evidence emphasizes growing tourism-related water demand and the need for integrated water–tourism governance (Ricart et al., 2024). The Quaternary aquifer in the study area faces growing risks. Randomly dug wells and poorly placed septic tanks are direct sources of contamination. Protecting this fragile water resource requires

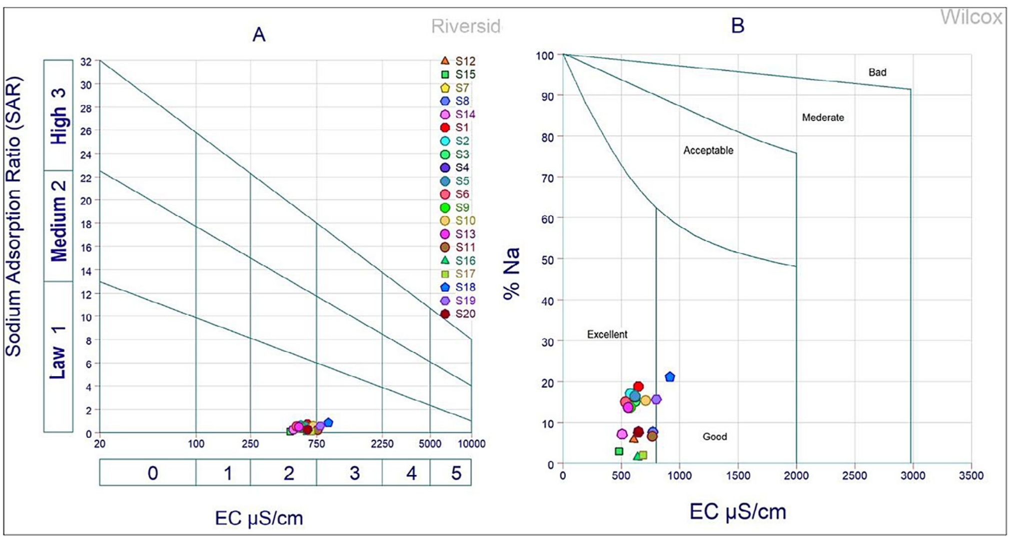

Figure 5. Riverside (A) and Wilcox (B) diagram for groundwater samples

several urgent actions. First, wastewater systems must be adapted to the region's geology and hydrogeomorphology, reducing pollutant migration. Next, detailed hydrogeophysical studies are needed to map vulnerable zones, track groundwater dynamics, and guide the proper sitting of wells and boreholes. It is also essential to identify underground features faults, fractures, permeability, and porosity that influence contaminant transport and protection strategies. Practical solutions include physical barriers, regular water quality monitoring, and sealing wells with protective layers. Finally, households and farmers must be made aware of best practices: keeping septic systems away from water points, avoiding random drilling, and using reliable sanitation systems.

Irrigation water quality

Based on the EC and the sodium adsorption ratio (SAR) (Figure 5A), it was concluded that all water samples were of good and fairly good quality for irrigation (C2S1 and C3S1). Consequently, these samples can be used for watering plants that have a moderate tolerance to salts without requiring specific controls. Furthermore, based on the classification of electrical conductivity and the percentage sodium classification (%Na), 95% and 5% of the groundwater samples demonstrate excellent and good water quality, respectively (Figure 5B). It is noteworthy that the SAR in the study area is less than two, indicating that the water does not present a risk of soil alkalization.

In conclusion, the groundwater in this rural Moroccan corridor is of high quality for agricultural uses, according to the EC and SAR values. In this environmentally sensitive and socioeconomically significant area, judicious use of this resource can promote both traditional small-scale farming and eco-friendly tourism routes.

CONCLUSIONS

This study assessed groundwater quality in a rural hydrogeological catchment bordered by the Talassemtane and Bouhachem UNESCO National Parks, an ecologically fragile area under increasing anthropogenic and ecotourism pressure. Hydrogeochemical results show a predominance of calcium–bicarbonate water type, with overall good quality in the flysch and calcareous-dorsal aquifers (WQI < 50; CF < 7 CFU/100 mL), ensuring safe drinking water. Conversely, the Quaternary aquifer exhibits localized contamination linked to inadequate sanitation, with eight points presenting moderate to high risk. Multivariate analysis revealed a west–east mineralization gradient tied to lithology and a contamination gradient from group 4 to group 1. Trace metal concentrations remain well below hazardous levels, excluding chronic exposure risks. Groundwater suitability for irrigation is also excellent, with 95% and 5% of samples classified as excellent and good, respectively. These findings highlight the strategic importance of preserving groundwater resources as both ecological heritage and a driver of sustainable local development.

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