Carpathian Journal of Earth and Environmental Sciences, February 2026, Vol. 21, No. 1, p. 49 – 60; DOI:10.26471/cjees/2026/021/351

GROUNDWATER QUALITY IN ALGERIA: THE CHALLENGE OF WATER STRESS AND POLLUTION

Naila MAIZI[1,2*], Naziha LAMRI[1,2], Taous BACHIRI[2], Karim BELHOCINE[3], Tiziri IDIR[4], Fadila KHALDI[5] & Nedjoud GRARA[6]

[1]*Laboratory for the Management and Valorisation of Natural Resources and Quality Assurance, Akli Mohand Oulhadj University, Bouira 10000, Algeria*

[2]*Department of Biology, Faculty of Natural and Life Sciences and Earth Sciences, University Akli Mohand Oulhadj, Bouira 10000, Algeria*

[3]*Department of Marine Sciences, Faculty of Natural and Life Sciences, University Chadli Bendjedid, El Tarf 36000, Algeria*

[4]*Faculty of Earth Sciences, Geography and Territorial Planning, University of Sciences and Technology Houari Boumediene, BP 32 Bab Ezzouar, 16111 - Algiers, Algeria*

[5]*Department de Biology, Faculty of Natural and Life Sciences, University, Mohamed-Chérif Messaadia, Souk Ahras 41000, Algeria*

[6]*Department of Biology, Faculty of Natural and Life Sciences, Earth and Universe Sciences, University 8 Mai 1945, Guelma 24000, Algeria*

Corresponding author: n.maizi@univ-bouira.dz

Abstract: Groundwater is a critical water resource in Algeria, especially in areas where surface water availability is limited by climatic conditions. However, its quality is increasingly threatened by human pressures such as intensive farming, uncontrolled wastewater discharges, and inadequate sanitation infrastructure. This study evaluates the physicochemical and bacteriological quality of groundwater from ten boreholes in the Bouira region, a semi-arid area facing growing water demands. Key physicochemical parameters (pH, electrical conductivity, temperature, major ions, nitrates, bicarbonates) and microbiological indicators (fecal coliforms, enterococci) were measured. Multivariate statistical analyses, including Principal Component Analysis (PCA) and Ascending Hierarchical Classification (AHC), revealed four distinct water quality clusters. Results indicate slightly acidic to neutral water (mean pH 7 ± 0.23) with moderate mineralization (mean conductivity 1271.8 ± 293.7 µS/cm). Significant correlations were found between electrical conductivity and several major ions, and between turbidity, calcium, and nitrate levels. While most samples met drinking water standards, elevated levels of nitrates, chlorides, and bicarbonates suggest contamination of both anthropogenic and geogenic origin. On a positive note, bacteriological assessments showed no evidence of fecal contamination. These findings provide valuable insights into groundwater vulnerability in semi-arid environments and may be of broad interest to researchers and practitioners in the fields of hydrogeology, environmental sciences, and water resource management.

Keywords: Groundwater, physicochemical parameters, bacteriological indicators, multivariate analysis, water pollution.

1. INTRODUCTION

Groundwater plays a crucial role in sustaining populations, particularly in arid and semi-arid regions where surface water resources are scarce, unreliable, or highly seasonal (Ali Rahmani et al., 2017; Azlaoui et al., 2021; Ncibi et al., 2021; Mansouri et al., 2022; Chougar et al., 2024; El-Rawy et al., 2023). Due to its relative stability against climatic variability, groundwater is considered a strategic resource for drinking water supply and irrigation (Huan, 2018; Kalaivanan et al., 2018; Ben Moussa et al., 2021). Globally, it provides nearly half of the drinking water supply and 40 % of agricultural water needs (Lora-Ariza et al., 2024).

However, this vital resource is increasingly threatened by multiple pressures, both natural and anthropogenic. On the one hand, geochemical processes such as rock weathering and the dissolution of evaporitic and carbonate minerals contribute to groundwater mineralization (Muhammad & Ahmad, 2020; Downing et al., 2021; Rehman et al., 2024; Wei et al., 2024). On the other hand, human activities, including urbanization, intensive agriculture, industry, mining, and poor wastewater management represent major sources of pollution (Bawa & Dwivedi, 2019; Rezig et al., 2022; Ojo et al., 2024). This situation is particularly alarming in developing countries, where untreated or contaminated water is often used for domestic and agricultural purposes, exposing populations to serious health risks (Egbuikwem et al., 2021; Lamri et al., 2022).

In Algeria, the growing degradation of groundwater represents a major challenge for the sustainability of water resources (Negm et al., 2020; Allaoua et al., 2024). Studies conducted in semi-arid areas such as the Sidi Bel Abbès plain and the Béchar region have highlighted persistent trends of declining water tables and deteriorating quality due to sustained overexploitation of aquifers (Bellaredj & Hamidi, 2020; Kendouci et al., 2023). Moreover, in eastern Algeria (Oum El Bouaghi), several analyses have revealed increased contamination (nitrates, high electrical conductivity), threatening the sustainable use of groundwater (Allaoua et al., 2024). Recent artificial recharge initiatives (Cheria basin) further underscore the need for preventive measures to address a depletion process that has yet to be managed in an integrated manner (Djellali et al., 2023).

Between 2010 and 2019, the national water stress index increased from 104.92 to 137.2, while the annual renewable freshwater availability per capita dropped from 314 to 263 m³/year (Bakhtache & Hadjene, 2023). This quantitative stress is often compounded by deteriorating water quality, marked by increased salinity, elevated nitrate levels, and the presence of trace metals, often linked to anthropogenic activities (Bougherira et al., 2017).

Moreover, the use of contaminated water, particularly for domestic purposes or human consumption, can cause harmful health effects, both in the short and long term (Rezig et al., 2021; Peng et al., 2022).

The Bouira region, located in north-central Algeria, illustrates the growing challenges of sustainable groundwater management. Essential for irrigation and drinking water supply, this resource is increasingly under pressure due to the widespread use of chemical fertilizers, the expansion of industrial zones, and insufficient sanitation infrastructure (Lamri et al., 2022; Rezig et al., 2022).

Pollution observed in the Bouira dam (Rezki, 2024) may also impact local aquifers. Several recent studies have highlighted a correlation between declining water quality and health risks in areas irrigated by oueds (Rezig et al., 2021), underscoring the vulnerability of this strategic resource.

In this context, a rigorous and integrated assessment of groundwater quality is essential to preserve this strategic resource, ensure public health, and support sustainable water management policies. Although some studies have sporadically reported groundwater degradation in various regions of Algeria, comprehensive investigations combining physicochemical, microbiological, and multivariate statistical analyses remain limited, particularly in semi-arid areas such as the Bouira region. Yet such approaches are crucial for accurately characterizing pollution profiles, identifying potential contamination sources, and revealing spatial variability in water quality parameters (Xiao et al., 2023).

Accordingly, this study aims to explore groundwater quality in the Bouira region by analyzing its physicochemical and bacteriological characteristics to evaluate its suitability for drinking water and to provide a scientific basis for sustainable management in a semi-arid environment.

2. MATERIALS AND METHODS

2.1. Study area

The Wilaya of Bouira is located in the northern part bordered to the north by the Wilayas of the country, southeast of Algiers (the capital), with a total area of 4,454 km². It has a population of 742,855 inhabitants, resulting in a population density of 167 inhabitants per km².

It is Boumerdes and Tizi-Ouzou, to the south by M'Sila and Medea, to the east by Bejaia and Bordj Bou Arreridj, and to the west by Blida and Medea (Figure 1).

The region's climate is a temperate Mediterranean type, characterized by hot and dry summers and cold, rainy, and humid winters. Annual precipitation reaches 665 mm, while average monthly temperatures range from 8.4 °C in January to 27.9 °C in July.

The proven water resource capacity across the Wilaya amounts to 235.4 hm³, with 35.5 hm³ coming from groundwater and 199.9 hm³ from surface water. Groundwater resources are mainly located in the northern region, particularly in the plateaus of El Asnam, Bled El Madjen, and the valleys of Oued Ed Dhous and Oued Sahel. These waters are extracted through wells, boreholes, and springs (Zerdane, 2013).

The region's drinking water supply is ensured through the transfer of surface water from the Tilesdit dam, with a regulated volume estimated at 672 m³/day, as well as groundwater sourced from boreholes, springs and wells.

2.2. Water Sampling and Analysis

The sampling covered two municipalities in the Bouira region: El Asnam and Oued El Berdi (Figure 1). Ten boreholes were carefully selected, considering their geographical location, geological characteristics, and the surrounding agricultural environment (Table 1). These boreholes are located near surface water flows, industrial and urban activity zones, as well as sources of liquid or solid waste discharges. They are primarily used for drinking water supply and irrigation.

Water samples were collected under strict aseptic conditions. Sterile 250 mL Pyrex glass bottles with wide necks and screw metal caps were used, previously sterilized at 180 °C for 20 minutes.

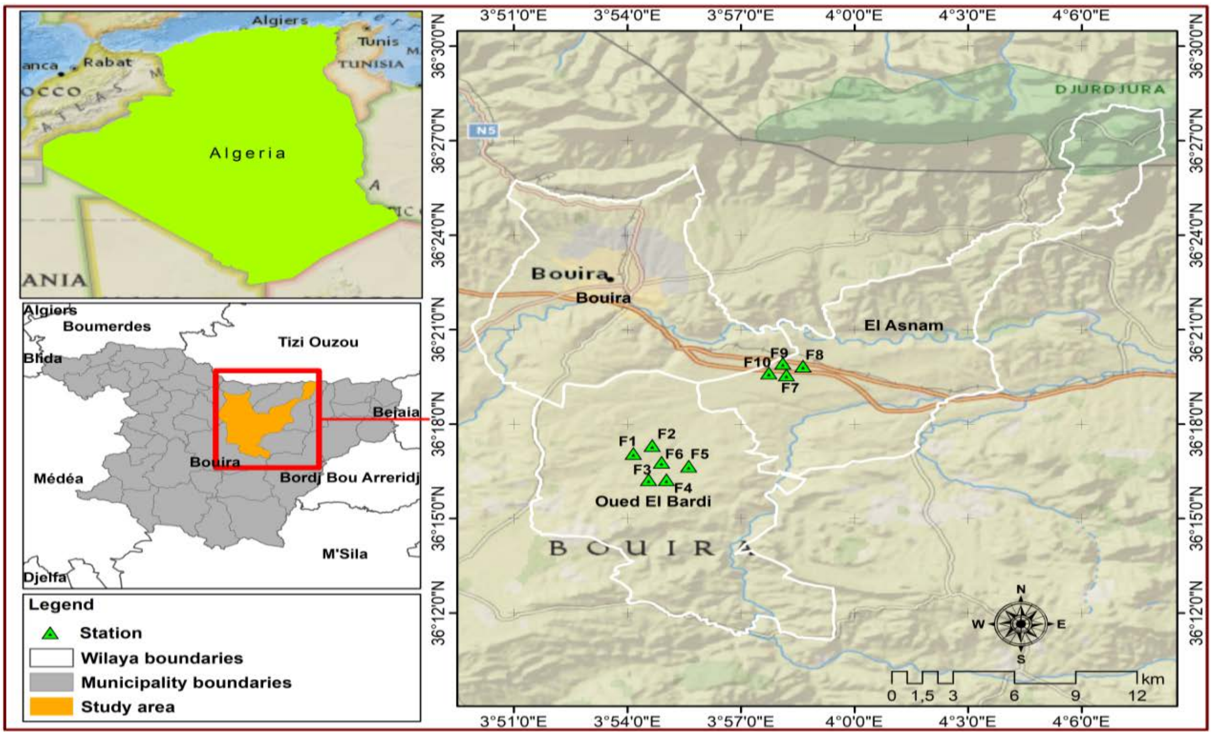

Figure 1. Map of the geographical location of the study drillings.

Table 1. Main characteristics of the borehole sampling locations in the Bouira region.

Bore-holes	Borehole Identification	Coordinates		Aquifer depth (m)	Activities nearby	Water use
		X	Y			
F1	**FOB1**	36,294220	3,923001	150	Houses and agricultural land	Drinking water and irrigation
F2	**FOB2**	36,296021	3,937144	150	Farms and agricultural land	Drinking water and irrigation
F3	**FOB3**	36,281053	3,931992	160	Houses and Agricultural land	Drinking water and irrigation
F4	**FOB4**	36,280576	3,936213	150	Houses and agricultural land	Drinking water and irrigation
F5	**FOB5**	36,281333	3,945093	140	Houses and Agricultural land	Drinking water and irrigation
F6	**FOB6**	36.281893	3.915602	150	Houses and agricultural land	Drinking water
F7	**FAS7**	36.329193	3.970703	108	Farms, houses, and agricultural land	Drinking water
F8	**FAS8**	36.331073	3.977937	107	Houses and agricultural land	Drinking water
F9	**FAS9**	36.329063	3.964271	115	Houses and agricultural land	Drinking water
F10	**FAS10**	36.332204	3.970729	96	Farms, houses, and agricultural land	Drinking water

Samples were kept at 4 °C, protected from light, and transported to the laboratory within 6 hours after sampling. Negative controls were included to detect potential contamination during transport and handling. Each sample was analyzed in triplicate to ensure reproducibility and statistical robustness (Rodier et al., 2016).

2.2.1. Bacteriological Analysis

Bacteriological analyses were conducted in accordance with both the Algerian national standard for drinking water quality (NA 6360-1992) and international microbiological standards (ISO) (WHO, 2017). The aim was to assess the sanitary quality of groundwater intended for human consumption. The microbial indicators analyzed included total coliforms (TC), fecal coliforms (FC), intestinal enterococci (IE), sulfite-reducing clostridia (SRC), and total aerobic mesophilic bacteria (TAMB) incubated at 22 °C and 37 °C.

TC and FC were quantified according to ISO 9308-2, using membrane filtration (0.45 µm) and incubation on Chromocult® Coliform Agar (Merck, Germany) at 37 °C for TC and at 44 °C for FC for 24 hours. Intestinal enterococci (IE) were enumerated following ISO 7899-2 by filtration and incubation at 36 °C for 48 hours on Slanetz and Bartley Agar (Biokar Diagnostics, France). Sulfite-reducing clostridia (SRC) were assessed using ISO 6461-2, by anaerobic incubation on Tryptose Sulfite Cycloserine (TSC) Agar at 44 °C for 24 hours. TAMB were determined by surface plating on Plate Count Agar (Biokar Diagnostics, France) incubated at 22 °C for 72 hours and at 37 °C for 48 hours, as recommended in ISO 6222.

2.2.2. Physicochemical Analysis

For these analyses, 1.5 L polyethylene bottles were used, rinsed three times with distilled water. These bottles were opened only at the time of sampling; once filled, they were sealed, labeled, and stored at 4 °C.

The analysis of the collected water samples was carried out according to the methods described by Rodier et al. (2016) and was conducted within a maximum timeframe of 24h.

The physico-chemical parameters (temperature, pH, conductivity, and turbidity) were measured in situ using a multiparameter device.

The total hardness (TH) was determined using the Mohr method, while ammonium, nitrates, sulfates, orthophosphate ions, chlorides, calcium, magnesium, sodium, potassium, and total iron (Fe^{2+}, Fe^{3+}) were analyzed using the spectrophotometry method.

2.3. Statistical analysis

A Principal Component Analysis was applied in order to highlight the possible relationships between the different physico-chemical tested parameters (pH, temperature, turbidity, electrical conductivity, calcium, magnesium, sodium, potassium, iron, nitrite, nitrate, ammonium, sulfate, bicarbonate and chloride).

Although the dataset is relatively limited, several studies have demonstrated that multivariate statistical techniques such as PCA remain relevant and robust even with small sample sizes, as they help reduce dimensionality, reveal latent correlations among variables, and improve the interpretation of hydrochemical datasets (Shrestha & Kazama, 2007; Souley Moussa et al., 2018; Kouame et al., 2021; Rahmani et al. 2022; Guenouche et al. 2024).

An Ascending Hierarchical Classification (AHC) was applied as a complementary analysis with the aim of identifying the number and composition of each homogeneous subgroup of tested drilling water. This clustering method has been shown to be effective in hydrogeological studies, even with relatively small datasets, as it allows a clearer classification of sampling sites based on similarities in water quality (Gupta & Mehrotra, 2020; Kouame et al., 2021; Taşan et al., 2022; El Hammioui et al., 2023; Masmoudi et al., 2024).

All statistical analyzes and graphical representations were carried out by the statistical software SPSS version 26 (IBM SPSS 2019).

3. RESULTS AND DISCUSSION

The analysis of groundwater quality in the Bouira region reveals a complex interplay of natural and anthropogenic factors.

3.1. Bacteriological quality of borehole water

The bacteriological analyses of the studied boreholes revealed the absence of total coliforms (TC), fecal coliforms (FC), intestinal enterococci (IE), and sulfite-reducing clostridia (SRC) (0 CFU/100 mL) at all 10 sampling points (Table 2).

Regarding microbiological parameters, the guidelines of the World Health Organization (WHO/EU) stipulate the total absence of pathogenic microorganisms in drinking water.

The enumeration of total aerobic mesophilic bacteria (TAMB) is considered a broad indicator of microbiological pollution, as it determines the total bacterial load. The stability of bacterial counts is therefore a good indicator of water protection (Khaldi et al., 2018).

The results obtained for total aerobic mesophilic bacteria counts ranged from 16 to 25 CFU/100 mL at 22 °C in boreholes FOB2, FOB4, FOB5, and FAS7, and from 6 to 14 CFU/100 mL at 37 °C in boreholes FOB3, FOB4, FOB5, FOB6, and FAS8.

These values exceed the Algerian regulatory standards, which set the limits at ≤ 20 CFU/mL at 22 °C in 72 h and ≤ 5 CFU/mL at 37 °C in 24 h.

Microbiological results indicate the total absence of fecal coliforms, enterococci, and sulfite-reducing clostridia, confirming good sanitary quality in all sampled boreholes. These findings contrast with observations reported in other Algerian regions, such as El-Harrouch, where frequent fecal contamination has been documented (Ayad & Kahoul, 2016).

The absence of bacterial colonies at 22 °C in certain samples (F3, F6, F8), despite the detection of mesophilic bacteria at 37 °C, can be explained by the specificity of microbial groups targeted at each incubation temperature. Incubation at 37 °C promotes the growth of mesophilic bacteria, often environmental saprophytes such, which thrive at temperatures close to human body temperature, without necessarily indicating the presence of coliforms (Figrella et al., 2001).

The contrast observed between the two incubation temperatures highlights the ecological diversity of microbial niches. The absence of growth at 22 °C in boreholes F3, F6, and F8 may also be related to a viable but non-culturable (VBNC) state, in which certain bacteria remain metabolically active but undetectable using conventional culture-based methods (Health Canada, 2020).

3.2. Physicochemical characteristics of groundwater

The results of the physicochemical analyses of the water from the studied drillings are recorded in (Table 4). Table 3 presents the drinking water quality standards, the average and extreme values of the different measured physicochemical parameters of the drilling water.

The average temperature of the water from the selected drillings is 18.7 ± 1.8 °C, ranging between 15.9 °C and 21.2 °C, which is consistent with the trends generally observed in groundwater, as it is less subject to thermal variations compared to surface water (Rodier, 2016). The temperatures reported in this study are similar to those obtained by Rahmani et al. (2022) in the Djelfa syncline, where groundwater temperatures range from 16 °C to 22.5 °C. This variation in groundwater temperature may be related to the depth of the aquifer.

Electrical conductivity values range between 1014 µS/cm and 1998 µS/cm, with an average of 1271.8 ± 293.76 µS/cm for all the studied drillings. Electrical conductivity is one of the key parameters used to assess the degree of mineralization in water (El Haissoufi et al., 2011).

These values sometimes exceed the WHO limit for drinking water (Table 3), suggesting potentially high salinity due to the dissolution of mineral salts from the geological substrate. Additionally, high conductivity may result from a slow recharge of aquifers or anthropogenic contamination, such as agricultural activities or industrial discharges (Bougherira et al., 2017).

Table 2. Bacteriological Analysis Results of Water from Selected Boreholes in Bouira City.

Well no.	Bore-holes	Total Coliforms (CFU/100mL)	Fecal Coliforms (CFU/100mL)	Intestinal Enterococci (CFU/100mL)	Total Aerobic Mesophilic Bacteria at 37 °C (CFU/100mL)	Total Aerobic Mesophilic Bacteria at 22 °C (CFU/100mL)	Sulfite-reducing clostridia (CFU/100mL)
FOB1	**F1**	0	0	0	0	0	0
FOB2	**F2**	0	0	0	0	18	0
FOB3	**F3**	0	0	0	06	0	0
FOB4	**F4**	0	0	0	11	25	0
FOB5	**F5**	0	0	0	12	16	0
FOB6	**F6**	0	0	0	08	0	0
FAS7	**F7**	0	0	0	0	18	0
FAS8	**F8**	0	0	0	14	0	0
FAS9	**F9**	0	0	0	0	0	0
FAS10	**F10**	0	0	0	0	0	0

CFU: Colony-Forming Unit

The pH values vary between 6.71 and 7.53, with an average of 7.05 ± 0.22, indicating neutral to slightly basic water. which are typical of carbonate aquifers. These results are consistent with those reported in the Hodna Basin and the Merdja aquifer (Belhadj et al., 2017; Gouaidia et al., 2017).

The variation in pH among samples could be explained by the geological nature of the terrain. The geological origin of aquifers significantly influences pH, as water circulating in limestone-rich formations often exhibits a more alkaline pH.

Nitrites (NO_2^-) and ammonium (NH_4^+) were detected in very low quantities, with average concentrations of (0.0007 ± 0.001) and (0.01 ± 0.02), respectively, suggesting good oxidation of organic matter and the absence of recent pollution.

The analysis of water from the studied boreholes revealed elevated chloride concentrations, ranging from 129.22 mg/L to 350 mg/L, with an average of 230.30 ± 70.96 mg/L. Given that chlorides are present in nearly all water sources at highly variable concentrations (Ould Cheikh et al., 2011), the high levels observed in these samples likely indicate the dissolution of evaporitic minerals (Bencer et al., 2016).

All compounds have values below the maximum allowable limit according to Algerian drinking water standards (JORA, 2014), except for nitrates, which exceed the standards, ranging from 50 mg/L to 103.66 mg/L with an average of 79.9 ± 17.81 mg/L, and bicarbonates, which range between 352.85 mg/L and 425.25 mg/L, with an average of 395.1 ± 24.9 mg/L, exceeding the 120 mg/L limit set by the WHO.

High nitrate concentrations can result from the use of fertilizers in agricultural activities. Both synthetic and organic fertilizers are widely used, leading to excessive fertilization. However, poor agricultural practices, such as leaving manure on the surface, facilitate the transfer of nitrogen-based fertilizers through runoff. Additionally, nitrogen enrichment can also originate from wastewater discharges.

This effect is explained by diffuse sources, mainly originating from agricultural and residential areas. These sources include sewage discharges, septic tank leaks, as well as the use of natural and synthetic fertilizers in agricultural practices (Ustaoğlu et al., 2020; Masmoudi et al., 2024).

The high bicarbonates (HCO_3^-) concentrations in groundwater can be attributed to various processes, including the dissolution of atmospheric CO_2, silicate weathering, and the dissolution of carbonate minerals such as limestone and dolomite, which contribute to increased HCO_3^- levels in groundwater (Roy et al., 2020).

3.3. Correlations Between the Different Physico-Chemical Parameters of the Studied Borehole Waters

The correlation matrix (Table 5) was used to identify statistically significant relationships between the physico-chemical parameters of groundwater. This tool helps detect interdependencies that may reveal common sources of contamination or similar geochemical behavior. It is also a prerequisite step for further multivariate analyses such as Principal Component Analysis (PCA) or Hierarchical Cluster Analysis (HCA), which require prior exploration of variable interactions. Similar approaches have been successfully applied in groundwater quality studies in Algeria and other arid regions (Souley Moussa et al., 2018; Kouame et al., 2021; Sakaa et al., 2022; Allaoua et al., 2024).

Table 3. Comparison of the Average Physico-Chemical Parameters with Standards.

Parameters	**Units**	**Minimum**	**Maximum**	**Mean ± standard-deviation**	**Algerian Standards (JORA, 2014)**	**WHO Standards (WHO, 2017)**
pH	/	6.71	7.53	7 ± 0.23	6.5 – 9	6.5 – 8.5
Temperature	°C	15.9	21.2	18.6 ± 1.8	25	25
Turbidity	NTU	0.21	0.76	0.4 ± 0.19	5	5
Conductivity	µS/cm	1014	1998	1271.8 ± 293.7	2800	2500
Ca^{2+}	mg/L	90	172.4	125 ± 27.3	200	200
Mg^{2+}	mg/L	19.49	81.6	41.6 ± 20	150	50
Na+	mg/L	62.5	107	83.3 ± 16.3	200	200
K+	mg/L	0.7	1.9	1.13 ± 0.4	12	12
Total Fe	mg/L	/	0.12	0.05 ± 0.04	0.3	0.3
NO_2^-	mg/L	/	0.004	0.0007 ± 001	0.2	3
NO_3^-	mg/L	50	103.66	79.9 ± 17.8	50	50
NH_4^+	mg/L	/	0.07	0.01 ± 0.02	0.5	0.5
SO_4^{2-}	mg/L	34.89	93.95	69.5 ± 19.3	400	500
HCO_3^-	mg/L	352.85	425.25	395.1 ± 24.9	/	120
Chloride	mg/L	129.22	350	230.3 ± 70.9	500	200

Table 4. Values of the physico-chemical parameters of some groundwater wells studied in the city of Bouira.

Well number	pH	Temp (°C)	Tur (NTU)	Cond (μS/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Total Fe (mg/L)	NO_2^{-} (mg/L)	NO_3^{-} (mg/L)	NH_4^{+} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^{-} (mg/L)	Cl^{-} (mg/L)
FOB1	7.53	17.3	0.26	1205	102.4	43.2	67.5	1.6	0.02	0	98.3	0	86.72	405.34	129.22
FOB2	6.71	15.9	0.28	1998	125	21.12	89	1.9	0	0.004	50	0	93.95	386.84	350
FOB3	7.11	21.2	0.3	1299	109	61.44	96	0.7	0.1	0	72.97	0.07	73.53	352.85	337.96
FOB4	7.12	21	0.21	1043	96	81.6	66.3	1.33	0.09	0	86.4	0.02	77.4	408.3	224.36
FOB5	7.2	20.7	0.27	1023	90	57.6	70.6	0.92	0.05	0.001	73	0.03	88.35	357.46	181.76
FOB6	6.91	18.8	0.44	1014	136.3	41.4	62.5	0.8	0.03	0	58.3	0	52.78	412.76	262.59
FAS7	7	18.3	0.76	1210	146.5	24.3	78.8	0.76	0.01	0	100.32	0.01	46.23	388.12	227.09
FAS8	6.88	18.4	0.72	1445	172.4	19.49	91	0.84	0.05	0	103.66	0	67.42	422.67	192.59
FAS9	7.2	16.8	0.46	1123	116.4	36.3	104.3	1.35	0.12	0.002	82.02	0	34.89	392.22	232.88
FAS10	6.9	18.1	0.38	1358	156.2	30.4	107	1.12	0.05	0	74.11	0	74.05	425.25	164.6

Table 5. Correlation matrix between physico-chemical parameters for all drillings.

Parameters	pH	Temp	Turbidity	Cond	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total Fe	NO^{2-}	NO_3^{-}	NH_4^{+}	SO_4^{2-}	HCO_3^{-}	Cl^{-}
pH	1														
Temperature	0.202	1													
Turbidity	-0.331	-0.238	1												
Conductivity	**-0.588**	**-0.567**	0.015	1											
Ca^{2+}	-0.635	-0.380	**0.782**	0.337	1										
Mg^{2+}	0.476	0.793	**-0.658**	**-0.575**	-0.771	1									
Na^{+}	-0.309	-0.312	0.209	0.427	0.419	-0.420	1								
K^{+}	0.083	-0.618	**-0.504**	**0.513**	-0.301	-0.098	0.024	1							
Total Fe	0.286	0.431	-0.196	-0.425	-0.302	0.540	0.376	-0.203	1						
NO^{2-}	-0.345	-0.580	-0.235	**0.667**	-0.159	-0.320	0.265	0.680	-0.154	1					
NO_3^{-}	0.467	0.082	**0.508**	-0.325	0.199	-0.052	-0.047	-0.239	0.097	-0.570	1				
NH_4^{+}	0.189	0.768	-0.309	-0.180	-0.456	0.609	0.037	-0.443	0.447	-0.224	-0.099	1			
SO_4^{2-}	0.043	0.137	**-0.648**	0.415	-0.361	0.233	-0.219	0.433	-0.336	0.210	-0.255	0.194	1		
HCO_3^{-}	-0.220	-0.389	0.287	0.033	0.604	-0.343	0.011	0.166	-0.196	-0.257	0.256	-0.769	-0.176	1	
Cl^{-}	-0.534	0.013	-0.114	0.476	-0.065	0.009	0.183	0.039	0.073	0.510	-0.629	0.410	-0.009	-0.456	1

The Principal Component Analysis (PCA) performed on the 15 physico-chemical parameters shows that the two axes account for 57.06 % of the total variance (the first axis explains 32.29 %, and the second axis 24.77 % of this variance).

According to the correlation matrix (Table 5) and the circle of correlations established by the PCA (Figure 2), electrical conductivity was positively correlated with potassium and nitrite (r ranging from 0.51 to 0.66) and negatively correlated with temperature, magnesium, and pH (r ranging from -0.56 to -0.58) (Table 5). The turbidity of the drillings was positively correlated with nitrate and calcium (r ranging from 0.50 to 0.78) and negatively correlated with potassium, sulfate, and magnesium (r ranging from -0.50 to -0.65) (Table 5).

According to the results of Ascending Hierarchical Classification (AHC) (Figures 3 and 4), the ten groundwater samples were grouped into four distinct and relatively homogeneous subgroups, each characterized by specific hydrochemical profiles:

- The 1st subgroup, composed only of drilling FOB2, which exhibits the highest concentrations of electrical conductivity, potassium, nitrite, and chloride, combined with low levels of temperature, magnesium, and a slightly acidic pH (6.71). These features may indicate local contamination sources, likely of anthropogenic origin, such as agricultural runoff or proximity to urban wastewater discharges.

- The 2nd subgroup, consisting only of FOB3, is distinguished by elevated levels of temperature, magnesium, sodium, iron, ammonium, and chloride**,**

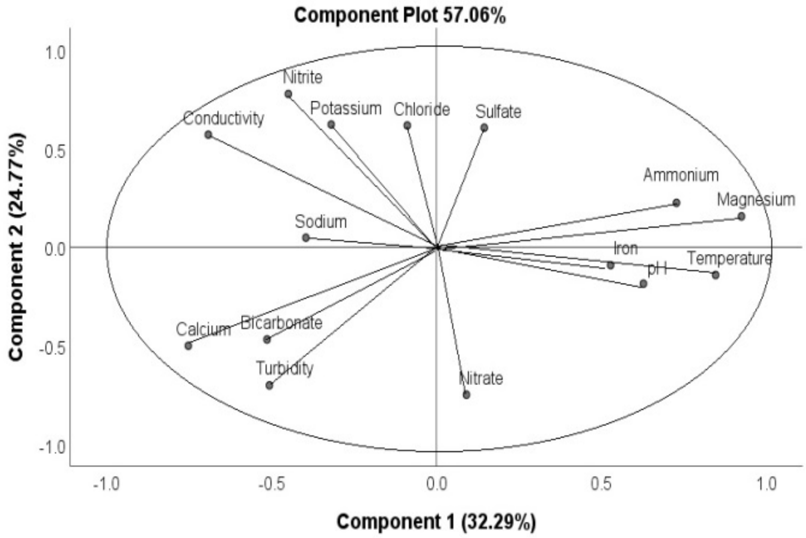

Figure 2. Factor map of physicochemical parameters in water from 10 boreholes, projection of all variables on components 1 and 2.

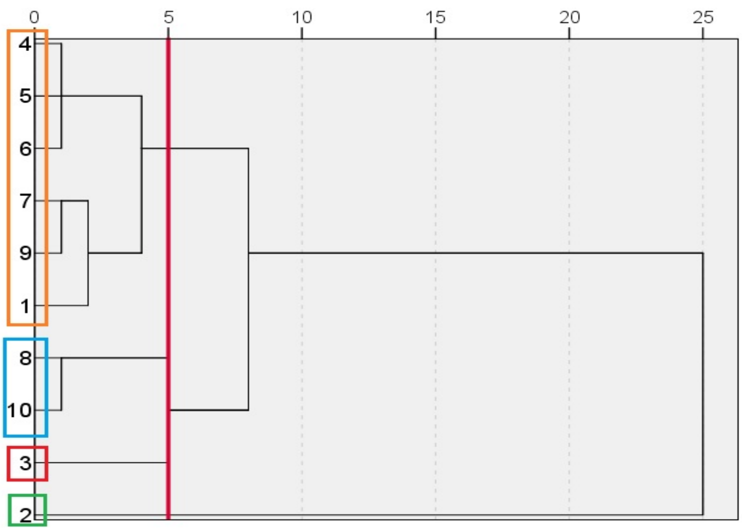

Figure 3. Dendrogram using the Average Linkage (Between Groups) method of ten groundwater samples according to the Ascending Hierarchical Classification (AHC). Legend: 1: FOB1, 2: FOB2, 3: FOB3. 4: FOB4. 5: FOB5. 6: FOB6. 7: FAS7. 8: FAS8. 9: FAS9. 10: FAS10.

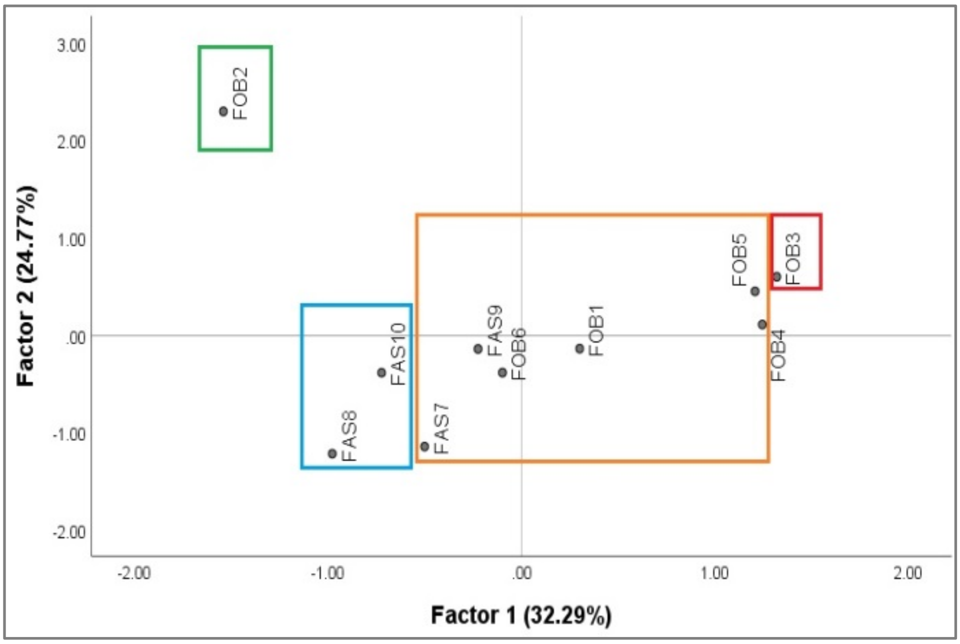

Figure 4. Projection of the ten groundwater samples on the factor (1,2).

with a moderately neutral pH (7.11). It also shows the lowest levels of potassium and bicarbonate, and no detectable nitrite. The singularity of this profile suggests a site-specific hydrogeological or contamination context.

- The 3rd subgroup, represented by of drillings FAS8 and FAS10, is characterized by high concentrations of calcium, sodium, and bicarbonate, intermediate levels of temperature and conductivity, and absence of nitrite and ammonium. This may reflect moderate mineralization possibly linked to geogenic processes, with limited anthropogenic influence.

- The last subgroup consisting of the remaining boreholes (FOB1, FOB4, FOB5, FOB6, FAS7 and FAS9) presents a heterogeneous profile in terms of the physicochemical parameters analyzed. The diversity within this cluster may be attributed to variable land use patterns and degrees of exposure to human activities.

From a practical standpoint, these groupings reveal spatial heterogeneity in groundwater quality and provide useful insight for targeted monitoring and management. Although some sites belong to different municipalities (Oued El Berdi and El Asnam), their hydrochemical similarities suggest that contamination pathways may be influenced more by land use and pollution sources than by administrative boundaries. This emphasizes the need for integrated, cross-regional groundwater management strategies in semi-arid contexts such as Bouira.

To enhance the understanding of groundwater vulnerability and pollution pathways, future investigations should adopt a multidisciplinary framework combining temporal sampling, hydrogeological modelling, and advanced microbial detection methods. Seasonal monitoring would help capture dynamic changes in water quality, particularly in response to agricultural runoff and climatic variability (Zhang et al., 2023; Zehra et al., 2024).

The integration of molecular tools, such as quantitative PCR, could improve the detection of pathogenic or VBNC bacteria, thus strengthening health risk assessments (Guo et al., 2021; Fan et al., 2024). An integrated assessment combining microbiological, geospatial and chemical data can deliver a more complete understanding of contamination sources and support evidence-based groundwater management strategies in semi-arid regions (Shehata et al., 2024).

4. CONCLUSIONS

This study explored the physicochemical and microbiological quality of groundwater in the Bouira region to evaluate its suitability for human consumption and provide a scientific basis for sustainable management in semi-arid environments.

The results highlighted that, although most parameters were within national and WHO standards, elevated nitrate, bicarbonate, and chloride concentrations in several boreholes reflected both geogenic contributions and anthropogenic pressures, particularly from agriculture and domestic wastewater. Multivariate analyses (PCA and AHC) proved effective in identifying contamination patterns and grouping boreholes with similar hydrochemical characteristics, thus supporting a more integrated interpretation of water quality variability.

Microbiological results confirmed the absence of fecal contamination but revealed low levels of mesophilic flora, suggesting minor environmental inputs.

Overall, these findings underline the importance of continuous monitoring, stricter land-use regulation, and preventive management strategies to ensure groundwater safety for drinking purposes and long-term resource sustainability in semi-arid regions such as Bouira.

REFERENCES

Ali Rahmani, S.E., Chibane, B. & Boucefiène, A., 2017. *Groundwater recharge estimation in semi-arid zone: a study case from the region of Djelfa (Algeria)*. Applied Water Science, 7, 2255–2265.

Allaoua, N., Hafid, H. & Chenchouni, H., 2024. *Exploring groundwater quality in semi-arid areas of Algeria: Impacts on potable water supply and agricultural sustainability*. Journal of Arid Land, 16(2), 147–167.

Ayad, W. & Kahoul, M., 2016. *Assessment of physico-chemical and bacteriological quality of well water in the region of El-Harrouch (NE-Algeria)*. Journal of Materials and Environmental Science, 7, 1288–1297.

Azlaoui, M., Zeddouri, A., Haied, N., Nezli, I.E. & Foufou, A., 2021. *Assessment and mapping of groundwater quality for irrigation and drinking in a semi-arid area in Algeria*. Journal of Ecological Engineering, 22, 19–32, https://doi.org/10.12911/22998993/140369.

Bakhtache, R. & Hadjene, O., 2023. *Les retombées du changement climatique sur le secteur agricole et hydraulique en Algérie (2010–2022)*. Revue Cahiers Économiques, 14(01), 80–95.

Bawa, R. & Dwivedi, P., 2019. *Impact of land cover on groundwater quality in the Upper Floridan Aquifer in Florida, United States*. Environmental Pollution, https://doi.org/10.1016/j.envpol.2019.06.054.

Belhadj, M.Z., Boudoukha, A., Amroune, A., Gaagai, A. & Ziani, D., 2017. *Caractérisation statistique de la qualité des eaux souterraines de la zone nord du bassin du Hodna, M'Sila, Algérie*. Larhyss Journal, 31, 177–194.

Bellaredj, A.E. & Hamidi, M., 2020. *Computer modelling of groundwater overexploitation: a case study from the plain of Sidi Bel Abbès (northwestern Algeria)*. Journal of Fundamental and Applied Sciences, 12(1), 1277–1297.

Bencer, S., Boudoukha, A. & Mouni, L., 2016. *Multivariate statistical analysis of groundwater in the Ain Djacer area (Eastern Algeria)*. Arabian Journal of Geosciences, 9, 1–10, https://doi.org/10.1007/s12517-015-2277-6.

Ben Moussa, A., Chandoul, S., Mzali, H., Bel Haj Salem, S., Elmejri, H., Zouari, K., Hafiane, A. & Mrabet, H., 2021. *Hydrogeochemistry and evaluation of groundwater suitability for irrigation purpose in the Mornag region, northeastern Tunisia*. Environment, Development and Sustainability, 23(2), 2698–2718.

Bougherira, N., Hani, A., Toumi, F., Haied, N. & Djabri, L., 2017. *Impact of urban and industrial discharges on water quality in the Meboudja plain (Algeria)*. Hydrological Sciences Journal, 62(8), 1290–1300, https://doi.org/10.1080/02626667.2015.1052451.

Chougar, R., Baali, F., Hadji, R., Ghrieb, L., Hamad, A. & Hamed, Y., 2024. *Assessing groundwater quality in semi-arid conditions: a geographic information systems integrated approach using water quality index*. Bulletin of the Mineral Research and Exploration, 174, 129–143.

Djellali, M., Guefaïfia, O., Fehdi, C., Djellali, A. & Hamad, A., 2023. *Assessing the impact of artificial recharge on groundwater in an overexploited aquifer: A case study in the Cheria Basin, North East of Algeria*. Journal of Groundwater Science and Engineering, 11(3), 263–277.

Downing, J.A., Polasky, S., Olmstead, S.M. & Newbold, S.C., 2021. *Protecting local water quality has global benefits*. Nature Communications, 12(1), 1–6.

Egbuikwem, P.N., Obiechefu, G.C., Hai, F.I., Devanadera, M.C.E. & Saroj, D.P., 2021. *Potential of suspended growth biological processes for mixed wastewater reclamation and reuse in agriculture: challenges and opportunities*. Environmental Technology Reviews, 10, 77–110, https://doi.org/10.1080/21622515.2021.1881829.

El Haissoufi, H., Berrada, S., Merzouki, M., Aabouch, M., Bennani, L., Benlemlih, M., Idir, M., Zanibou, A., Bennis, Y. & El Ouali Lalami, A., 2011. *Pollution des eaux de puits dans certains quartiers de Fès, Maroc*. Revue de Microbiologie Industrielle, Sanitaire et Environnementale, 5(1), 37–68.

El Hammioui, Y., Anarghou, H., Belghiti, M.L., Elhamdouni, D., Saidi, A., Hilali, A., Boutagayout, A. & Abba, E., 2023. *Evaluation of the physicochemical and bacteriological quality of water wells in Khenifra province (Morocco)*. Modeling Earth Systems and Environment, 10, 2239–2255, https://doi.org/10.1007/s40808-023-01902-3.

El-Rawy, M., Wahba, M., Fathi, H., Alshehri, F., Abdalla, F. & El Attar, R.M., 2023. *Assessment of groundwater quality in arid regions utilizing principal component analysis, GIS, and machine learning techniques*. Water, 15(8), 1466, https://doi.org/10.3390/w15081466**.**

Fan, Z., Zhu, H., Tao, C., Deng, N. & Huang, X., 2024. *Quantitative detection of VBNC state* Pseudomonas aeruginosa *contributing to accurate assessment of microbial inactivation in drinking water disinfection*. Water, 16(2), 236, https://doi.org/10.3390/w16020236.

Figarella, J., Leyral, G. & Terret, M., 2001. *Microbiologie générale et appliquée*. Éditions Jacques Lanore, Paris, 285 p.

Gouaidia, L., Laouar, M.S., Defaflia, N. & Zenati, N.,

2017. *Origine de la minéralisation des eaux souterraines dans une région semi-aride: Cas de l'aquifère de Lamerdja, Nord-Est Algérien*. International Journal of Environment and Water, 6(2), 104–114.

Guenouche, F.Z., Mesbahi-Salhi, A., Zegait, R., Chouia, S., Kimour, M.T., & Bouslama, Z. 2024. *Assessing water quality in North-East Algeria: a comprehensive study using water quality index (WQI) and PCA*. Water Practice and Technology, 19(4), 1232–1248, https://doi.org/10.2166/wpt.2024.073.

Guo, L., Wan, K., Zhu, J., Ye, C., Chabi, K. & Yu, X., 2021. *Detection and distribution of VBNC/viable pathogenic bacteria in full-scale drinking water treatment plants*. Journal of Hazardous Materials, 406, 124335, https://doi.org/10.1016/j.jhazmat.2020.124335.

Gupta, S. & Mehrotra, P., 2020. *Assessment of surface water quality of Mahoba Lakes using multivariate statistical tools*. International Journal of Scientific & Technology Research, 9(3), 4737.

Huan, H., 2018. *Comprehensive assessment of groundwater pollution risk based on HVF model: A case study in Jilin City of the Songhua River Basin, Northeast China*. Science of the Total Environment, 628, 1518–1530.

Health Canada, 2020. *Guidelines for Canadian Drinking Water Quality: Guideline Technical Document – Escherichia coli*. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, Ontario.

JORA, 2014. *Journal officiel de la République Algérienne Démocratique et Populaire, n°13, dimanche 9 mars 2014 (7 Joumada El Oula 1435)*.

Kalaivanan, K., Gurugnanam, B., Pourghasemi, H.R., Suresh, M. & Kumaravel, S., 2018. *Spatial assessment of groundwater quality using water quality index and hydrochemical indices in the Kodavanar sub basin, Tamil Nadu, India*. Sustainable Water Resources Management, 4, 627–641.

Kendouci, M.A., Mebarki, S. & Kharroubi, B., 2023. *Investigation of overexploitation groundwater in arid areas: case of the lower Jurassic aquifer, Bechar province, Southwest of Algeria*. Applied Water Science, 13, 102.

Khaldi, F., Smati, H., Grara, N., Smati, N., Maizi, N., Boukehili, K. & Gheid, A., 2018. *Mesure et contrôle des propriétés de quelques eaux souterraines de l'agglomération d'Ouled Driss, Algérie*. Environnement, Risques & Santé, 17(3), 253–261.

Kouame, Y.F., Kedi, A.B.B., Kouassi, S.S., Konan, N.J.A., Assohoun, E.S., Yapo, O.B. & Gnagne, T., 2021. *Caractéristiques physico-chimiques des eaux de forages à usage domestique dans la ville de Daloa (centre-ouest de la Côte d'Ivoire)*. International Journal of Biological and Chemical Sciences, 15(2), 835–845, https://dx.doi.org/10.4314/ijbcs.v15i2.33.

Lamri, N., Bachouche, N. & Bentaleb, L., 2022. *Evaluation of the treatment of purified wastewater in the city of Bouira (Algeria)*. Technium Social Sciences Journal, 37(1), 573–591, https://doi.org/10.47577/tssj.v37i1.7695.

Lora-Ariza, B., Piña, A. & Donado, L.D., 2024. *Assessment of groundwater quality for human consumption and its health risks in the Middle Magdalena Valley, Colombia*. Scientific Reports, 14(1), 11346.

Mansouri, Z., Leghrieb, Y., Kouadri, S., Al Ansari, N., Najm, H.M., Mashaan, N., Eldirderi, M.M.A. & Khedher, K.M., 2022. *Hydro-geochemistry and groundwater quality assessment of Ouargla Basin, South of Algeria*. Water, 14(15), 2441, https://doi.org/10.3390/w14152441.

Masmoudi, T., Benakcha, M., Abdennour, M.A., Bouzekri, A., Amrane, A. & Alcala, F.J., 2024. *Groundwater quality evaluation for drinking and agricultural purposes: A case study in semi-arid region (Zab El-Gharbi SE-Algeria)*. Desalination and Water Treatment, 319, 100476, https://doi.org/10.1016/j.dwt.2024.100476.

Muhammad, S. & Ahmad, K., 2020. *Heavy metal contamination in water and fish of the Hunza River and its tributaries in Gilgit–Baltistan: Evaluation of potential risks and provenance*. Environmental Technology and Innovation, 20, 101159, https://doi.org/10.1016/j.eti.2020.101159.

Ncibi, K., Hadji, R., Hajji, S., Besser, H., Hajlaoui, H., Hamad, A. & Hamed, Y., 2021. *Spatial variation of groundwater vulnerability to nitrate pollution under excessive fertilization using index overlay method in central Tunisia (Sidi Bouzid basin)*. Irrigation and Drainage, 70(5), 1209–1226, https://doi.org/10.1002/ird.2623.

Negm, A.M., Bouderbala, A., Chenchouni, H. & Barcelo, D. (eds.), 2020. *Water Resources in Algeria*. Springer, Vol. 97–98, https://doi.org/10.1007/978-3-030-18326-0.

Ojo, J.T., Ojo, O.M., Olabanji, T.O. & Aluko, R.T., 2024. *Urbanization impact on groundwater quality of selected rural and urban areas in Ondo State, Nigeria using Water Quality Index*. Discover Water, 4, 19, https://doi.org/10.1007/s43832-024-00131-z.

Ould Cheikh Mek, E., El Kacemi, K. & Idrissi, L., 2011. *Caractérisation physico-chimique de l'eau potable dans la ville de Tijikja (Mauritanie)*. International Journal of Biological and Chemical Sciences, 5(5), 2133–2139, http://dx.doi.org/10.4314/ijbcs.v5i5.

Peng, H., Yang, W., Ferrer, A.S.N., Xiong, S., Li, X., Niu, G. & Lu, T., 2022. *Hydrochemical characteristics and health risk assessment of groundwater in karst areas of southwest China: A case study of Bama, Guangxi*. Journal of Cleaner Production, 341, 130872, https://doi.org/10.1016/j.jclepro.2022.130872.

Rahmani, B.E., Baali, F. & Fehdi, C., 2022. *Using PCA and ANN in the explanation of groundwater chemism: Case of the Messaad plateau, South*

Algerian steppe region. Journal of Fundamental and Applied Sciences, 14(1), 88–106, https://doi.org/10.4314/jfas.v14i1.5.

Rehman, N.U., Ali, W., Muhammad, S. & Tepe, Y., 2024. *Evaluation of drinking and irrigation water quality, and potential risks indices in the Dera Ismail Khan district, Pakistan*. Kuwait Journal of Science, https://doi.org/10.1016/j.kjs.2023.11.001.

Rezki, M., 2024. *The impact of pollution on the Algerian water dams—with particular emphasis on a Bouira dam.* Algerian Journal of Chemical Engineering, 2, 60–63.

Rezig, A., Marinangeli, L. & Saggai, S., 2022. *Comparative study for assessing vulnerability to pollution in El Asnam plain, North of Algeria*. Water Supply, 22(6), 5894–5914, https://doi.org/10.2166/ws.2022.129.

Rezig, A., Saggai, S., Baloul, D., Dahmani, S., Bouamria, M. & Djafer Khodja, H., 2021. *Groundwater pollution risk in the region of Bouira (North Center of Algeria): origin and consequences on health*. Journal of Fundamental and Applied Sciences, 13(1), 58–74.

Rodier, J., Legube, B. & Merlet, N., 2016. *L'analyse de l'eau: eaux naturelles, eaux résiduaires, eau de mer*. 10e ed., Dunod, Paris, 1824 p.

Roy, A., Keesari, T., Mohokar, H., Pant, D., Sinha, U.K. & Mendhekar, G.N., 2020. *Geochemical evolution of groundwater in hard-rock aquifers of South India using statistical and modelling techniques*. Hydrological Sciences Journal, 65(6), 951–969, https://doi.org/10.1080/02626667.2019.1708914.

Sakaa, B., Elbeltagi, A., Boudibi, S., Chaffaï, H., Islam, A.R.M.T., Kulimushi, L.C., Choudhari, P., Hani, A., Brouziyne, Y. & Wong, Y.J., 2022. *Water quality index modeling using random forest and improved SMO algorithm for support vector machine in Saf-Saf river basin*. Environmental Science and Pollution Research, 29, 48491–48508, https://doi.org/10.1007/s11356-021-18370-1.

Shehata, M., Zaid, S.M., Al-Goul, S.T., Shami, A., Al Syaad, K.M., Ahmed, A.E., Mostafa, Y.S., Al-Quwaie, D.A., Ashkan, M.F., Alqahtani, F.S., Hassan, Y.A., Taha, T.F., El-Tarabily, K.A. & AbuQamar, S.F., 2024. *Integrated management of groundwater quantity, physicochemical properties, and microbial quality in West Nile Delta using a new MATLAB code and geographic information system mapping*. Scientific Reports, 14, 7762, https://doi.org/10.1038/s41598-024-57036-8.

Shrestha, S., & Kazama, F. 2007. *Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji River basin, Japan*. Environmental Modelling & Software, 22(4), 464–475, https://doi.org/10.1016/j.envsoft.2006.02.001.

Souley Moussa, R., Malam Alma, M.M., Laouali, M.S., Natatou, I. & Issa, H., 2018. *Caractérisation physico-chimique des eaux des aquifères du Continental Intercalaire / Hamadien et du Continental Terminal de la région de Zinder (Niger)*. International Journal of Biological and Chemical Sciences, 12(5), 2395–2411, https://dx.doi.org/10.4314/ijbcs.v12i5.37.

Taşan, M., Demir, Y. & Taşan, S., 2022. *Groundwater quality assessment using principal component analysis and hierarchical cluster analysis in Alaçam, Turkey*. Water Supply, **22**(3), 3431–3447, https://doi.org/10.2166/ws.2021.390.

Ustaoğlu, F., Tepe, Y. & Taş, B., 2020. *Assessment of stream quality and health risk in a subtropical Turkey river system: A combined approach using statistical analysis and water quality index*. Ecological Indicators, 113, 105815, https://doi.org/10.1016/j.ecolind.2019.105815.

Wei, Z., Alam, S., Verma, M., Hilderbran, M., Wu, Y., Anderson, B., Ho, D.E. & Suckale, J., 2024. *Integrating water quality data with a Bayesian network model to improve spatial and temporal phosphorus attribution: Application to the Maumee River Basin*. Journal of Environmental Management, 360, 121120, https://doi.org/10.1016/j.jenvman.2024.121120.

WHO, 2017. *Guidelines for drinking-water quality: 4th ed. incorporating first addendum*. Geneva: World Health Organization, 564 p.

Xiao, J., Gao, D., Zhang, H., Shi, H., Chen, Q., Li, H., Ren, X. & Chen, Q., 2023. *Water quality assessment and pollution source apportionment using multivariate statistical techniques: A case study of the Laixi River Basin, China*. Environmental Monitoring and Assessment, 195, 287, https://doi.org/10.1007/s10661-022-10855-6.

Zehra, A., Kaur, S., Gill, J.P.S. & Singh, R., 2024. *Integrated assessment of groundwater contamination: A multi-marker approach for comprehensive water quality monitoring*. Water Supply, 24(5), 1447–1461, https://doi.org/10.2166/ ws.2024.065.

Zerdane, D., 2013. *Étude hydrologique et hydrogéologique de la région de Bouira*. Magister Thesis, University USTHB, 139 p.

Zhang, X., Gao, X., Li, C., Luo, W., Wang, Y. & Luo, X., 2023. Seasonal dynamics and interaction of shallow groundwater geochemical properties and microbial community patterns. *Chemical Geology*, 638, 121703, https://doi.org/10.1016/j.chemgeo.2023.121703.

Received: 22. 06. 2025
Revised: 10.10.2025
Accepted: 19. 10 2015
Published: 21. 10. 2025