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Seasonal Hydrochemical and Microbiological Statistical Assessment of Lake Al-Mallah Water (Northeast Algeria) Using PCA and Hydrochemical Diagrams

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The present study investigates the hydrochemical, physico-chemical and microbiological characteristics of Lake Al-Mallah and its tributaries in northeast Algeria to identify the major factors controlling water quality and pollution sources. A total of 17 sampling stations distributed across wadis, wastewater discharge points, the wastewater treatment plant (WWTP) and the lake were monitored during high-water and low-water periods. Physico-chemical, hydrochemical and microbiological parameters were analysed using standard methods. Hydrochemical facies and irrigation suitability were evaluated using Piper, Schoeller-Berkaloff and Riverside diagrams, while principal component analysis (PCA) was applied to interpret spatial and seasonal variations in water quality. The results revealed significant spatial and seasonal variability influenced by both natural and anthropogenic factors. Lake waters were mainly characterized by hyper-chlorinated and hyper-sulphated calcium facies due to marine intrusion, evaporation and dissolution of gypsum formations, whereas wadi waters exhibited chlorinated and sulphated calcium–magnesium facies. PCA distinguished two dominant controlling factors *viz*. mineralisation associated with seawater intrusion and geological formations and anthropogenic pollution linked to wastewater discharge and agricultural runoff. Increased concentrations of nutrients, BOD_5, suspended solids and microbial indicators were recorded during summer, while dissolved oxygen levels decreased due to intensified microbial activity and reduced dilution capacity. Electrical conductivity values approached seawater salinity, confirming strong mineralisation processes. Sodium adsorption ratio (SAR) and riverside assessments indicated generally low alkalinisation risk and acceptable irrigation suitability for most tributary waters. However, persistent microbial contamination and nutrient enrichment near the WWTP and downstream regions demonstrated the considerable impact of urban wastewater and agricultural activities on the ecological condition of Lake Al-Mallah. The study highlights the effectiveness of integrated hydrochemical and multivariate statistical approaches for understanding environmental pressures affecting coastal aquatic ecosystems.

Keywords: Lake Mellah, Environmental pollution, Wastewater, Principal component analysis (PCA), Physico-chemical data.

INTRODUCTION

Surface water quality is a dynamic reflection of the complex interaction between natural geological processes and increasing human pressures [1]. In sensitive ecosystems such as Lake Melah in the Kalaa region (northeast Algeria), where the sub-watersheds and the surface area of Lake Melah are considered sites for social and economic activities that gradually alter the environmental characteristics [2]. The importance of studying the physical and chemical properties is highlighted to understand the fundamental transformations that occur in the waters of the valleys as they flow from their sources to the final outlet in the lake. River systems, in this context, serve as sensitive indicators of the Anthropocene epoch, where human determinants often overshadow the natural controls of the Earth's system [1].

This study is based on the need to evaluate the environmental status of this unique aquatic system, which is subjected to dual influences. The first involves natural geological factors, including interactions with gypsum-rich rock formations and the surrounding soil composition. The second arises from marine intrusion caused by water exchange with the Mediterranean sea, leading to significant increases in mineralisation and electrical conductivity, particularly during the summer season. Secondly, the aquatic system is exposed to considerable anthropogenic pressures associated with the discharge of urban wastewater and agricultural runoff [3]. These activities promote the accumulation of organic pollutants and nutrient loads, particularly nitrogen and phosphorus compounds [4], leading to progressive deterioration of water quality, especially in the middle reach influenced by effluents from the sewage treatment plant [5,6].

The scientific significance of this study lies in the application of a multivariate analytical approach to differentiate between natural and anthropogenic sources of pollution within the aquatic system. Hydrochemical characterization was performed using Piper and Schoeller–Berkaloff diagrams to identify the dominant chemical facies and to determine the origin of dissolved ions. In addition, the suitability of the water for agricultural purposes was evaluated through the sodium adsorption ratio (SAR) and the Riverside classification diagram based on the criteria proposed by Richards [7]. Seasonal variations in water quality were also systematically investigated.

Principal component analysis (PCA), recognised as an effective tool for interpreting spatial and temporal variations in complex hydrological datasets [8], was employed to identify the major factors controlling water quality and pollution sources. Particular attention was given to the differences between high-water (HW) and low-water (LW) periods, during which pollutant concentrations and microbiological indicators tend to increase in summer due to reduced dilution capacity and elevated temperatures that stimulate microbial activity. Understanding these hydrochemical and environmental dynamics is essential for developing effective strategies for sustainable water resource management, improving wastewater treatment efficiency and protecting the biodiversity and ecological integrity of Al-Mallah Lake (Northeast Algeria) from progressive environmental degradation.

EXPERIMENTAL

This study was based on an integrated field and laboratory investigation designed to evaluate the physico-chemical and microbiological characteristics of the waters of Al-Mallah Lake and its tributaries. A total of 17 sampling stations were selected along river channels, discharge outlets, the wastewater treatment plant and the central region of the lake. The geographical coordinates of each station were determined using a Global Positioning System (GPS). The sampling locations were strategically selected to represent the impacts of urban expansion, surface runoff and domestic and agricultural discharges within the study basin (Fig. 1, Table-1).

Sampling campaigns were conducted during two monitoring periods. The first involved monthly sampling during 2023 at selected reference stations, while the second comprised four seasonal campaigns during 2024 to assess temporal and spatial variations in water quality. Water samples were collected in clean, airtight polyethylene containers pre-rinsed with sample water. Samples intended for microbiological analysis were preserved at 4 ºC in refrigerated containers and transported to the laboratory within 4 h, whereas physico-chemical analyses were completed within 24 h of sampling. The analyses were carried out in specialised laboratories for physico-chemical and bacteriological investigations. *In situ* measurements included temperature, pH, oxidation-reduction potential (ORP), electrical conductivity, salinity and dissolved oxygen using multiparameter probes. Turbidity was measured under laboratory conditions using a dedicated turbidity meter. Chemical analyses included the determination of major ions and water quality parameters such as chlorides, sodium, calcium, potassium, magnesium, total hardness, calcium hardness, alkalinity, suspended solids, organic matter, nitrite, nitrate, ammonium and orthophosphate using standard analytical procedures including titration, spectrophotometry, atomic absorption spectroscopy and gravimetric filtration. Microbiological quality assessment focused on indicators of faecal contamination, including total coliforms, thermotolerant coliforms and faecal streptococci. These analyses were performed using the most probable number (MPN) method with selective culture media through presumptive and confirmatory stages in accordance with standard microbiological protocols.

Data processing and statistical analysis: The hydrochemical and statistical analyses were performed to evaluate the water quality and identify the factors influencing the hydrochemical characteristics of Al-Mallah Lake and its tributaries. Hydrochemical interpretation was conducted using the software, which facilitates the representation and classification of water samples according to their ionic composition and suitability for agricultural use [9,10]. The principal graphical representations employed included the Piper diagram, Schoeller-Berkaloff semi-logarithmic diagram and Riverside diagram. These diagrams were used to determine hydrochemical facies, compare water samples and assess irrigation suitability.

Considering the large number of measured variables, principal component analysis (PCA) was applied using XLSTAT software to interpret relationships among physico-chemical and microbiological parameters. PCA is a multivariate statistical technique that reduces data dimensionality while preserving the maximum amount of information contained within the dataset. The method enabled the identification of the major factors controlling water quality and facilitated the interpretation of spatial and temporal variations through graphical projection onto factorial axes [11].

RESULTS AND DISCUSSION

The physico-chemical data of Lake Mellah and its tributaries on the Piper diagram enabled the identification of the hydrochemical facies and the determination of their natural or anthropogenic origins [12,13]. The Piper diagrams for both high-water (HW) and low-water (LW) periods clearly distinguished saline lake waters from freshwater sources associated with the wastewater treatment plant (WWTP) and the surrounding wadis (Fig. 2). The results indicate marked spatial variability in hydrochemical characteristics among the sampling stations, whereas temporal variations between the two hydrological periods were comparatively less pronounced.

The waters of Lake Mellah were characterized by hyperchlorinated calcium and hyper-sulphated calcium facies during both study periods. The increased chloride concentrations are mainly attributed to the dissolution of saline geological formations and marine intrusion resulting from water exchange

Fig. 1. Geographic location and satellite view of the sampling sites in Lake Mellah and its effluents

TABLE-1
LIST OF SAMPLING STATIONS WITH THEIR NAMES AND GEOGRAPHIC COORDINATES

Name of the sampling station		No.	Coordinate North	Coordinate East
Wastewater treatment plant	Raw water	1	N36º51′.51.5″	E008º20′.38.4″
	Purified water/Treated water	2	N36º51′53.8″	E008º20′36″
Wadis	Wadi El Aroug upstream	3	N36º50′51.6″	E008º19′30.9″
	Wadi El Aroug downstream	4	N36º51′45.2″	E008º20′06.6″
	Wadi Mellah upstream	5	N36º52′07.0″	E008º17′35.1″
	Wadi Mellah downstream	6	N36º52′08.6″	E008º19′38.3″
	Wadi Souk Rguibet upstream	7	N36º54′08.3″	E008º15′56.8″
	Wadi Souk Rguibet downstream	8	N36º54′01.4″	E008º17′42.6″
	Wadi Boumalek upstream	9	N36º53′40.8″	E008º20′41.4″
	Wadi Boumalek downstream	10	N36º53′40.6″	E008º20′35.0″
Lake	Channel of lake	11	N36º54′36.1″	E008º19′07.4″
	Exit of Wadi Souk Rguibet	12	N36º54′08.4″	E008º18′22.4″
	Exit of Wadi Boumalek	13	N36º53′49.7″	E008º20′16.2″
	Center of the lake	14	N36º53′27.6″	E008º19′45.0″
	Exit of Wadi Mellah	15	N36º52′36.0″	E008º19′39.8″
	Exit of Wadi El	16	N36º52′29.03″	E008º20′16.1″
	Exit of the wastewater treatment plant	17	N36º52′35.1″	E008º20′25.4″

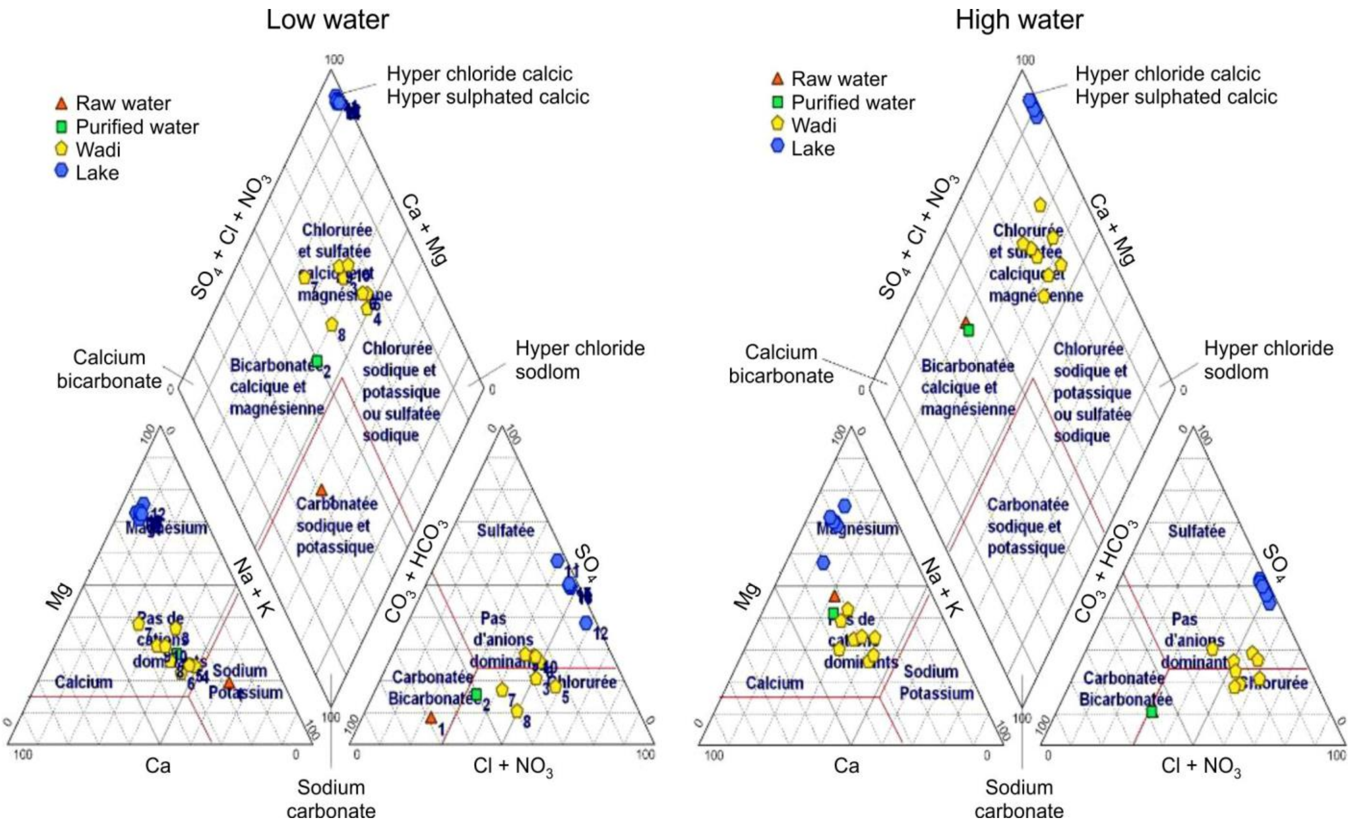

Fig. 2. Piper diagram showing the hydrochemical facies of water samples during high and low water periods

between the lake and the Mediterranean sea. The sulphate enrichment is associated with the dissolution of gypsum formations ($CaSO_4 \cdot 2H_2O$). The waters of the wadis exhibited chlorinated and sulphated calcium–magnesium facies during both hydrological periods. This hydrochemical composition is controlled by combined dilution–concentration processes [14], enhanced evaporation and anthropogenic inputs. The widespread occurrence of chloride ions reflects the influence of domestic and agricultural pollution sources, while calcium originates primarily from the leaching of gypsum-rich formations and magnesium is partly derived from clay minerals.

The raw influent waters of the WWTP displayed bicarbonate calcium–magnesium facies during the high-water period, indicating the influence of local geological formations and limestone leaching during runoff events. During the low-water period, the influent waters shifted toward sodium–potassium carbonate facies, likely due to increased wastewater discharge and the contribution of agricultural fertilizers, which elevate sodium concentrations. In contrast, treated effluent waters from the WWTP maintained a bicarbonate calcium–magnesium facies during both hydrological periods. The dominance of bicarbonate ions may be associated with anthropogenic discharges and agricultural effluents that promote photosynthetic activity and algal development within the treatment system.

$$HCO_3^- + H_2O = CO_2 + H_2O \qquad (1)$$

Assessment of the water quality of Lake Mellah tributaries for agricultural use: The concentration of Na^+ ions in the soluble state in the soil is important; these ions most frequently replace the Ca^{2+} cations (base exchange) in the absorbent complex. Salt-laden water can cause this action. This risk is determined using the value of absorbable sodium (sodium absorption ratio, SAR). For the same conductivity, the risk is greater the higher the coefficient. SAR is defined by the following relationship:

$$SAR = \frac{(Na^+ + K^+)}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \qquad (2)$$

All the ions are expressed in meq L^{-1}.

All water points are plotted on the Riverside diagram [7]. According to the electrical conductivity and the SAR value (Fig. 3), it can be observed that the water quality of the tributaries of the waters of the watershed of Lake Mellah according to the Riverside method presents a low danger of alkalinisation and could be used in irrigation. A comparison of the two SAR distribution periods showed a similar distribution of the irrigation ability classes.

Study of pollution sources in the waters of Lake Al-Mallah and its tributaries: The statistical analysis of the physico-chemical and microbiological characteristics of the waters of Lake Al-Mallah and its tributaries included data collected from seventeen sampling stations distributed across the wastewater treatment plant (WWTP), wadis and lake environments during the study period. Nineteen variables were analysed using PCA following the approach of Davis [15]. The analysis was performed on standardized variables using XLSTAT software, a method widely applied in hydrochemical investigations for the interpretation of complex environmental datasets [16,17].

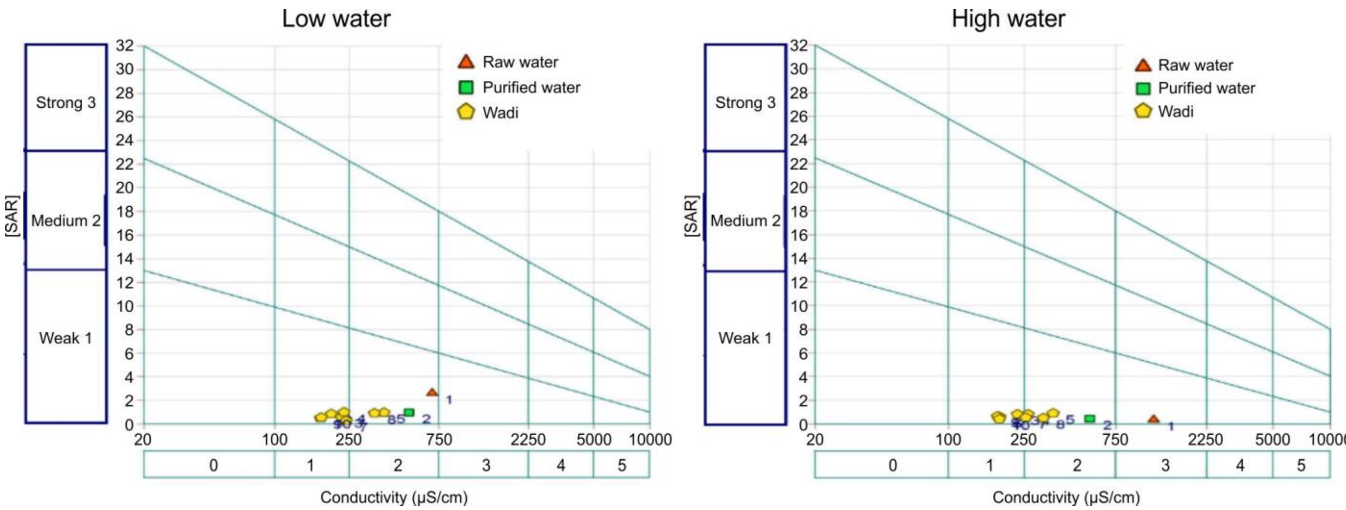

Fig. 3. Riverside diagram for the assessment of tributary water quality for irrigation purposes

Descriptive statistics: Table-2 summarizes the descripttive statistics of the physico-chemical and microbiological parameters measured in the study area. The results reveal considerable spatial variability in water quality among the 17 investigated stations, reflecting the combined influence of natural processes and anthropogenic activities.

Microbiological indicators: The microbiological analysis showed increased levels of total coliforms (TC) and thermotolerant coliforms (TTC), with maximum values reaching 1400 MPN/100 mL at several stations. These high concentrations indicate significant faecal contamination, particularly in areas located near the wadi outlets and the wastewater treatment plant. The elevated mean values suggest that microbial pollution represents a persistent environmental condition rather than isolated contamination events.

Seasonal variation was also evident, as TTC concentrations increased markedly during the summer period, with average values reaching 472.67 MPN/100 mL compared with 188.17 MPN/100 mL during winter. This increase can be attributed to higher water temperatures, averaging approximately 26.1 ºC, which provide favourable conditions for bacterial growth and reproduction. In addition, the elevated organic matter content, reflected by increased BOD_5 values during summer season, may contribute to the formation of protective biofilms that enhance bacterial survival despite high salinity conditions.

Organic pollutants and suspended solids

BOD_5: The BOD_5 values ranged from 10 to 150 mg/L. The maximum recorded value (150 mg/L) greatly exceeded

TABLE-2
DESCRIPTIVE STATISTICS OF THE PHYSICO-CHEMICAL AND MICROBIOLOGY PARAMETERS OF LAKE MELLAH AND ITS TRIBUTARIES (MEAN ± SD, MIN, MAX)

Variable	Name of the sampling station	Winter (HW) Dynamics				Summer (LW) Dynamics			
		Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation
Cl^-	Wastewater treatment Plant + Wadis + Lake	23.10	1354.50	545.17	632.90	8.90	1278.00	482.18	572.38
HCO_3^-		12.20	143.40	69.81	48.80	15.300	371.600	90.394	87.119
Mg^{2+}		7.20	594.40	232.57	280.10	2.400	665.000	251.671	309.32
SO_4^{2-}		16.00	1773.00	613.38	810.81	5.000	1785.50	598.71	814.53
Na^+		11.00	173.30	67.48	63.33	2.900	130.30	59.55	49.96
K^+		0.00	8.10	2.21	2.61	0.000	11.400	2.047	3.00
Ca^{2+}		12.00	288.60	120.24	130.83	4.000	316.60	119.28	135.13
Cond.		181.00	53500.00	21730.29	25741.66	174.000	56009.00	22076.85	26836.89
NH_4^+		0.00	0.70	0.21	0.21	0.000	2.70	0.40	0.70
PO_4^{3-}		0.00	1.40	0.47	0.39	0.000	1.40	0.31	0.40
NO_2^-		0.10	0.300	0.224	0.07	0.000	10.00	0.95	2.62
NO_3^-		0.60	6.500	1.918	1.48	0.700	32.80	6.74	7.65
DBO_5		0.00	140.00	22.81	31.57	0.000	150.00	32.64	40.35
MES		2.00	96.50	17.91	21.92	5.000	139.00	18.61	31.46
TC		92.50	1400.00	1021.61	472.99	9.000	1400.00	853.91	579.33
TTC		0.00	1400.00	188.17	385.31	2.000	1400.00	472.67	513.09
STREP		4.50	704.50	58.79	167.01	0.500	60.00	17.82	18.94
O_2		1.30	11.00	8.37	2.52	1.570	6.80	4.23	1.33
Temperature		19.850	29.850	26.109	2.614	19.850	29.850	26.109	2.614

the permissible limits for surface waters, indicating a high organic pollution load [18]. The seasonal variation was also observed, with the average BOD_5 concentration increasing during the summer season (32.64 mg/L) compared with winter season (22.81 mg/L), likely due to elevated temperatures and intensified microbial degradation of organic matter.

Suspended solids (SS): Suspended solids (SS) showed considerable variation, with concentrations ranging from 2 to 139 mg/L. Elevated SS values are mainly associated with surface runoff during the winter season and the discharge of untreated domestic wastewater, both of which contribute to increased particulate matter in the aquatic environment.

Dissolved oxygen (DO): Dissolved oxygen concentrations were generally lower during the summer period, with an average value of 4.23 mg/L compared with 8.37 mg/L in winter. This decrease can be attributed to elevated summer temperatures, which reduce oxygen solubility in water, while simultaneously enhancing bacterial decomposition of organic matter and increasing oxygen consumption [19].

Electrical conductivity (EC): Electrical conductivity values reached a maximum of 54,754 µS/cm, approaching the salinity level of seawater. Seasonal analysis revealed higher conductivity values during summer (56,009 µS/cm) compared with winter (53,500 µS/cm). This trend reflects the strong influence of marine intrusion combined with intense evaporation during the dry season, resulting in increased mineralisation and concentration of dissolved salts.

Nutrients (nitrogen and phosphate): Nitrate (NO_3^-) concentrations increased significantly during summer, with average values rising from 1.91 mg/L in winter to 6.74 mg/L in summer season. This increase is associated with intensive agricultural activities, wastewater inputs and enhanced nitrification processes under elevated temperatures, which stimulate microbial conversion of ammonia into nitrate.

Hydrochemical and microbiological variability: PCA is widely applied in hydrochemical studies to interpret complex environmental datasets and identify the major factors controlling water quality [20-22]. The hydrochemical and microbiological datasets obtained from the 17 sampling stations, including the wastewater treatment plant, wadis and Al-Mallah Lake, were analysed using PCA performed on standardized variables with XLSTAT software.

The PCA results for both winter and summer seasons were interpreted using the factorial axes F1 and F2. During the winter season, the correlation circle and factor projection formed by the F1-F2 axes (Fig. 4a) explained 71.88% of the total variance, with F1 accounting for 47.36% and F2 contributing 24.52%. Similarly, the summer PCA results (Fig. 4b) showed that the F1-F2 factorial plane explained 71.95% of the total variance. In this case, the F1 axis represented 42.16% of the variance, while the F2 axis accounted for 29.78%. These results indicate that the first two principal components adequately describe the spatial and seasonal variability of the hydrochemical and microbiological characteristics of the study area.

During both observation periods, the PCA correlation analysis showed that the F1 axis was mainly associated with electrical conductivity together with chloride, sodium, sulphate, magnesium and calcium ions at the positive pole, whereas nutrients and microbiological indicators were positioned toward the negative pole. The F2 axis was characterized by ammonium, orthophosphate, nitrate, BOD_5, total suspended solids (TSS), bicarbonate and potassium at the positive pole, while dissolved oxygen was represented at the negative pole.

The graphical representation of the variables revealed two major groups controlling water quality in the study area. The first group included Cl^-, SO_4^{2-}, Na^+, Mg^{2+}, Ca^{2+}, Mg^{2+}, Ca^{2+}, HCO_3^- and K^+, indicating a strong contribution of these ions to water mineralisation. This group reflects the influence of both geological formations and marine intrusion on the hydrochemical composition of the waters. Calcium, magnesium and sulphate ions are mainly associated with the dissolution of evaporitic gypsum formations, whereas chloride and sodium

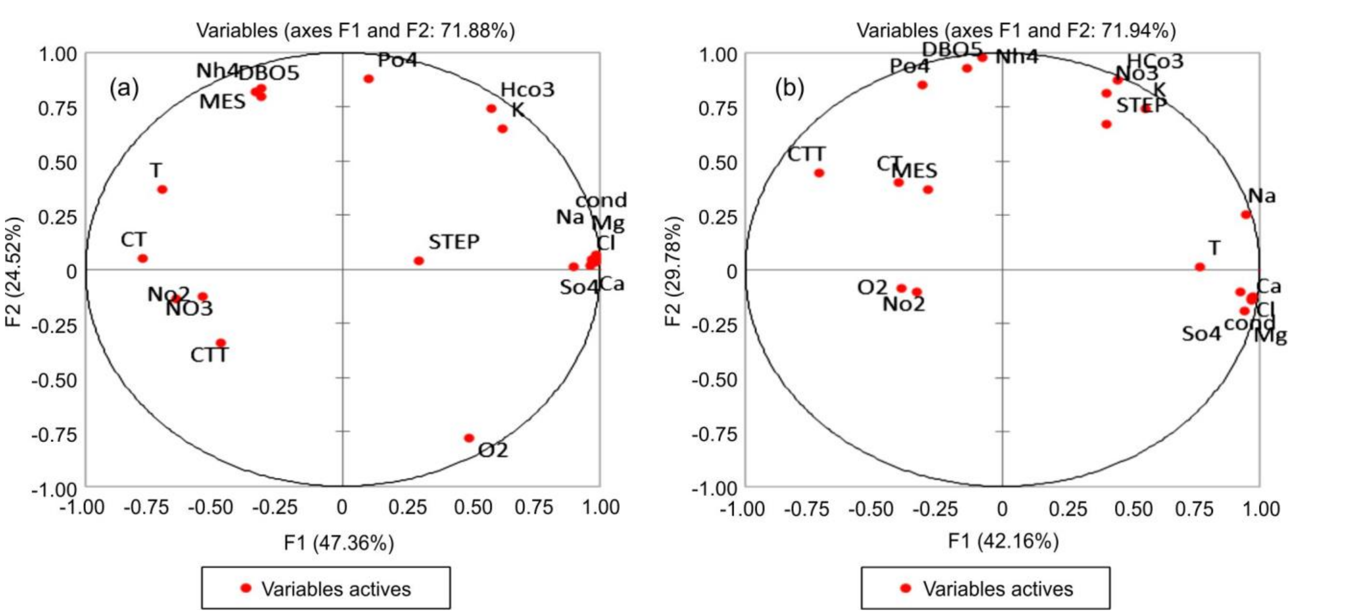

Fig. 4. Projection of physico-chemical and microbiological parameters on the factorial plane (F1-F2) for the winter season (a) high water and (b) low water

enrichment are linked to seawater intrusion and evaporation processes, as confirmed by the Piper and Schoeller-Berkaloff diagrams.

The second group comprised nitrates, ammonium, phosphates, BOD_5, suspended solids and microbiological indicators, reflecting anthropogenic pollution associated with urban runoff, untreated domestic wastewater and agricultural activities, including fertilizer application and livestock farming. The strong association between nutrients, organic matter and microbiological contamination confirms the significant impact of human activities on water quality degradation.

The results also demonstrated marked seasonal variation between the winter (high-water) and summer (low-water) seasons. During summer season, most of the physico-chemical and microbiological parameters showed substantially higher concentrations, particularly nutrients (NH_4^+, NO_3^- and PO_4^{3-}), organic pollution indicators (BOD_5) and microbial contamination indicators (TC and TTC). Elevated temperatures during summer season accelerate organic matter decomposition and stimulate nitrification processes, leading to increased ammonium and nitrate concentrations [19]. In contrast, dissolved oxygen concentrations decreased during summer season due to intensified biological activity and oxygen consumption during organic matter degradation [4].

Electrical conductivity and salinity also increased significantly during the summer season, reflecting enhanced mineralisation caused by intense evaporation and reduced dilution capacity. Consequently, dissolved ions such as Cl^-, SO_4^{2-} and Na^+ became more concentrated, with some stations, particularly stations 10 and 12, recording conductivity values exceeding 14,000 μS/cm.

Spatial and seasonal relationships between microbiological and physico-chemical indicators: Understanding the relationship between microbiological contamination and physico-chemical properties is essential for assessing water quality in aquatic ecosystems [4,23]. The present study investigated the spatial and seasonal distribution of pollution across wadis, wastewater discharge points and Lake Al-Mallah in order to identify the interactions between anthropogenic inputs and natural environmental processes (Fig. 5).

The PCA results revealed that the most pronounced deterioration in water quality occurred in the middle reaches directly influenced by the wastewater treatment plant (WWTP). Stations located near the plant outlet showed strong correlations with elevated BOD_5, NH_4^+ and PO_4^{3-} concentrations, indicating substantial organic and nutrient enrichment. Although the WWTP treats incoming wastewater, the persistence of high organic and nutrient levels in treated effluents suggests that the facility may be operating beyond its effective treatment capacity. Similar observations have been reported by Cooper *et al*. [24], who observed that wastewater treatment plants may become significant point sources of nutrient pollution when treatment efficiency declines. The discharge from the WWTP produced a distinct chemical signature dominated by nitrogen and phosphorus compounds, clearly differentiating anthropogenic pollution from the natural hydrochemical background represented by the F2 axis. Pollution intensity increased during summer season, likely due to reduced dilution capacity and lower disinfection efficiency under the elevated temperatures.

In contrast, the F1 axis mainly reflected the natural geological and hydrological influences controlling water chemistry. As water flowed downstream, prolonged interaction with geological formations increased mineralisation, resulting in higher electrical conductivity and elevated concentrations of calcium and magnesium ions. The lake stations no. 11-17 exhibited a predominantly mineralized character associated with both evapouritic formations and seawater intrusion processes. According to APHA [25], ion exchange and mixing between lake water and seawater contribute significantly to salinity increases within coastal aquatic systems. Consequently, Lake Al-Mallah acts as a terminal basin for dissolved salts and mineral constituents [26].

A longitudinal gradient in dissolved oxygen was also observed from upstream to downstream locations. Upstream waters maintained relatively high oxygen concentrations due to the turbulence and lower organic loads, whereas oxygen

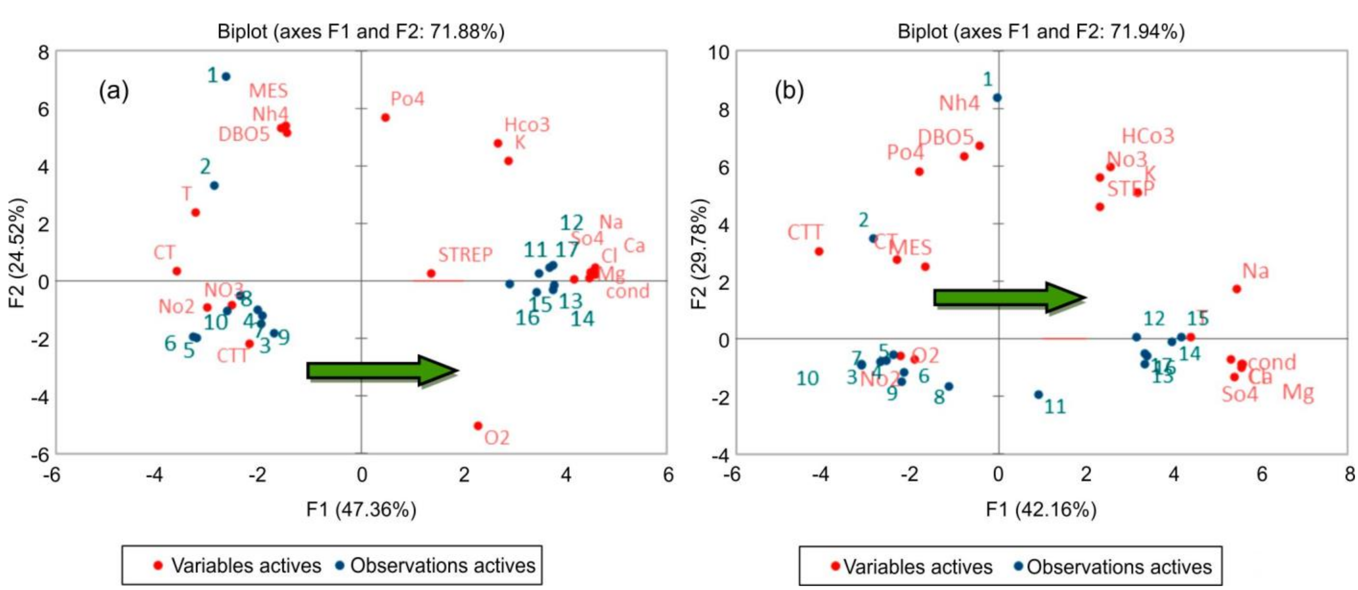

Fig. 5. The graphical representation of the stations and parameters on the factorial plane (F1, F2) period of (a) high water and (b) low water

levels declined significantly near the estuarine and lake regions due to intensified microbial decomposition of organic matter originating from wastewater discharges [27]. Although certain microorganisms may tolerate elevated salinity, faecal indicator bacteria generally decrease in highly saline environments. Therefore, the persistence of high microbial counts within the lake indicates the existence of continuous and active pollution sources affecting the ecological health of Lake Al-Mallah.

Seasonal impact: Seasonal variation strongly influenced the upstream-downstream dynamics of the study area, particularly in Wadi Al-Malih (stations 5 and 6). During the winter season (high water), increased flow rates promoted dilution and partially reduced pollutant concentrations. In contrast, the summer season (low water) was characterized by elevated concentrations of nutrients and microbial indicators at downstream station 6, reflecting the concentration of domestic pollutants under reduced flow conditions [28].

Stations no. 11-16, located within Lake Al-Mallah, exhibited marked increases in electrical conductivity and salinity ions (Na^+ and Cl^-) during summer season due to intense evaporation and seawater intrusion. Increased salinity can alter microbial community structure and reduce the survival of certain coliform strains [29]. Simultaneously, increasing water temperature led to lower dissolved oxygen concentrations, favouring anaerobic processes and supporting the persistence of thermotolerant coliform bacteria (TTC). The positive correlation observed between (BOD_5) and total coliform counts (TC) indicates that organic matter may act as a protective medium that enhances pathogen survival against natural degradation processes [30]. Consequently, the summer season intensified pollutant accumulation due to the limited dilution capacity, whereas the winter season produced a dilution effect but also increased suspended solids (TSS/SS) through enhanced surface runoff and soil erosion processes [31].

Conclusion

This study provided a comprehensive assessment of the hydrochemical, physico-chemical and microbiological characteristics of Lake Al-Mallah (Northeast Algeria) and its tributaries under the influence of natural and anthropogenic factors. The results demonstrated pronounced spatial and seasonal variability in water quality across the study area. Hydrochemical analyses indicated that lake waters are strongly affected by marine intrusion, evaporation and dissolution of evaporitic formations, leading to increased salinity and mineralisation, particularly during summer, while tributary waters reflected combined geological and anthropogenic influences. PCA successfully differentiated between natural mineralisation processes and pollution originating from wastewater discharge and agricultural runoff. Elevated concentrations of nutrients, BOD_5 and microbial indicators during the low-water period confirmed the influence of reduced dilution and enhanced biological activity in summer. The WWTP was identified as a major point source contributing to nutrient enrichment and microbiological deterioration of downstream waters. Although most tributary waters showed acceptable irrigation suitability according to SAR and riverside classifications, persistent salinity and microbial contamination may pose ecological risks if pollution inputs continue to increase. The combined use of hydrochemical diagrams and multivariate statistical techniques proved effective for interpreting water quality dynamics and identifying pollution sources in Lake Al-Mallah. These findings emphasise the need for improved wastewater management, continuous monitoring and sustainable protection strategies to preserve this sensitive coastal aquatic ecosystem.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language. The authors reviewed and edited the content and take full responsibility for the published work.

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