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Application of WQI, OPI, and statistical analyses for monitoring water quality in the El Hammam wetlands using GIS under anthropogenic pressures in northern Algeria

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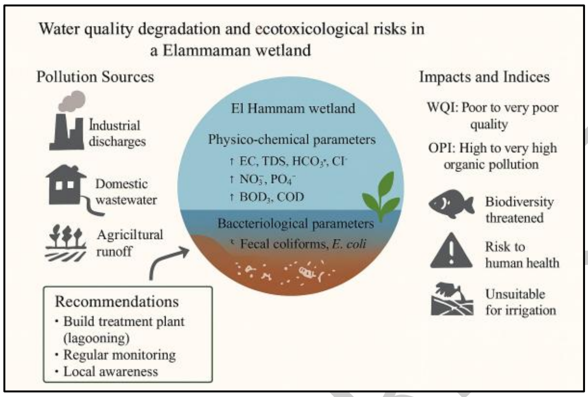
Graphical abstract



Abstract

Wetlands as vital reservoirs of biodiversity and ecosystem services, are increasingly threatened by anthropogenic pressures and inadequate environmental management. Despite their ecological importance, few studies have focused on the integrated assessment of water quality and ecotoxicological risks in the Mediterranean wetlands of Algeria. This study aims to evaluate the physicochemical, bacteriological, and ecological quality of surface waters in the El-Hammam wetland (Medjana) region, Bordj Bou Arreridj, Eastern Algeria. A comprehensive set of parameters including temperature, pH, electrical conductivity, dissolved oxygen, BOD_5, nutrients ((HCO_3^-) levels ranged from 353 mg/L to 475.8 mg/L , (Cl^-) concentrations were also elevated, varying between 497 mg/L and 798 mg/L ,(NH_4^+) concentrations ranged from 0.64 mg/L to 2.86 mg/L and Nitrate (NO_3^-) concentrations ranged from 10.54 mg/L to 35 mg/L with (NO_2^-) values were relatively low, ranging from 0.02 mg/L to 0.41 mg/L), and microbiological indicators (total and fecal coliforms, fecal streptococci, mesophilic flora) was analyzed across multiple sampling sites. The Pearson correlation matrix was used to identify significant relationships among the physicochemical variables and to determine the primary pollution sources. The results reveal substantial degradation of water quality, primarily driven by urban, agricultural, and industrial discharges, as well as climatic and edaphic factors. BOD_5 values exceeded 10 mg/L in several sites, and nitrate concentrations reached up to 40 mg/L, indicating organic and agricultural contamination. Faecal coliforms exceeded 2000 CFU/100 mL, highlighting serious sanitary and ecological risks. The Organic Pollution Index (IPO) and other quality indicators confirmed an alarming ecological imbalance, threatening both biodiversity and human health. Overall, this study provides a comprehensive diagnosis of surface water degradation in a semi-arid region north of Africa.

Keywords: Water Quality index, Bacteriological Analysis, Physiochemical Parameters. Statistical analysis. El Hammam wetlands, Northern Algeria

1. Introduction

Water is a vital natural resource, essential for all forms of life. This resource primarily exists as freshwater from surface water sources such as rivers, lakes, and ponds (Meskine *et al.* 2025). Due to its uneven distribution worldwide, water has become a major political, economic, and strategic issue (Ben Salem *et al.* 2023). As a key factor in sustainable development, water supports all human activities and constitutes an essential pillar for ecosystem survival (Garba *et al.* 2025).

Globally, water quality is increasingly deteriorating due to growing natural and anthropogenic pressures. Natural factors include rapid climate change, drought, and soil

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erosion (Abuni *et al.* 2025) Anthropogenic pressures encompass intensified industrial, agricultural, and urban activities, as well as the discharge of domestic and industrial wastewater. These pollutants, capable of migrating and accumulating in environmental and biological compartments, become toxic at threshold levels, causing adverse effects on human health and the environment (Ucheana *et al.* 2024). Such pressures have significantly altered the physicochemical and biological quality of water, rendering it unsuitable for various uses such as drinking, irrigation, or livestock watering (Zhang *et al.* 2022).

Among the most sensitive and strategic ecosystems are wetlands. These habitats, representing between 4% and 6% of the global terrestrial surface (Alikhani *et al.* 2021), play a critical role in the hydrological cycle and biodiversity conservation (Mohan *et al.* 2019; Yang *et al.* 2021). They provide essential ecosystem services, including groundwater recharge, sediment retention, natural water purification, and habitat for a wide variety of plant and animal species (Raveena and Surendran 2024). Wetlands also hold significant economic importance, supporting agriculture, fisheries, and tourism (Aliat *et al.* 2018). In Algeria, wetlands exhibit considerable biological and ecological value (Benzina *et al.* 2024), yet, similar to other Mediterranean countries, they are threatened by drainage, drying, climate change, and pollution (Emmanuel and Moses *et al.* 2023).

Wetlands frequently receive effluents from industrial and domestic wastewater, as well as agricultural runoff enriched in nutrients and organic and inorganic pollutants (Egbueri and Unigwe 2019; Egbueri and Unigwe 2019). These inputs disrupt the physicochemical and microbiological balance of water, leading to dissolved oxygen depletion, anoxic conditions, and eutrophication. Such alterations severely degrade water quality, flora, and fauna, and pose potential risks to public health (Saalidong *et al.* 202; Singh *et al.* 2022). Since 1900, nearly 50% of global wetlands have disappeared, particularly in regions under intense pressure, such as the Mediterranean basin (Bouahim *et al.* 2015; Rifai *et al.* 2018). El-Hammam wetland (Medjana) the subject of this study, exemplifies this trend, experiencing significant degradation characterised by biodiversity loss and alteration of the natural landscape due to urbanisation, industrialisation, and intensive agriculture.

In this context, a detailed assessment of water quality is essential to understand the ecological status of wetlands and guide management and conservation measures. A comprehensive field survey was conducted to explore the site and identify priority intervention areas. The study relies on physicochemical, bacteriological, and microbiological analyses to measure concentrations of major elements, potential pollutants, and contamination indicators.

Numerous indices are used to assess water quality (Gad *et al.* 2020). Several parameters are typically examined as part of water quality monitoring and project evaluation. The development of numerical models for water quality assessment has become essential, as they help structure and optimize the interpretation of a wide range of parameters (Unigwe and Egbueri 2023). Indices such as the Water Quality Index (WQI) and Organic Pollution Index (OPI) were calculated to characterize the ecological status of surface waters (Agbasi *et al.* 2024). These investigations are complemented by Geographic Information Systems (GIS), which have remained influential and indispensable in water quality assessment, providing unmatched capabilities for spatial visualization and analytical processing (Ucheana *et al.* 2024). In addition, environmental modelling to produce spatial maps illustrating parameter distribution and highlighting the most vulnerable areas. Multivariate statistical methods, including Principal Component Analysis (PCA), were employed to identify potential pollution sources and understand the interactions between natural and anthropogenic factors (Maruthai *et al.* 2025).

The integration of these approaches, laboratory analyses, GIS mapping, and advanced statistical interpretation, provides a robust framework for diagnosing the current environmental status of the El Hammam wetland and assessing its impact on the environment and public health. This work also enables evidence-based recommendations to strengthen the resilience of this vulnerable aquatic ecosystem, which is currently threatened by irreversible degradation.

2. Materials and Methods

2.1. Study area

Medjana is located in the northwestern part of the Bordj Bou Arréridj province in Algeria. (**Figure 1**). It covers an area of 195.30 km² and is characterised by varied topography, with elevations ranging from 800 meters at Oued Mhadjer to 1668 meters at Mount Tafertaset. The region lies on relatively flat land, surrounded by agricultural fields and bordered by several mountainous areas, as shown in **Figure 1**, including the Ragouba Mountains (1125 m) and Sidi Dilmi (1142 m) to the north, and Bouchâra (1099 m) to the east.

From a hydrological perspective, Medjana features a relatively dense hydrographic network, although it is subject to highly irregular rainfall. Two primary water resources are present: groundwater, represented by shallow aquifers and wells, and surface water, including water towers and temporary streams that flow mainly during the rainy season. The most critical thalwegs in the region are Oued Mhadjer to the north and Oued Ouerdigue to the east.

Geologically, Medjana belongs to the mountainous region of northeastern Algeria. It is composed of a series of relatively recent sedimentary formations (Loucif and Chenchouni and Abuni *et al.* 2024). The key geological units in the study area include flint-bearing limestones, alternating clay, quartzite, conglomerate, and sandstone, the Medjanian sandstone, sandstone-limestone and breccia, ancient Senonian alluvium, Triassic-phytogypsum formations, and extensive limestone zones.

Regarding the climate, data from 1992 to 2024 were collected from the meteorological station of Bordj Bou Arréridj. The average annual rainfall is 321.9 mm, with the highest precipitation recorded in May (41.4 mm), and the lowest in July (8.2 mm). Temperature analysis shows that the coldest month is January, with an average of 2.5°C, while the hottest month is July, with an average of 36.7°C. The mean annual temperature is approximately 15.95°C.

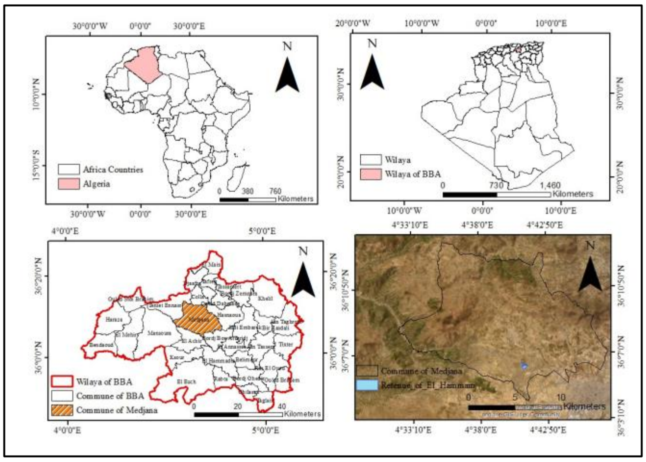

Figure 1. Location and Geographical Setting of the El Hammam Wetland.

2.2. Sampling and analysis

As part of this study, to assess surface water contamination in the El Hammam wetland, a sampling campaign was conducted in February. Eight sampling stations were selected based on their location (inlet, centre, and outlet of the lake) (**Figure 2**), as well as the proximity to potential impact zones and known wastewater discharge points. Sixteen water samples were collected, eight for physicochemical analysis and eight for bacteriological analysis. Physicochemical parameters, including temperature (°C), pH, electrical conductivity (µS/cm), and total dissolved solids (TDS, mg/l), were measured directly in the field using a portable multiparameter analyzer (WTW 3420i). The biochemical oxygen demand (BOD_5) was determined using the OXITOP system, which measures the oxygen consumed by microorganisms during a 5-day incubation at a constant temperature of 20°C in a thermostatic chamber with continuous agitation. The chemical oxygen demand (COD) was measured using an instrumental method based on oxidation with potassium dichromate in a sulfuric medium, following the OMS (2011) standard. Results were expressed in mg of O_2 per litre, indicating the amount of oxygen required to oxidize the organic matter present in the water chemically. The water quality was then assessed using the Water Quality Index (WQI), which provides a global classification of water quality based on predefined thresholds (Vystavna *et al.* 2015). The results were subsequently compared with international guidelines (WHO 2011) to assess their suitability for human use and ecological sustainability. To extend the assessment, three types of Water Quality Indices (WQI) were calculated to determine the suitability of surface water for (i) irrigation, (ii) aquatic life, and (iii) general surface water uses. Each index was computed using a standardized procedure that normalized parameters, assigned relative weights, and aggregated sub-indices. The selection of parameters and their corresponding reference standards was based respectively on FAO guidelines for irrigation water and (WHO 2011). criteria for general surface water quality. For the Irrigation WQI, the analysis incorporated key physicochemical parameters such as (EC, TDS, Na^+, HCO_3^-, Cl^-, NH_4^+, $NO_3^-NO_2^-$) which are essential indicators of salinity and ionic composition in agricultural water supply. The categorical classifications presented in (**Table 2**) (excellent, good, poor, very poor, unsuitable) were derived directly from the recommended ranges associated with each WQI type. This methodological framework ensures that the values reported in **Table 2** accurately reflect the suitability of the El Hammam wetland waters for irrigation, the protection of aquatic life, and general surface water uses.

In addition to descriptive analysis, multivariate statistical tools were applied to explore the structure of the data and identify key pollution sources (Agbasi and Egbueri *et al.* 2024).

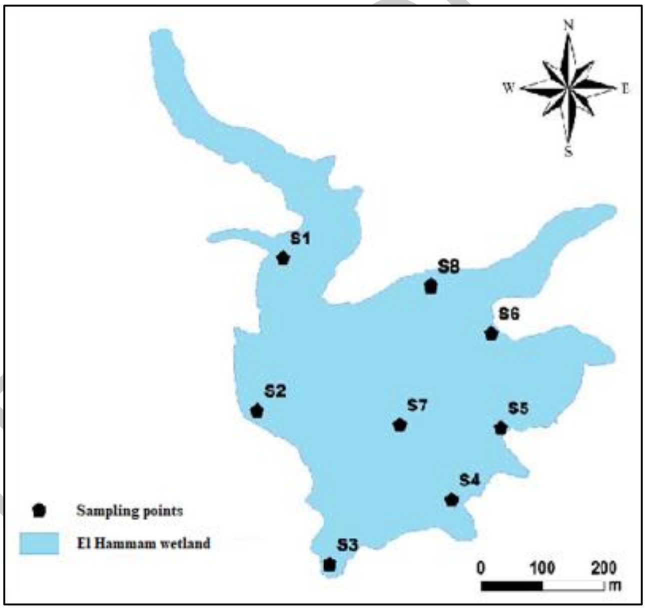

Figure 2. Location of sampling points in the El Hammam wetland

When analyzing the chemical variability of wetland waters, multivariate statistical methods particularly Principal Component Analysis (PCA) are crucial for identifying the most influential physicochemical parameters and assessing the interactions among them (Egbueri *et al.* 2024). These techniques help researchers gain clearer insight into the dominant factors controlling the spatial and temporal distribution of water quality variables (Gad *et al.* 2023), thus facilitating the identification of dominant contamination factors (Sánchez-González *et al.* 2023). Furthermore, the Organic Pollution Index (OPI) was calculated based on key parameters such as BOD_5, ammonium, nitrate, and orthophosphates (Pande *et al.* 2025), enabling the assessment of the trophic status of the wetland and the potential impact of organic loading (Alliouche *et al.* 2022). This integrative approach, combining WQI-based classification, statistical analysis, and pollution indexing, provides a robust framework for evaluating the ecological integrity of wetland systems and supports evidence-based management and conservation strategies (Gad *et al.* 2020). To better visualize the spatial variability in water quality within the El Hammam wetland, all measured physicochemical and nutrient parameters were presented in thematic maps. This cartographic approach allows a more straightforward interpretation of the distribution patterns (El Osta *et al.* 2022). Spatial gradients and hotspots of contamination across the wetland. Thematic maps of water quality parameters were produced using ArcGIS 10.4. Sampling station coordinates were imported as a point layer, and measured values were added to the attribute table. Spatial distribution was generated using the Inverse Distance Weighted (IDW) interpolation method, which estimates values based on the influence of nearby sampling points.

2.3. Water Quality Index (WQI)

The application of the Water Quality Index (WQI) method represents an effective and integrative approach to assess the overall environmental status of a given hydrosystem **(**Ramadan *et al.* 2016; Khaldia *et al.* 2024**)**. This method provides a single numerical value that reflects the cumulative effect of various physicochemical parameters on water quality, thereby simplifying complex data into a clear and interpretable format.

In this study, the relative weight (Wi) of each selected parameter and the constant k were first calculated using recognized international and national guidelines. Specifically, the standards of the Food and Agriculture Organization (FAO, 1994) (**Table 1**) for irrigation water were used to assess agricultural suitability, additionally, Algerian national standards for surface water intended for human consumption were applied. For irrigation water quality evaluation, the selected parameters included Total Dissolved Solids (TDS), pH, Electrical Conductivity (EC), Nitrates (NO_3^-), Orthophosphates (PO_4^{3-}), Bicarbonates (HCO_3^-), and Chlorides (Cl^-). These indicators are essential for understanding potential soil salinization, nutrient overload, and plant tolerance. To assess the suitability of water for aquatic life, the following variables were considered Temperature (T), TDS, pH, Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Nitrites (NO_2^-), Nitrates (NO_3^-), and Chlorides (Cl^-). These parameters influence oxygen availability, toxicity, and the general ecological balance within aquatic ecosystems. For the evaluation of water intended for human consumption, the selected indicators included Temperature, TDS, pH, BOD_5, COD, NO_2^-, NO_3^-, PO_4^{3-}, and Cl^-. These parameters were assessed against national thresholds to ensure compliance with health and safety standards for domestic use (Ramadan 2016). By integrating these parameters through the WQI model, a comprehensive evaluation of the water quality in the El Hammam wetland was achieved, allowing for its classification according to different uses (agricultural, ecological, and domestic) and aiding in the formulation of management and remediation strategies. It is important to note that the World Health Organization (WHO) does not set specific numerical standards for BOD_5 and COD in drinking water. It only emphasizes that these values should remain very low, as they indicate organic pollution. The commonly cited thresholds (< 2–5 mg/L for BOD_5 and < 5–10 mg/L for COD) (Sivasubramanian *et al.* 2025).

Table 1. Water Quality Guideline Values According to WHO (2011) and Irrigation Suitability Thresholds According to FAO

Parameters	Unit	Weight (wi)	WHO (2011)	FAO
pH	/	4	6,5-8,5	8.5
HCO3-	mg/L	3	300-500	610
Cl-	mg/L	3	250-600	1060
NO2-	mg/L	5	3	< 1
NO3-	mg/L	5	50,0000	30
SO4--	mg/L	4	250-400	960
K+	mg/L	2	12,0000	2
EC	µS/cm	4	500-1500	3000
BOD	mg/L	/	/	< 20–25
COD	mg/L	/	/	< 100–120

The Water Quality Index (WQI) used to assess the water quality of the El Hammam wetland was calculated following the weighted arithmetic index method, as described by Brown *et al.* (1972), through several steps

$$WQI = \frac{\sum QiWi}{\sum Wi}$$

The quality rating scale (Qi) for each parameter is calculated using the following expression:

$$Qi = 100 \times \frac{(ViV0)}{(ViV0)}$$

Where:

Vi: measured concentration of the *i*th parameter in the analyzed water sample (**Table 1**).

Vo: ideal value of this parameter in pure water.

Vo = 0 (except for pH = 7 and DO = 14.6 mg/L).

Si: recommended standard value for the *i*th parameter.

The unit (relative) weight (**Wi**) for each water quality parameter is calculated using the following formula:

$$Wi = \frac{K}{Si}$$

Where:

K: proportionality constant, calculated using the following equation:

$$K = \frac{1}{\sum\left(\frac{1}{Si}\right)}$$

The WQI is classified into five categories. Table V.7 presents the five (05) water quality classes based on the Weighted Arithmetic WQI method (**Table 2**).

Table 2. Classification and possible use of water according to WQI (Brown *et al.*, 1972)

WQI Value	Water Quality Evaluation
0–25	Excellent water quality
26–50	Good water quality
51–75	Poor water quality
76–100	Very poor water quality
>100	Unsuitable for use

2.4. Irrigation Water Quality Index (WQI–Irrigation)

The Integrated Weight Water Quality Indices (IWQI) this tool is employed to rank and assess the cumulative impact of physicochemical parameters on water quality (Hfaiedh *et al.* 2025). The Irrigation WQI was computed using the weighted arithmetic index method. The selected parameters include key salinity and alkalinity indicators such as electrical conductivity (EC), total dissolved solids (TDS), and major ions (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}). The quality rating for each parameter was calculated as:

$$q_i = \left(\frac{V_i - V_0}{S_i - V_0}\right) \times 100$$

Where Vi is the measured value, V0 the ideal value (commonly zero), and Si the FAO guideline value. Normalized weights were assigned to each parameter using:

$$Wi = \frac{wi}{\sum wi}$$

The global index was obtained as:

$$WQI_{irr} = \sum \left(Wi \times qi\right)$$

Table 3. Irrigation Water Quality Classification Based on WQI–Irrigation Values

WQI_{irr} Value	Water Quality Evaluation
0–25	Excellent water quality
26–50	Good water quality
51–75	Poor water quality
76–100	very poor water quality
>100	Unsuitable water quality

2.5. Aquatic Life Water Quality Index (WQI–Aquatic Life)

This index was based on parameters that strongly influence aquatic ecosystems: DO, BOD_5, COD, NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, pH and temperature (Okeke *et al.* 2025). For parameters where higher values indicate deterioration (BOD_5, COD, NH_4^+, NO_3^-), the rating was calculated as (**Table 4**):

$$q_i = \left(\frac{V_i - V_0}{S_i - V_0}\right) \times 100$$

For DO, an inverse relationship was applied:

$$q_{DO} = \left(\frac{S_{DO} - V_{D0}}{S_{DO} - V_0}\right) \times 100$$

The normalized weight for each parameter was:

$$W_i = \frac{Wi}{\sum W_i}$$

The overall index is

$$WQI_{aq} = \sum \left(W_i \times q_i\right)$$

Table 4. Water Quality Evaluation for Aquatic Life Based on WQI Classification

WQI_{aq} Value	Water Quality Evaluation
0–25	Excellent water for aquatic life
26–50	Good water for aquatic life
51–75	Poor water for aquatic life
76–100	very poor water for aquatic life
>100	Unsuitable water for aquatic life

2.6. The Organic Pollution Index (OPI)

The Organic Pollution Index (OPI), initially developed by Leclercq and Maquet (New record of Lestica bibundica Leclercq 1972) is used to assess organic pollution in surface waters. It is based on four key parameters: biochemical oxygen demand (BOD_5), ammonium ions (NH_4^+), nitrites (NO_2^-), and phosphates (PO_4^{3-}). Each parameter is categorized into five pollution classes based on predefined thresholds (**Table 5**). The final index is calculated as the average of these class values.

Table 5. Classes of the Organic Pollution Index (OPI).

Parameters Classes	BOD_5 (mg O_2/l)	Ammonium (mg N/l)	Nitrite (µg N/l)	Phosphates (µg P/l)
5	<2	<0.1	5	15
4	2-5	0. 1-0.9	6-10	16-75
3	5.1-10	2.4	11-50	76-250
2	10.1-15	2.5-6	51-150	251-900
1	>15	>6	>150	>900

2.7. Statistical Treatment of Data

In order to calculate the relationship between various physicochemical parameters and to better assess the water quality in the study area, the Pearson correlation coefficient was used. Additionally, this statistical tool helps identify potential sources of pollution (Okeke *et al.* 2025). Geochemical processes, and interactions between variables, such as salinity, nutrient enrichment, and organic matter content. Strong positive or negative correlations can provide insights into common origins or coupled behaviors of specific parameters in the aquatic environment (**Table 6**). To better understand the relationships among the different physicochemical parameters and to evaluate the influence of anthropogenic activities on the surface water quality of the El Hammam wetland.

3. Results

3.1. Physicochemical parameters

The analysis of the physico-chemical parameters of the El Hammam wetland waters revealed several noteworthy characteristics. Water temperature showed slight variation among the sampling stations (**Figure 3**), with the fluctuations mainly attributed to differences in the sampling schedule. Regarding the hydrogen potential (pH), recorded values ranged from 7.4 at station 5 to 9.71 at station 4 (**Figure 4**), indicating a pronounced alkalinity across the site. It is worth noting that several stations exceeded the World Health Organisation's tolerance range (6.5–8.5), potentially posing a risk to sensitive aquatic organisms. Furthermore, electrical conductivity (EC) measurements varied from 2.56 mS/cm at station 2 to 3.13 mS/cm at station 8 (**Figure 12**), reflecting a high level of water mineralization. All recorded values exceeded the 1000 µS/cm threshold, which is commonly considered an indicative limit for natural water quality, and point to a significant concentration of dissolved ions.

Analysis of anion concentrations in the Medjana wetland revealed noticeable variability among sampling stations. Bicarbonate (HCO_3^-) levels ranged from 353 mg/L at station 6 to 475.8 mg/L at station 2, indicating consistently high concentrations throughout the study period. Chloride (Cl^-) concentrations were also elevated, varying between 497 mg/L at station 2 and 798 mg/L at station 7 (**Figure 7**), with most stations exceeding the WHO (2011) guideline range of 250–600 mg/L. Regarding nitrogen compounds, ammonium (NH_4^+) concentrations ranged from 0.64 mg/L (station 5) to 2.86 mg/L (station 1), well above the WHO recommended limit of 0.2 mg/L The figure highlights a distribution pattern that changes following the measured concentration levels (**Figure 8**). Nitrate (NO_3^-) concentrations ranged from 10.54 mg/L (station 7) to 35 mg/L (station 8), remaining below the WHO limit of 50 mg/L The spatial distribution shows a gradual variation from east to west and from north to south, in accordance with the concentrations displayed in the (**Figure 9**). Nitrite (NO_2^-) values were relatively low, ranging from 0.02 mg/L (stations 4 and 5) to 0.41 mg/L (station 8), all within acceptable standards A spatial gradient is observed along both the east–west and north–south directions, reflecting the concentration variations illustrated in the (**Figure 10**). Orthophosphate (PO_4^{3-}) concentrations also showed spatial variability, ranging from 0.23 mg/L at station 4 to 1.22 mg/L at station 8. These results reflect varying degrees of mineralisation and nutrient enrichment within the wetland system generly exceeding the recommended limits (**Figure 11**).

3.2. Biological analyses

Biochemical oxygen demand (BOD_5) values ranged from 35 mg/L at Station 7 to 120 mg/L at Station 8. These variations reflect differences in organic load at the sampling sites. Chemical oxygen demand (COD) values were also high, ranging from 77.6 mg/L (Station 7) to 140 mg/L (Station 1), indicating the presence of oxidizable organic matter in the water. Biological analyses revealed a high presence of total viable bacteria (mesophilic aerobic flora) in all water samples. The confluent growth of bacterial colonies on culture media evidenced this. Total coliforms and thermotolerant (faecal) coliforms were detected in significant quantities across most stations. Notably, Escherichia coli, a key indicator of faecal contamination, was present in several samples. According to the World Health Organisation (WHO), drinking water should contain no faecal coliforms in 100 mL of sample.

Finally, results from the Principal Component Analysis (PCA) showed that the first two components (F1 and F2) accounted for 72.22% of the total variance in the dataset, with F1 alone accounting for 46.74% and F2 accounting for 25.84% (**Table 3)**. These components were used further to interpret the relationships between sampling sites and physico-chemical parameters.

Table 6. Eigenvalues of Principal Components for the El Hammam Wetland Area.

Principal Component	Eigenvalue	Variance (%)	Cumulative (%)
F1	7,4788	46,7423	46,7423
F2	4,076	25,4752	72,2176
F3	1,5952	9,9702	82,1877
F4	1,1853	7,4079	89,5957
F5	0,9191	5,7443	95,34
F6	0,4697	2,9356	98,2756
F7	0,2759	1,7244	100

The classification of surface water quality for irrigation use in the El Hammam wetland, based on the Water Quality Index (WQI), shows a gradient ranging from poor to low quality. Stations 2, 3, 4, 5, and 7 exhibit poor water quality, with WQI values ranging from 50.29 to 74.26. Stations 6 and 8 fall under the lower category, with WQI values of 83.88 and 91.72, respectively. When applying the WQI for the protection of aquatic life, Station 4 (WQI = 59.79) and Station 5 (WQI = 64.47) are considered poor, Station 7 is very poor (WQI = 80.57). At the same time, Stations 1, 2, 6, 7, and 8 exceed the threshold of 100, making them unsuitable for aquatic life. In accordance with Algerian surface water standards for human consumption, Stations 2 through 6 are classified as poor, Station 8 as very poor, and the remaining stations are unsuitable for human consumption. These classifications depended on high levels of pollutants such as electrical conductivity (EC), total dissolved solids (TDS), bicarbonates (HCO_3^-), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), orthophosphates (PO_4^{3-}), nitrates (NO_3^-), nitrites (NO_2^-), and chlorides (Cl^-). Regarding the Organic Pollution Index (IPO), the map analysis (**Figure 9**) shows that Stations 1, 2, 6, and 8 have IPO values between 1.25 and 1.75, indicating very high organic pollution. Stations 3, 4, 5, and 7 show IPO values ranging from 2.0 to 2.75, indicating high pollution. Although the upstream stations record the lowest IPO values in the dataset, they still exhibit elevated concentrations of key physicochemical indicators, particularly BOD_5, reflecting substantial input of biodegradable organic matter.

4. Discussion

4.1. Physico-Chemical Analysis of Wetland Water

The slight temperature differences observed between stations do not reflect any significant environmental variations but are primarily due to time lags in the sampling schedule. In general, water temperature is strongly influenced by local climatic conditions (Hammana *et al.* 2024), particularly ambient air temperature (**Figure 3**). Several combined factors can explain the pronounced alkalinity of the waters. On the one hand, the photosynthetic activity of aquatic organisms, especially phytoplankton, can raise pH by consuming carbon dioxide (Alaeddine *et al.* 2024). On the other hand, the geological nature of the substrate, characterised by the dominance of limestone formations, naturally promotes alkaline conditions (Zahi *et al.* 2024). Additionally, anthropogenic inputs, such as domestic and urban wastewater discharges (Benmarce *et al.* 2023), can disrupt the acid–base balance of the aquatic environment (**Figure 4**). The elevated electrical conductivity indicates a high concentration of dissolved ions in the wetland waters (Bouchama *et al.* 2022). This increased mineralisation all recorded EC values exceeded 1000 µS/cm, indicating a high level of mineralization. When compared with the WHO (2011) guideline where electrical conductivity values above approximately 2500 µS/cm are considered unpalatable the observed EC values in this study approach or exceed this threshold, confirming that the increased salinity results from the abundance of electrically conductive dissolved ions, particularly major cations and anions such as Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-, whose elevated concentrations enhance the overall ionic strength of the water. The accumulation of these ions increases electrical conductivity by facilitating charge transport within the solution (Agbasi *et al.* 2025). The likely source of this ionic pollution is the discharge of domestic and industrial effluents, particularly in the upstream part of the site, where human activities are more concentrated. (**Figure 5**).

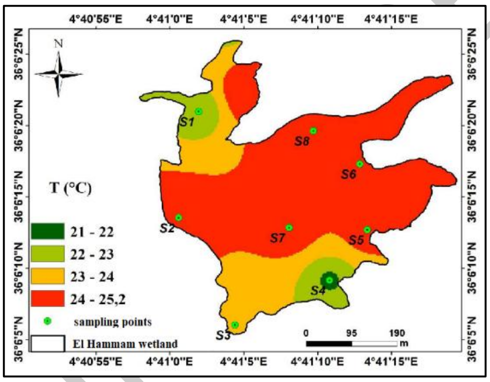

Figure 3. Temperature variation in the El Hammam wetland

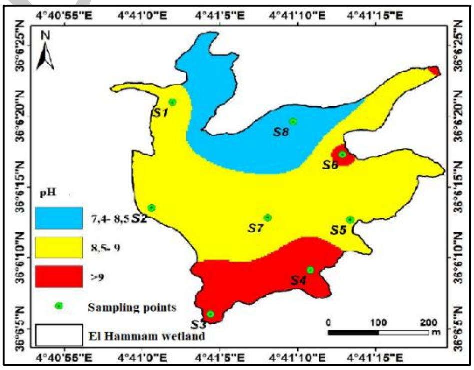

Figure 4. Variation of water potential in the El Hammam wetland

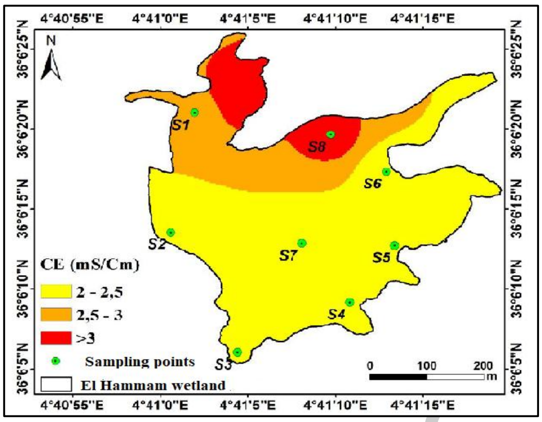

Figure 5. Variation of electrical conductivity in the El Hammam wetland

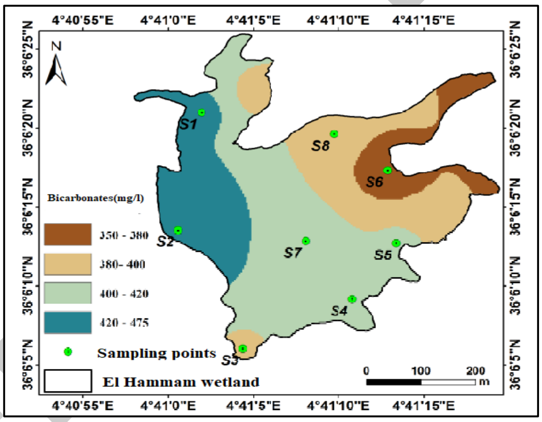

Figure 6. Variation of bicarbonates (HCO_3^-) in the El Hammam wetland

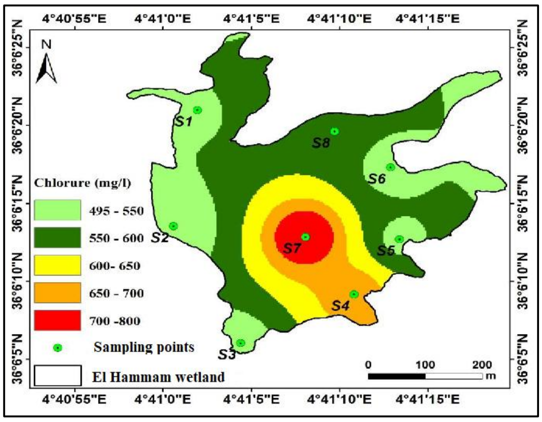

Figure 7. Variation of chlorides (Cl^-) in the El Hammam wetland

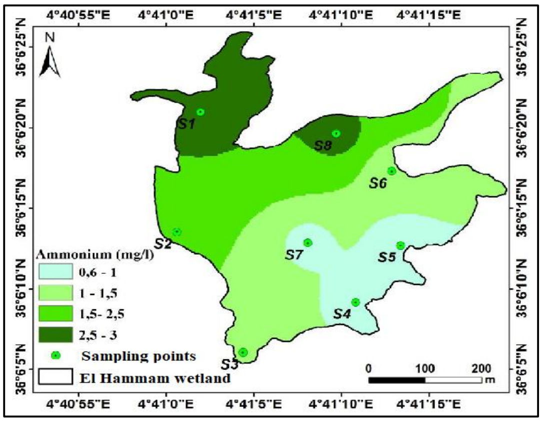

Figure 8. Variation of ammonium (NH_4^+) in the El Hammam wetland

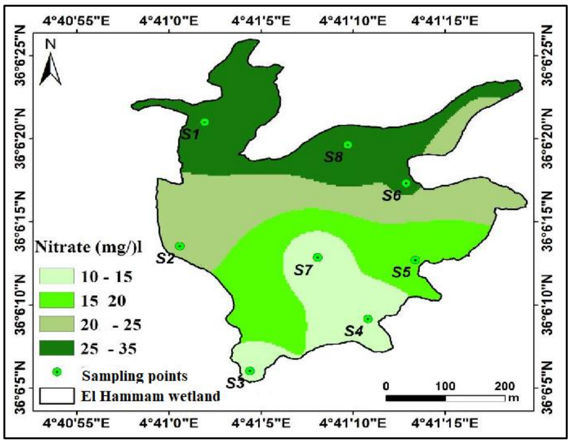

Figure 9. Variation of nitrates (NO_3^-) in the El Hammam wetland

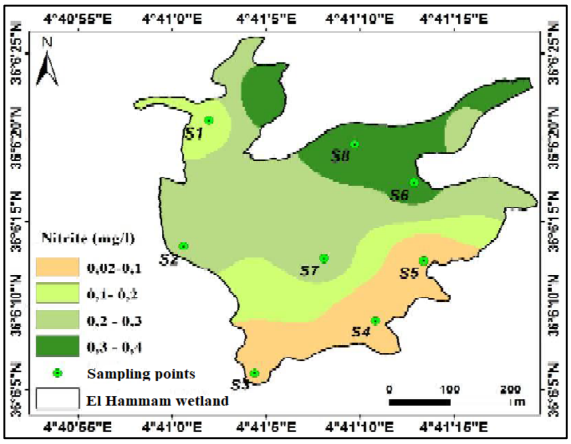

Figure 10. Variation of nitrites (NO_2^-) in the El Hammam wetland

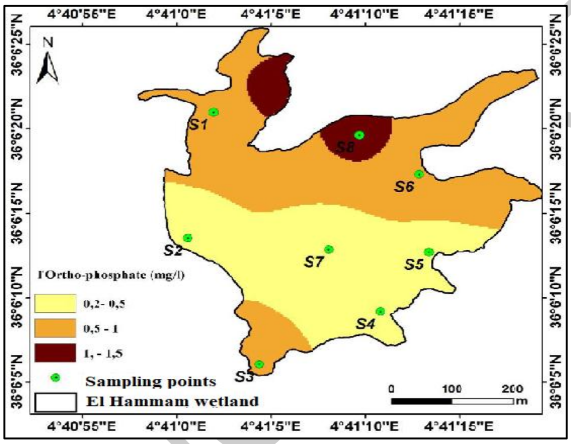

Figure 11. Variation of orthophosphates (PO_4^{3-}) in the El Hammam wetland

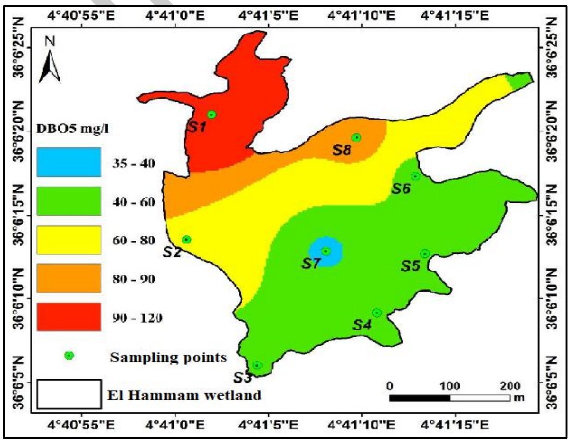

Figure12. Variation of BOD_5 in the El Hammam wetland

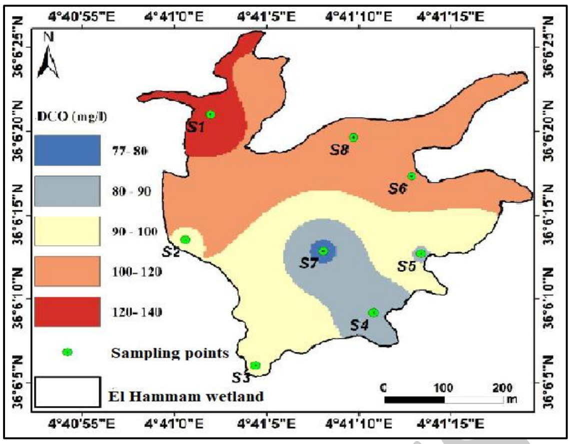

Figure13. Variation of COD in the El Hammam wetland

The elevated bicarbonate concentrations observed across all sampling stations (**Figure 6**) are primarily attributed to the region's geological context (El Osta *et al.* 2022), notably the predominance of carbonate-rich formations such as limestone and dolomite (Gad *et al.* 2024). These rocks, composed mainly of calcium- and magnesium-carbonates, react with infiltrating water to release bicarbonate ions, thereby contributing to the wetland's high alkalinity (Ghrabi *et al.* 2011). Additionally, anthropogenic influences, such as domestic and industrial wastewater discharges, solid waste accumulation, and microbial decomposition of organic matter, further enhance CO_2 production in the system. This dissolved CO_2 forms carbonic acid, which accelerates the chemical weathering of carbonate rocks and promotes the formation of additional bicarbonate (Dontsova *et al.* 2020). Elevated chloride levels (**Figure 7**) are likely due to both natural processes, such as the dissolution of evaporitic rocks, and human activities, including wastewater disposal, irrigation return flows, and industrial effluents. The high ammonium concentrations (**Figure 8**) can be linked to the input of untreated sewage and organic waste, especially in areas with limited water circulation (Gad *et al.* 2022), where reducing conditions of ammonification. These conditions contribute to eutrophication risks by stimulating algal growth and reducing dissolved oxygen levels (Chen *et al.* 2010). Although nitrate concentrations (**Figure 9**) remain below the WHO threshold, the higher values detected near station eight suggest agricultural runoff from fertilized fields and wastewater infiltration from nearby settlements. The presence of nitrites (**Figure 10**), even in small amounts, indicates transitional processes in the nitrogen cycle, such as partial nitrification or denitrification, which often occur in oxygen-poor zones. Finally, the presence of orthophosphates (**Figure 11**) is associated with domestic and industrial sources, particularly detergents and agricultural runoff (Badamasi *et al.* 2019). Geological contributions from phosphate-bearing rocks may also enhance phosphate levels in the wetland, leading to nutrient enrichment and potential ecological imbalance (Elsayed *et al.* 2020).

The elevated BOD_5 values observed (**Figure 12**), particularly upstream of the El Hammam wetland, indicate a significant accumulation of biodegradable organic matter, mainly due to untreated domestic and industrial wastewater discharges (Ilavarasan *et al.* 2016), as well as surface runoff from agricultural lands treated with organic fertilizers. These conditions lead to reduced dissolved oxygen concentrations, affecting aquatic life and reflecting substantial organic pollution. Similarly (Egbueri *et al.* 2025). High COD levels (**Figure 13**) confirm the presence of both organic and inorganic oxidizable substances in the water (Halicki and Halicki 2021). This pollution results from combined anthropogenic pressures and local geology (Akhtar *et al.* 2021), especially the marl and clay formations, which enhance pollutant retention and mobility (Akhtar *et al.* 2021).

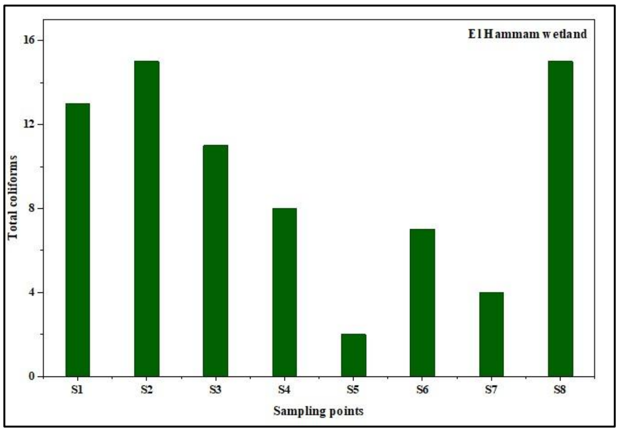

Figure 14. Variation of total coliforms in the waters of the El Hammam wetland.

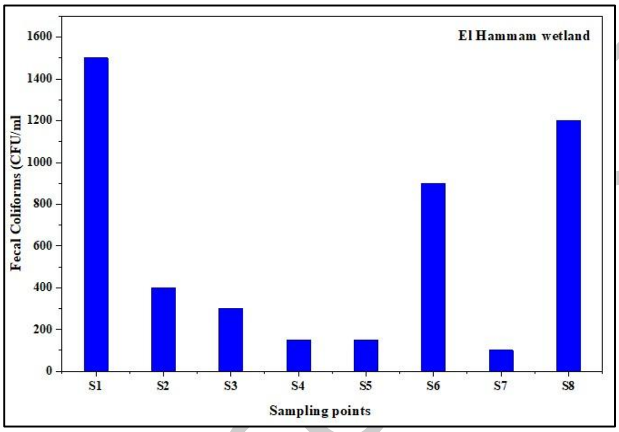

Figure 15. Variation of fecal coliforms in the waters of the El Hammam wetland.

4.2. Biological analyses

Biological analyses indicate that total viable bacteria (revivable germs) or mesophilic aerobic flora were extremely high in all water samples collected from the El Hammam wetland, as evidenced by the presence of confluent bacterial colonies on culture media. These elevated levels suggest significant microbial contamination (Ouma *et al.* 2016), most likely resulting from untreated domestic or industrial wastewater discharge (Kaushal *et al.* 2018), confirming that the waters of the study area are heavily loaded with potentially pathogenic microorganisms. Moreover, total coliforms and thermotolerant (faecal) coliforms were detected in considerable quantities (**Figure 14**). Coliform bacteria are commonly used as indicators of sanitary water quality (Venkatraman *et al.* 2025), while total coliforms can be found naturally in soil and vegetation, the presence of faecal streptococci, especially Escherichia coli (**Figure 16**). The most well-known species clearly indicates faecal contamination, as these bacteria are found explicitly in the intestinal tracts of warm-blooded animals (Wanja *et al.* 2023). According to the World Health Organisation (WHO 11), no faecal coliforms should be detectable in 100 mL of drinking water. Therefore, the presence of these bacteria in surface waters implies a serious risk of microbiological pollution (**Figure 15**). Rendering the water unsafe for direct human use without appropriate treatment.

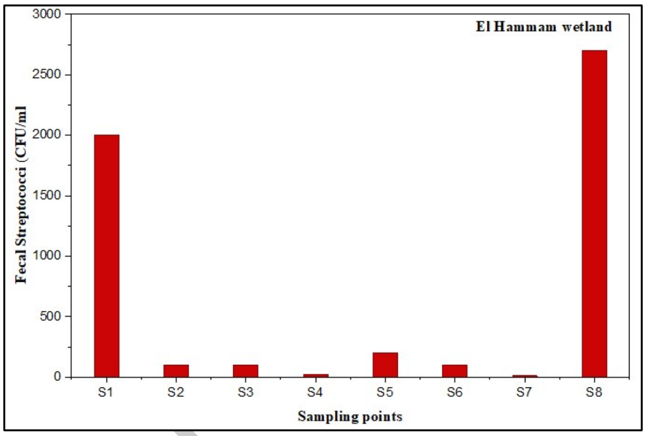

Figure16. Variation of fecal streptococci in the waters of the El Hammam wetland

4.3. Water Quality Status

The classification of water quality for irrigation use in the El Hammam wetland indicates a range from poor quality (**Table 7**) in Stations 2, 3, 4, 5, and 7 where the Water Quality Index (WQI) values range between 50.29, 53.50, 56.20, and 74.26 to lower quality in Stations 6 and 8, with WQI values of 83.88 and 91.72, respectively. According to the guidelines for the protection of aquatic life, the WQI results indicate poor water quality at Stations 4 (WQI = 59.79) and 5 (WQI = 64.47), very low quality at Station 7 (WQI = 80.57), and unsuitable water (WQI > 100) at Stations 1, 2, 6, 7, and 8. When evaluated against the Algerian standards for surface water intended for human consumption, the water in Stations 2, 3, 4, 5, and 6 is classified as poor, while Station 8 falls under very poor, and the remaining stations are deemed unsuitable for human use. These elevated WQI values are primarily linked to high concentrations of key pollutants such as electrical conductivity (EC), (TDS), (HCO_3^-), (BOD_5), (COD), (PO_4^{3-}), (NO_3^-), (NO_2^-), and (Cl^-) (**Table 3**). Overall, the results point to a significant pollution load, particularly in the upstream portion of the wetland. This degradation is largely attributed to untreated domestic and industrial wastewater discharges (Dar *et al.* 2022). The city of Medjana and its industrial zone have improper solid waste disposal, and intensive agricultural activities along the margins of the wetland. Consequently, the ongoing pollution of surface waters in the El Hammam wetland due to human activities poses a serious threat to water quality (Ajloon *et al.* 2024).

The assessment of groundwater quality for irrigation, based on the Irrigation Water Quality Index (IWQI), shows values ranging from 50.29 to 91.72, indicating generally poor to very poor water quality (**Table 4**). The classification results reveal that 50% of the samples (Stations 1, 3, 6, and 8) fall into the “very poor” category, reflecting high to severe restrictions and suitability limited to salt-tolerant crops. The remaining 50% (Stations 2, 4, 5, and 7) are classified as “poor”, corresponding to low to moderate restrictions and requiring appropriate management practices to mitigate soil salinization risks (Gad *et al.* 2022). No sample exhibited good or acceptable quality for irrigation, highlighting the vulnerability of groundwater resources in the studied plain to salinity and elevated mineralization.

4.4. Pearson Correlation Matrix.

The Pearson correlation matrix of the parameters measured during our study (**Table 5**) reveals several significant relationships. Temperature showed a strong positive correlation with turbidity ($r = 0.813$, $p < 0.05$), suggesting that more turbid water absorbs heat more efficiently due to increased suspended particles that retain thermal energy (El Osta *et al.* 2022). Conversely, pH exhibited a negative correlation with electrical conductivity (EC) ($r = –0.751$, $p < 0.05$) and salinity ($r = –0.786$, $p < 0.05$), indicating that an increased concentration of inorganic substances in water tends to lower its pH levels, possibly due to acidifying processes (Selvanarayanan *et al.* 2024). Electrical conductivity demonstrated significant positive correlations with salinity ($r = 0.757$, $p < 0.05$), total dissolved solids (TDS) ($r = 0.931$, $p < 0.01$), nitrates ($r = 0.775$, $p < 0.05$), ammonium (NH_4^+) ($r = 0.842$, $p < 0.01$), orthophosphates (PO_4^{3-}) ($r = 0.751$, $p < 0.05$), and biochemical oxygen demand (BOD_5) ($r = 0.708$, $p < 0.05$). These correlations underline the association of EC with nutrient loads and ion concentrations, reflecting both natural geochemical interactions and anthropogenic pollution inputs (Aslam *et al.* 2023). Furthermore, TDS was positively correlated with nitrates ($r = 0.741$, $p < 0.05$) and ammonium ($r = 0.747$, $p < 0.05$), reinforcing the role of dissolved nutrient-rich contaminants in increasing water mineral content (Tariq and Mushtaq 2023). Salinity also showed a significant positive correlation with orthophosphates ($r = 0.726$, $p < 0.05$), highlighting the influence of anthropogenic inputs, such as fertilisers and wastewater discharge, on the elevated levels of inorganic dissolved solids in the aquatic system (Egbueri *et al.* 2024).

4.5. Analyse factorielle

In the factorial plane defined by the first two principal components, F1 and F2 (**Figures17, 18**), axis F1 mainly groups the variables NO_3^-, NO_2^-, EC, BOD_5, TDS, COD, turbidity, TSS, salinity, PO_4^{3-} and TH, which are strongly and positively correlated. These parameters are characteristic of stations S1, S2, S6 and S8, located upstream of the study area. This clustering reflects significant organic and mineral pollution (Solovey *et al.* 2021), associated with untreated domestic and industrial discharges (Pande *et al.* 2025). These waters are enriched in biodegradable organic matter, suspended solids, and oxidised nitrogen species (NO_3^- and NO_2^-), indicating an increased risk of eutrophication in the receiving environment (Axis F2) for its part, is defined by a positive correlation with temperature and a negative correlation with bicarbonates (HCO_3^-). This opposition suggests a differentiation between stations influenced by thermal conditions potentially linked to greater exposure to solar radiation or thermal discharges and others characterised by more pronounced carbonate mineralization (Egbueri *et al.* 2025). Moreover, stations S3, S4, S5, and S7 are located at opposite ends of the factorial plane. They are characterised by lower concentrations of the variables above, indicating relatively better water quality and less exposure to organic and inorganic pollution (Eid *et al.* 2025). These stations correspond to areas that are better protected or less exposed to direct anthropogenic inputs.

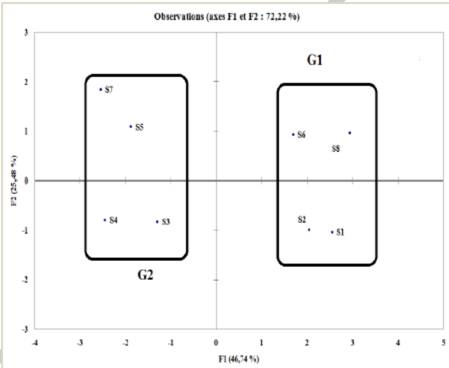

Figure 17. Répartition des stations dans le plan factoriel F1 × F2.

4.6. Organic Pollution Index (IPO)

As part of the assessment of surface water quality, the Organic Pollution Index (IPO) serves as an essential indicator. The analysis of the IPO map (Figure 29) helps evaluate the degree of surface water degradation in the El Hammam wetland. According to the IPO classification (**Table 9**), stations S1, S2, S6, and S8 show IPO values between 1.25 and 1.75, indicating very high organic pollution. The other stations (S3, S4, S5, and S7) have IPO values ranging from 2.0 to 2.75, which corresponds to high organic pollution (Munir *et al.* 2024). The upstream stations of the lake record the lowest IPO values but still show high concentrations of physicochemical parameters, particularly BOD_5, reflecting a high load of biodegradable organic matter (Egbueri *et al.* 2025). This pollution is attributed to untreated domestic and industrial discharges, solid waste, and the leaching of nitrogen-rich agricultural soils fertilised with nitrogen fertilisers (Hu *et al.* 2021), especially from manure use. This degrades water quality and affects the ecological balance of the wetland ecosystem.

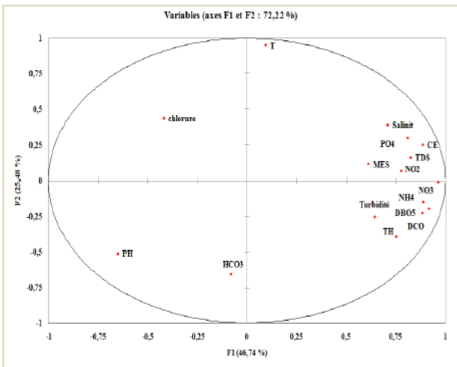

Figure 18. Ce.rcle de corrélation des différentes variables selon le plan F1 × F2.

Table 7. WQI and Its Categorization in Surface Waters of the El Hammam Wetland for Irrigation, Aquatic Life, and Surface Water Uses.

Stations	WQI Irrigation	Water Quality Class	WQI Aquatic Life	Water Quality Class	WQI Surface Waters	Water Quality Class
Station 1	83.10	Very poor	301.89	Unsuitable	399.89	Unsuitable
Station 2	62.37	Poor	409.65	Unsuitable	54.89	Poor
Station 3	74.26	Poor	80.57	Very poor	65.74	Poor
Station 4	53.50	Poor	59.79	Very poor	53.48	Poor
Station 5	56.20	Poor	64.47	Poor	52.06	Poor
Station 6	83.88	Very poor	614.73	Unsuitable	54.33	Poor
Station 7	50.29	Poor	421.74	Unsuitable	152.18	Unsuitable
Station 8	91.72	Very poor	705.43	Unsuitable	63.38	Very poor

Table 8. Pearson Correlation between the Different Physicochemical Parameters of Water

Parameters	T	pH	EC	TDS	Salinity	NO_3^-	NO_2^-	NH_4^+	PO_4^{3-}	Turbidity	Cl^-	TSS	HCO_3^-	TH	BOD_5	COD
T	1															
pH	0.253	1														
EC	0.445	-0.751*	1													
TDS	0.412	-0.601	0.931**	1												
Salinity	0.428	-0.786*	-0.757*	0.622	1											
NO_3^-	0.605	-0.602	0.775*	0.741*	0.511	1										
NO_2^-	0.244	-0.652	0.49	0.726*	0.586	0.674	1									
NH_4^+	0.601	0.051	-0.842**	0.473	0.727*	0.743*	0.399	1								
PO_4^{3-}	0.473	0.576*	0.751*	0.687*	0.726*	0.764*	0.497	0.687	1							
Turbidity	0.813*	0.392	0.416	0.109	0.1	0.52	0.09	0.09	0.09	1						
Cl^-	-0.194	0.019	-0.067	0.184	0.012	0.009	-0.348	-0.48	-0.532	1	1					
TSS	0.015	-0.297	0.179	0.639*	0.845**	0.346	0.349	0.078	-0.104	0.011	0.489	1				
HCO_3^-	0.331	-0.011	-0.132	-0.252	0.158	0.402	0.589	0.048	-0.375	0.199	0.333	0.315	1			
TH	0.486	0.045	0.185	0.152	0.833*	0.469	0.354	0.342	0.199	0.145	0.333	0.315	0.850*	1		
BOD_5	0.856	-0.452	0.604	0.926**	0.511	0.625	0.429	0.539	-0.577	0.489	0.315	0.830*	0.885**	0.887**	1	
COD	0.391	-0.151	0.534	0.604	0.434	0.792*	0.234	0.795*	0.448	0.456	0.309	0.530	0.833*	0.915*	0.950**	1

Table 9. Variation of the Organic Pollution Index (OPI) in the El Hammam wetland.

Stations	OPI Classes	Level of Organic Pollution
S1	1.75	Very high organic pollution
S2	1.75	Very high organic pollution
S3	2.25	High organic pollution
S4	2.75	High organic pollution
S5	2.50	High organic pollution
S6	1.75	Very high organic pollution
S7	2.00	High organic pollution
S8	1.25	Very high organic pollution

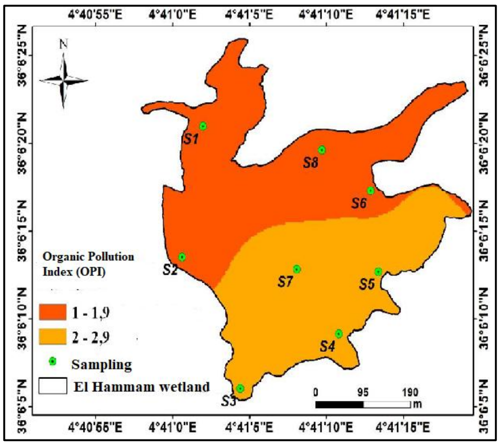

Figure 19. Spatial Variation of the IPO in the El Hammam Wetland

5. Conclusion

The main objective of this study was to characterize the physicochemical and bacteriological parameters of surface waters in the El Hammam wetland to assess its ecological status and propose appropriate measures for its preservation. Spatial analysis of the collected data revealed heterogeneous pollution levels across the various sampling stations. The presence of significant concentrations of chemical pollutants such as nitrates, nitrites, orthophosphates, biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD), as well as microbiological contaminants, notably faecal indicator organisms, reflects increasing anthropogenic pressure. These pressures are mainly due to untreated domestic and industrial wastewater discharges and diffuse agricultural runoff.

To gain a more integrated understanding of the water quality, composite indices such as the Water Quality Index (WQI) and the Organic Pollution Index (OPI) were applied. The WQI values indicated that water quality ranged from poor to very poor at many stations and, in some cases, was unsuitable for essential uses such as irrigation, supporting aquatic life, or potential human consumption, according to international water quality standards. Meanwhile, the OPI results confirmed high to very high levels of organic pollution, indicating a substantial load of biodegradable organic matter in the aquatic system.

The Pearson correlation analysis confirmed strong interrelationships among key physicochemical parameters, particularly between electrical conductivity, salinity, total dissolved solids (TDS), and nutrients (NO_3^-, NH_4^+, PO_4^{3-}). These associations highlight the combined influence of mineralization processes and anthropogenic discharges on water quality degradation. This finding reinforces the interpretation that both organic and inorganic pollutants, mainly from agricultural runoff, domestic effluents, and industrial waste, contribute significantly to the observed ecological imbalance in the El-Hammam wetland.

These results collectively demonstrate the urgent need to implement effective, science-based environmental management measures. In this context, several recommendations are proposed: the construction of a wastewater treatment plant using lagoon-based systems for nearby urban areas; improved regulation and monitoring of industrial effluent discharges; awareness campaigns directed at farmers and local communities to emphasize the ecological and hydrological importance of wetlands; regular monitoring of physical, chemical, and biological water quality parameters; and the official registration of the El Hammam wetland on the Ramsar List to benefit from international recognition and conservation support.

The protection of this wetland is essential not only for the conservation of regional biodiversity but also for the long-term sustainability of water resources and overall ecological health in the region. The findings of this research provide a scientific foundation for local authorities and decision-makers to develop sustainable management strategies to mitigate pollution and preserve the ecological integrity of the El Hammam ecosystem.

Future research on the El Hammam wetland should aim to strengthen the understanding of the hydro-ecological processes and the long-term evolution of water quality in this semi-arid system. A first priority is the implementation of a multi-seasonal and multi-year monitoring programme to capture temporal variability more accurately, as the current assessment is limited to a single sampling period. Additional attention should be given to emerging contaminants such as pharmaceuticals, microplastics, and persistent organic pollutants which are increasingly reported in Mediterranean wetlands and may pose significant ecotoxicological risks that were not evaluated in the present study.

From a methodological standpoint, the integration of advanced modelling tools including machine-learning-based predictive models, multivariate source-apportionment techniques, and risk-based decision support systems would provide a more robust framework for forecasting water quality trends and identifying dominant pollution drivers. Further laboratory experimentation and controlled-environment tests would also help validate the indices used (WQI, OPI, PCA-derived factors) by quantifying their accuracy and reliability under varying hydrochemical conditions.

At the ecosystem scale, future studies should explore the response of biological communities phytoplankton, macroinvertebrates, and wetland vegetation to the physicochemical pressures identified here, thereby linking chemical degradation to ecological impacts. Finally, the development of scenario-based analyses addressing climate change, land-use dynamics, and wastewater-management strategies would be essential for supporting evidence-based policy decisions and long-term conservation planning for the El Hammam wetland.

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Author's Contribution

Toufik Aliat contributed to supervision, methodology, and preparation of the original draft. Khaldia Si Tayeb was responsible for writing, reviewing, literature collection, and manuscript editing. Abdelghani Elhoussaoui contributed to statistical analysis and literature review. Maurizio Barbieri contributed to manuscript revision, as well as scientific and language editing.

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Declarations

Conflict of interest the authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare that artificial intelligence was used solely for translation and language editing of the manuscript. All scientific content was entirely produced by the authors.

References

Abuni, D. I., Nyamaizi, S., Mbabazize, D., & Atugonza, C. (2025). Effect of Different Land Use Types on Nutrient Distribution across Soil Depth in Busega Wetland, Uganda. Open Journal of Soil Science, 15(1), 84-101. https://doi.org/10.4236/ojss.2025.151005

Agbasi, J. C., & Egbueri, J. C. (2022). Assessment of PTEs in water resources by integrating HHRISK code, water quality indices, multivariate statistics, and ANNs. *Geocarto international*, *37*(25), 10407-10433. https://doi.org/10.1080/10106049.2022.2034990

Agbasi, J. C., Alkasimi, A., Turki, A. F., Abba, S. I., Khan, M. Y. A., & Egbueri, J. C. (2025). Reimagining water quality assessment: a nutritional indexing perspective for drinking water resources management. *International Journal of Environmental Analytical Chemistry*, 1-27. https://doi.org/10.1080/03067319.2025.2482187

Agbasi, J. C., Onuba, L. N., Nweke, N. D., Egbueri, J. C., & Ayejoto, D. A. (2024). The Nexus Between the Transport Mechanisms and Remediation Techniques of Microplastics. In *Microplastics in African and Asian Environments: The Influencers, Challenges, and Solutions* (pp. 259-292). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-64253-1_14

Ajloon, F. H., Dong, X., Ayejoto, D. A., Ayeni, E. A., & Sabo, M. Y. (2024). Seasonal assessment of water quality and water quality index (WQI) variations, in Jiangsu Kunshan Tianfu National Wetland Park, China. *International Journal of Environmental Analytical Chemistry*, *104*(17), 5444-5463. https://doi.org/10.1080/03067319.2022.2125309

Akhtar, N., Syakir Ishak, M. I., Bhawani, S. A., & Umar, K. (2021). Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water*, *13*(19), 2660. https://doi.org/10.3390/w13192660

Alaeddine, T. E. R. C. H. I., & Setitra, A. (2024). *Analyse des paramètres physico-chimiques et leur influence* (Doctoral dissertation, university centre of abdelhafid boussouf-mila-). http://dspace.centre-univ-mila.dz/jspui/handle/123456789/3804

Aliat, T. (2018). *Les écosystèmes humides des hautes plaines orientales algériennes Biodiversité: Préservation et Valorisation*. http://dspace.univ-setif.dz:8888/jspui/handle/123456789/1548

Alikhani, S., Nummi, P. and Ojala, A. (2021) Urban Wetlands: A Review on Ecological and Cultural Values. Water, 13, Article 3301. https://doi.org/10.3390/w13223301

Alliouche, F., Arab, A., & Baitiche, L. (2022, November). The Organic Pollution Indices and the Phytoplanktonic Index, Do They Allow to Assessing the Freshwater Quality, Case of Algeria. In *Euro-Mediterranean Conference for Environmental Integration* (pp. 245-248). Cham: Springer Nature Switzerland.

Aslam, A., Ahmad, T., & Ranjan, R. K. (2023). Differential responses of hydrochemical factors and LULC changes on the spatial and temporal hydrogeochemistry of the eco-sensitive Baraila wetland, Bihar, India. *Environmental Science and Pollution Research*, *30*(13), 39223-39245. https://doi.org/10.1007/s11356-022-25005-1

Aswal, R. S., Prasad, M., Patel, N. K., Srivastav, A. L., Egbueri, J. C., Kumar, G. A., & Ramola, R. C. (2023). Occurrences, sources and health hazard estimation of potentially toxic elements in the groundwater of Garhwal Himalaya, India. *Scientific Reports*, *13*(1), 13069. https://doi.org/10.1038/s41598-023-40266-7

Badamasi, H., Yaro, M. N., Ibrahim, A., & Bashir, I. A. (2019). Impacts of phosphates on water quality and aquatic life. *Chem. Res. J*, *4*(3), 124-133.

Ben Salem, S., Ben Salem, A., Karmaoui, A., & Yacoubi Khebiza, M. (2023). Vulnerability of water resources to drought risk in southeastern Morocco: case study of ziz basin. Water, 15(23), 4085 https://doi.org/10.3390/w15234085

Benmarce, K., Hadji, R., Hamed, Y., Zahri, F., Zighmi, K., Hamad, A., Gentilucci, M., Ncibi, K., & Besser, H. (2023). Hydrogeological and water quality analysis of thermal springs in the Guelma region of north-eastern Algeria: A study using hydrochemical, statistical, and isotopic approaches. *Journal of African Earth Sciences, 205*, 105011. https://doi.org/10.1016/j.jafrearsci.2023.105011

Benzina, I., Bachir, A. S., Arar, A., Perennou, C., & Guelmami, A. (2024). Using DPSIR framework for the implementation of wetlands observatory: case study Sebkhates of Aures wetlands complex (Northerneast, Algeria). *Present Environment & Sustainable Development*, *18*(1). https://doi.org/10.47743/pesd2024181021

Bouahim, S., Rhazi, L., Ernoul, L., Mathevet, R., Amami, B., Er-Riyahi, S., ... & Grillas, P. (2015). Combining vulnerability analysis and perceptions of ecosystem services in sensitive landscapes: A case from western Moroccan temporary wetlands. *Journal for Nature Conservation*, *27*, 1-9. https://doi.org/10.1016/j.jnc.2015.05.003

Bouchama, K. (2022). Efficiency of Constructed Wetlands and Wastewater Stabilization Ponds for Wastewater Treatment in Northern Algerian Sahara. In *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates* (pp. 21-42). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-03600-2_2

Chen, S., Wu, W., Hu, K., & Li, W. (2010). The effects of land use change and irrigation water resource on nitrate contamination in shallow groundwater at county scale. *Ecological Complexity*, *7*(2), 131-138. https://doi.org/10.1016/j.ecocom.2010.03.003

Dar, S. A., Hamid, A., Rashid, I., & Bhat, S. U. (2022). Identification of anthropogenic contribution to wetland degradation: Insights from the environmetric techniques. *Stochastic environmental research and risk assessment*, *36*(5), 1397-1411.

Dontsova, K., Balogh-Brunstad, Z., & Chorover, J. (2020). Plants as drivers of rock weathering. *Biogeochemical cycles: Ecological drivers and environmental impact*, 33-58. https://doi.org/10.1002/9781119413332.ch2

Egbueri, J. C., & Unigwe, C. O. (2019). An integrated indexical investigation of selected heavy metals in drinking water resources from a coastal plain aquifer in Nigeria. SN Applied Sciences 1 (11): 1422. https://doi.org/10.1007/s42452-019-1489-x

Egbueri, J. C., & Unigwe, C. O. (2019). An integrated indexical investigation of selected heavy metals in drinking water resources from a coastal plain aquifer in Nigeria. SN Applied Sciences 1 (11): 1422. https://doi.org/10.1007/s42452-019-1489-x

Egbueri, J. C., Agbasi, J. C., AlSaleh, S. S., Abba, S. I., Aralu, C. C., Khan, M. Y. A., ... & Usman, A. G. (2025). Towards environmental sustainability: multi-pathway exposure and health risk assessment of urban groundwater PTEs using the HHRISK code and indexical computing. *International Journal of Environmental Health Research*, 1-26. https://doi.org/10.1080/09603123.2025.2534419

Egbueri, J. C., Agbasi, J. C., ElKashouty, M., Khan, M. Y. A., Abba, S. I., & Khan, N. (2025). An integrated computational and graphical approach for evaluating the geochemistry and health risks of nitrate-contaminated water for six age groups. *Journal of Environmental Science and Health, Part C*, *43*(1), 82-115.

Egbueri, J. C., Agbasi, J. C., ElKashouty, M., Khan, M. Y. A., Abba, S. I., & Khan, N. (2025). An integrated computational and graphical approach for evaluating the geochemistry and health risks of nitrate-contaminated water for six age groups. *Journal of Environmental Science and Health, Part C*, *43*(1), 82-115. https://doi.org/10.1080/26896583.2024.2436804

Egbueri, J. C., Agbasi, J. C., Ezugwu, A. L., Omeka, M. E., Ucheana, I. A., Aralu, C. C., & Abugu, H. O. (2024). Metal (loid) s, nitrate, polycyclic aromatic hydrocarbons, and radioactive contaminants in Nigerian water resources: state-of-the-art of their ecological and health risk assessments. *Environment, Development and Sustainability*, 1-50. https://doi.org/ 10.1007/s10668-024-05423-6

Egbueri, J. C., Agbasi, J. C., Ikwuka, C. F., Chiaghanam, O. I., Khan, M. I., Khan, M. Y. A., ... & Uwajingba, H. C. (2024). Nitrate health risk and geochemical characteristics of water in a semi-urban: implications from graphical plots and statistical computing. *International Journal of Environmental Analytical Chemistry*, *104*(19), 8491-8511. https://doi.org/10.1080/ 03067319.2023.2206022

Eid, M. H., Saeed, O., Szűcs, P., Kovács, A., Székács, A., Mörtl, M., ... & Gad, M. (2025). Impacts and sources of potential toxic elements on water quality and optimizing machine learning models for sustainable management. *Modeling Earth Systems and Environment*, *11*(5), 375. https://doi.org/10.1007/ s40808-025-02548-z

El Osta, M., Masoud, M., Alqarawy, A., Elsayed, S., & Gad, M. (2022). Groundwater suitability for drinking and irrigation using water quality indices and multivariate modeling in makkah Al-Mukarramah province, Saudi Arabia. *Water*, *14*(3), 483. https://doi.org/10.1016/j.rineng.2025.105027

El Osta, M., Masoud, M., Alqarawy, A., Elsayed, S., & Gad, M. (2022). Groundwater suitability for drinking and irrigation using water quality indices and multivariate modeling in makkah Al-Mukarramah province, Saudi Arabia. *Water*, *14*(3), 483. https://doi.org/10.1016/j.rineng.2025.105027

El Osta, M., Masoud, M., Alqarawy, A., Elsayed, S., & Gad, M. (2022). Groundwater suitability for drinking and irrigation using water quality indices and multivariate modeling in makkah Al-Mukarramah province, Saudi Arabia. *Water*, *14*(3), 483. https://doi.org/10.3390/w14030483

Elsayed, S., Hussein, H., Moghanm, F. S., Khedher, K. M., Eid, E. M., & Gad, M. (2020). Application of irrigation water quality indices and multivariate statistical techniques for surface water quality assessments in the Northern Nile Delta, Egypt. *Water*, *12*(12), 3300. https://doi.org/10.3390/w12123300

Emmanuel, N., & Moses, M. (2023). The influence of climate on water potential of wetland in uganda.

Gad, M., Elsayed, S., Moghanm, F. S., Almarshadi, M. H., Alshammari, A. S., Khedher, K. M. & Hussein, H. (2020). Combining water quality indices and multivariate modeling to assess surface water quality in the Northern Nile Delta, Egypt. *Water*, *12*(8), 2142. https://doi.org/10.3390/w12082142

Gad, M., Elsayed, S., Moghanm, F. S., Almarshadi, M. H., Alshammari, A. S., Khedher, K. M. & Hussein, H. (2020). Combining water quality indices and multivariate modeling to assess surface water quality in the Northern Nile Delta, Egypt. *Water*, *12*(8), 2142. https://doi.org/10.3390/w12082142

Gad, M., Gaagai, A., Agrama, A. A., El-Fiqy, W. F., Eid, M. H., Szűcs, P. & Ibrahim, H. (2024). Comprehensive evaluation and prediction of groundwater quality and risk indices using quantitative approaches, multivariate analysis, and machine learning models: An exploratory study. *Heliyon*, *10*(17). https://doi.org/10.1016/j.heliyon.2024.e36606

Gad, M., Gaagai, A., Eid, M. H., Szűcs, P., Hussein, H., Elsherbiny, O. & Ibrahim, H. (2023). Groundwater quality and health risk assessment using indexing approaches, multivariate statistical analysis, artificial neural networks, and GIS techniques in El Kharga Oasis, Egypt. *Water*, *15*(6), 1216. https://doi.org/10.3390/w15061216

Gad, M., Saleh, A. H., Hussein, H., Farouk, M., & Elsayed, S. (2022). Appraisal of surface water quality of nile river using water quality indices, spectral signature and multivariate modeling. *Water*, *14*(7), 1131. https://doi.org/10.3390/w14071131

Gad, M., Saleh, A. H., Hussein, H., Farouk, M., & Elsayed, S. (2022). Appraisal of surface water quality of nile river using water quality indices, spectral signature and multivariate modeling. *Water*, *14*(7), 1131. https://doi.org/10.3390/w14071131

Garba, S. I., Ebmeier, S. K., Bastin, J. F., Mollicone, D., & Holden, J. (2025). Wetland fragmentation associated with large populations across Africa. Nature Communications, 16(1), 5065. https://doi.org/10.1038/s41467-025-59373-2

Ghrabi A, Bousselmi L, Masi F, Regelsberger M (2011) Constructed wetland as a low cost and sustainable solution for wastewater treatment adapted to rural settlements: the Chorfech wastewater treatment pilot plant. Water Sci Technol 63(12):3006–3012. https://doi.org/10.2166/ wst.2011.563

Halicki, W., & Halicki, M. (2022). From domestic sewage to potable water quality: New approach in organic matter removal using natural treatment systems for wastewater. *Water*, *14*(12), 1909. https://doi.org/10.3390/w14121909

Hammana, C., Pereña-Ortiz, J. F., Meddad-Hamza, A., Hamel, T., & Salvo-Tierra, Á. E. (2024). The Wetlands of Northeastern Algeria (Guelma and Souk Ahras): Stakes for the Conservation of Regional Biodiversity. *Land*, *13*(2), 210. https://doi.org/10.3390/land13020210

Hfaiedh, E., Gaagai, A., Petitta, M., Ben Moussa, A., Mlayah, A., Eid, M. H., ... & Gad, M. (2025). Hydrogeochemical characterization and water quality evaluation associated with toxic elements using indexing approaches, multivariate analysis, and artificial neural networks in Morang, Tunisia. *Environmental Earth Sciences*, *84*(13), 361. https://doi.org/10.1007/s12665-025-12165-9

Hu, J., Zhu, C., Long, Y., Yang, Q., Zhou, S., Wu, P., ... & Hu, X. (2021). Interaction analysis of hydrochemical factors and dissolved heavy metals in the karst Caohai Wetland based on PHREEQC, cooccurrence network and redundancy analyses. *Science of the Total Environment*, *770*, 145361. https://doi.org/10.1016/j.scitotenv.2021.145361

Ilavarasan, N., Ilangovan, R., & Prasanna, P. R. (2016). Water quality assessment on Ooty lake in Nilgiris district. *Journal of environmental biology*, *37*(6), 1463.

Kaushal, M., Patil, M. D., & Wani, S. P. (2018). Potency of constructed wetlands for deportation of pathogens index from rural, urban and industrial wastewater. *International Journal of Environmental Science and Technology*, *15*(3), 637-648. https://doi.org/10.1007/s13762-017-1423-y

Khaldia, S. T., Belgacem, H., Miyada, O., Vincent, V., Abdelghani, E., Barbieri, M., & Boschett, T. (2024). Identification of the hydrogeochemical processes and assessment of groundwater quality using Water Quality Index (WQI) in semi-arid area F'kirina eastern Algeria. https://doi.org/10.1007/s12665-024-11917-3

Loucif, K., & Chenchouni, H. (2024). Water physicochemical quality as driver of spatial and temporal patterns of microbial community composition in lake ecosystems. *Applied Water Science*, *14*(6), 115. https://doi.org/10.1007/s13201-024-02176-5

Maruthai, S., Rajendran, S., Selvanarayanan, R., & S, G. (2025). Wastewater Recycling Integration with IoT Sensor Vision for Real-time Monitoring and Transforming Polluted Ponds into Clean Ponds using HG-RNN. *Global NEST Journal*, *27*(4), 1-11. https://doi.org/10.30955/gnj.06758

Meskine, A., Zerouali, B., Ouadja, A., Santos, C. A. G., Bailek, N., Bouznad, I. E., & Baba, A. (2025). Decision-support approaches for sustainable water resource management in northwest Algeria. *Journal of Ecological Engineering*, *26*(7), 24-43. https://doi.org/10.12911/22998993/202996

Mohan, R. R., Nagesh, T., Das, A., Sahu, S., Reddy, D. R., & Paturi, A. P. (2019). Physico-chemical characteristics of Nalban wetland of east Kolkata wetlands, a Ramsar site, West Bengal, India. International Journal of Current Microbiology and Applied Sciences, 8(04), 1264-1275.

Munir, R., Muneer, A., Sadia, B., Younas, F., Zahid, M., Yaseen, M., & Noreen, S. (2024). Biochar imparted constructed wetlands (CWs) for enhanced biodegradation of organic and inorganic pollutants along with its limitation. *Environmental Monitoring and Assessment*, *196*(5), 425.

New record of Lestica bibundica Leclercq, 1972 (Hymenoptera, Crabronidae) from West Africa

Okeke, E. S., Egbueri, J. C., Emmanuel, S. S., Ezeudoka, B. C., Nwuche, C. O., Okeke, V. C., & Enochoghene, A. E. (2025). Antibiotic resistance in Nigeria's water system: an urgent public health challenge impeding the achievement of Sustainable Development Goals (SDGs). *Integrated Environmental Assessment and Management*, vjaf143. https://doi.org/10.1007/s44378-025-00074-z

Okeke, E. S., Egbueri, J. C., Emmanuel, S. S., Ezeudoka, B. C., Nwuche, C. O., Okeke, V. C., & Enochoghene, A. E. (2025). Antibiotic resistance in Nigeria's water system: an urgent public health challenge impeding the achievement of Sustainable Development Goals (SDGs). *Integrated Environmental Assessment and Management*, vjaf143. https://doi.org/10.1007/s44378-025-00074-z

Ouma, S. O., Ngeranwa, J. N., Juma, K. K., & Mburu, D. N. (2016). Seasonal variation of the physicochemical and bacteriological quality of water from five rural catchment areas of lake victoria basin in Kenya. http://dx.doi.org/10.4172/2380-2391.1000170

Pande, C. B., Tolche, A. D., Egbueri, J. C., Mohd Sidek, L., Singh, R., Mishra, A. P., ... & Sammen, S. S. (2025). Implications of seasonal variations of hydrogeochemical analysis using GIS, WQI, and statistical analysis method for the semi-arid region. *Applied Water Science*, *15*(4), 80. https://doi.org/10.1007/s13201-025-02387-4

Pande, C. B., Tolche, A. D., Egbueri, J. C., Mohd Sidek, L., Singh, R., Mishra, A. P., ... & Sammen, S. S. (2025). Implications of seasonal variations of hydrogeochemical analysis using GIS, WQI, and statistical analysis method for the semi-arid region. *Applied Water Science*, *15*(4), 80. https://doi.org/10.1080/00032719.2025.2569841

RamadanFSM (2016) Sedimentological and hydrogeochemical studies of the quaternary groundwater aquifer in El Salhyia area. Sharkia governorate. Egypt. Middle East J Appl Sci

Raveena, S., & Surendran, R. (2024, November). Real-Time Monitoring and Optimization of Recycled Water Irrigation in Coffee Plantations using Bi-Directional RNNs and IoT Sensors. In 2024 International Conference on Innovation and Intelligence for Informatics, Computing, and Technologies (3ICT) (pp. 116-123). IEEE. https://doi.org/10.30955/gnj.07324

Rifai, N., Khattabi, A., Moukrim, S., Arahou, M., & Rhazi, L. (2018). Évaluation de la dynamique de l'occupation du sol dans la zone humide RAMSAR de Tahaddart (Nord-Ouest du Maroc). *Revue d'Écologie*, *73*(2), 142-152. https://hal.science/hal-03532629v1

Saalidong, B. M., Aram, S. A., Otu, S., & Lartey, P. O. (2022). Examining the dynamics of the relationship between water pH and other water quality parameters in ground and surface water systems. *PloS one*, *17*(1), e0262117

Sánchez-González, A., Fuentes-García, R., Pablo-Trujillo, C., Hernández-Quiroz, M., & Ponce de León Hill, C. A. (2021). Sediment organic matter description from an urban wetland: multivariate analysis of FT-IR bands to determine its origin. *International Journal of Environmental Analytical Chemistry*, *101*(7), 1007-1025. https://doi.org/10.1080/03067319.2019.1675650

Selvanarayanan, R., Rajendran, S., Pappa, C. K., & Thomas, B. (2024). Wastewater recycling to enhance environmental quality using fuzzy embedded with RNN-IOT for sustainable coffee farming. *GLOBAL NEST JOURNAL*, *26*(8). https://doi.org/10.30955/gnj.006346

Singh, D., Kumar, K., Singh, C., & Ahmad, T. (2022). Assessment of water quality of Holy Kali Bein rivulet (Punjab) India, using multivariate statistical analysis. *International Journal of Environmental Analytical Chemistry*, *102*(18), 6784-6800. https://doi.org/10.1080/03067319.2020.1817425

Sivasubramanian, S., Venkatesan, S. K. G., Thanarajan, T., & Rajendran, S. (2025). Al-Biruni Earth Radius Optimization for enhanced environmental data analysis in remote sensing imagery. *Agrociencia*, 1-18.

Solovey T, Wojewódka-Przybył M, Janica R (2021) Hydrochemical indicators of water source and contamination in fen peatlands of varying hydrogeomorphic settings in northern and central Poland. Ecol Indic 129:107944

Tariq, A., & Mushtaq, A. (2023). Untreated wastewater reasons and causes: A review of most affected areas and cities. *Int. J. Chem. Biochem. Sci*, *23*(1), 121-143.

Ucheana, I. A., Omeka, M. E., Ezugwu, A. L., Agbasi, J. C., Egbueri, J. C., Abugu, H. O., & Aralu, C. C. (2024). A targeted review on occurrence, remediation, and risk assessments of bisphenol A in Africa. Environmental Monitoring and Assessment, 196(12), 1193. https://doi.org/10.1007/s10661-024-13337-z

Ucheana, I. A., Omeka, M. E., Ezugwu, A. L., Agbasi, J. C., Egbueri, J. C., Abugu, H. O., & Aralu, C. C. (2024). A targeted review on occurrence, remediation, and risk assessments of bisphenol A in Africa. *Environmental Monitoring and Assessment*, *196*(12), 1193. https://doi.org/10.1007/s10661-024-13337-z

Unigwe, C. O., & Egbueri, J. C. (2023). Drinking water quality assessment based on statistical analysis and three water quality indices (MWQI, IWQI and EWQI): a case study. *Environment, Development and Sustainability*, *25*(1), 686-707. https://doi.org/10.1007/s10668-021-02076-7

Venkatraman, M., Surendran, R., Senduru, S., & Vijayakumar, K. (2025). Water quality prediction and classification using Attention based Deep Differential RecurFlowNet with Logistic Giant Armadillo Optimization. *Global NEST Journal*, *27*(1), 1-13. https://doi.org/10.30955/gnj.06799

Vystavna Y, Yakovlev V, Diadin D, Vergeles Y, Stolberg F (2015) Hydrochemical characteristics and water quality assessment of surface and ground waters in the transboundary (Russia/Ukraine) Seversky Donets basin. Environ Earth Sci 74:585–596. https:// doi.org/ 10. 1007/ s12665- 015- 4060-0

Wanja, D. W. (2023). Seasonal prevalence, molecular characterization, antimicrobial resistance and factors associated with thermophilic Campylobacter in cattle, chicken and water in Kajiado County, Kenya (Doctoral dissertation, University of Nairobi). http://erepository.uonbi.ac.ke/ handle/11295/164251

WHO (2011) Guidelines for drinking-water quality. WHO Chron 38:104–108

Yang, Z., Bai, J., & Zhang, W. (2021). Mapping and assessment of wetland conditions by using remote sensing images and POI data. Ecological Indicators, 127, 107485. https://doi.org/10.1016/j.ecolind.2021.107485

Zahi, F., Drouiche, A., Medjani, F., Azzeddine, R., & Djidel, M. (2024). Hydrogeochemical processes controlling surface water quality for irrigation in a Mediterranean wetland ecosystem, Northeast Algeria. *Environmental Monitoring and Assessment*, *196*(10), 881. https://doi.org/10.1007/s10661-024-13019-w

Zhang, Y., Wang, L., Jiang, J., Zhang, J., Zhang, Z. and Zhang, M. (2022) Application of Soil Quality Index to Determine the Effects of Different Vegetation Types on Soil Quality in the Yellow River Delta Wetland. Ecological Indicators, 141, Article ID: 109116. https://doi.org/10.1016/j.ecolind.2022.109116