Integrated Seasonal Assessment of Spring Water Quality for Drinking and Domestic Purposes in El Kala, Northeastern Algeria

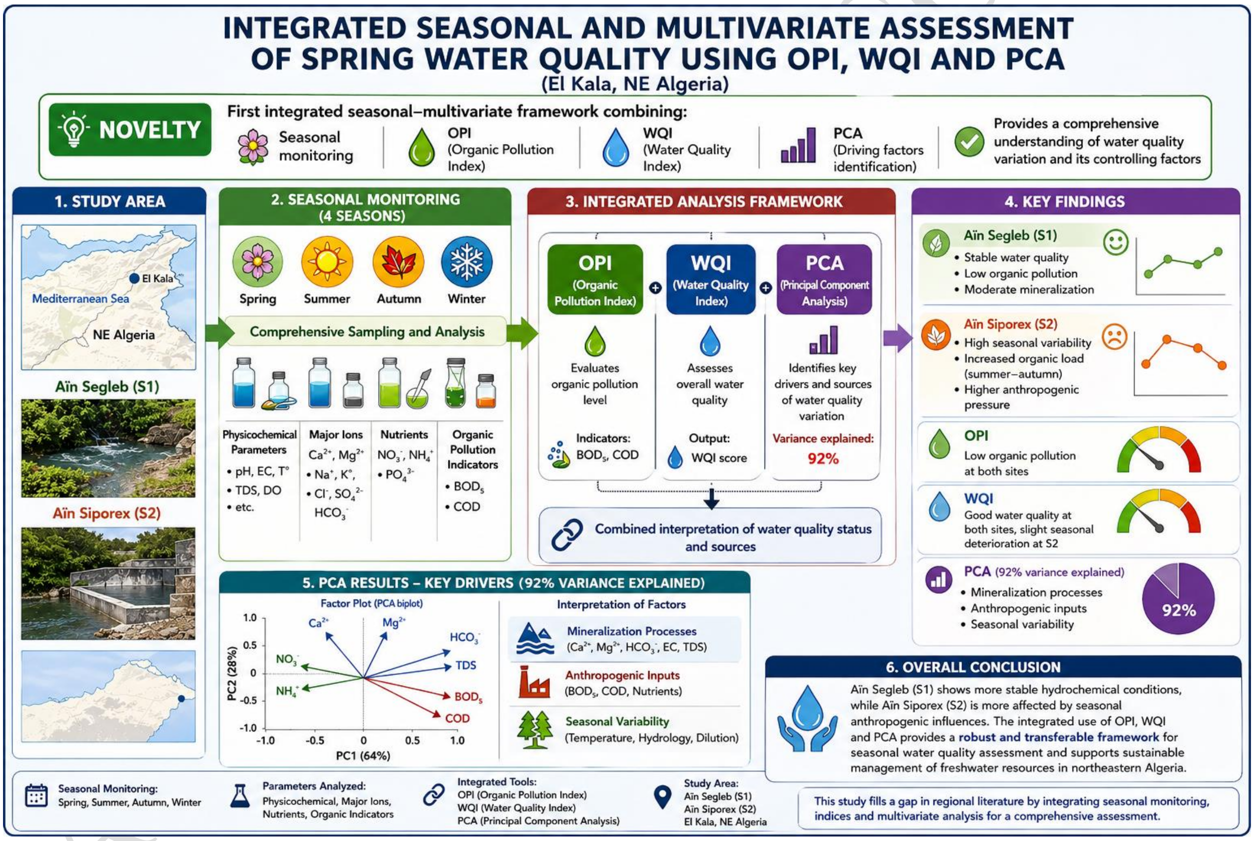
Amira BERGAL[1,3*], Warda BOUMARAF[1], Loubna NEFLA[2], Chahrazed BOUKSIBA [2], and Djamel Eddine BENOUARETH[3]

[1]Laboratory of Environmental Sciences and Agroecology, Department of Biology, Faculty of Natural and Life Sciences, University of Chadli Bendjedid, EL-Tarf, B.P73, 36000, Algeria.

[2]Laboratory of Biodiversity and Ecosystem Pollution, Department of Biology, Faculty of Natural and Life Sciences, University of Chadli Bendjedid, EL-Tarf, B.P73, 36000, Algeria

[3]Laboratory of Molecular and cellular Biology, Department of Biology, Faculty of Natural and Life Sciences and Earth and Universe Sciences, University of 8 May, Guelma, Algeria.

* To whom all correspondence shoud be addressed: e-mail: a.bergal@univ-eltarf.dz



INTEGRATED SEASONAL AND MULTIVARIATE ASSESSMENT OF SPRING WATER QUALITY USING OPI, WQI AND PCA
(El Kala, NE Algeria)

NOVELTY First integrated seasonal–multivariate framework combining: Seasonal monitoring | OPI (Organic Pollution Index) | WQI (Water Quality Index) | PCA (Driving factors identification) | Provides a comprehensive understanding of water quality variation and its controlling factors

1. STUDY AREA

Aïn Segleb (S1)

Aïn Siporex (S2)

2. SEASONAL MONITORING (4 SEASONS)

Spring, Summer, Autumn, Winter

Comprehensive Sampling and Analysis

Physicochemical Parameters	Major Ions	Nutrients	Organic Pollution Indicators
• pH, EC, T° • TDS, DO • etc.	Ca^{2+}, Mg^{2+} • Na^+, K^+, • Cl^-, SO_4^{2-} HCO_3^-	NO_3^-, NH_4^+ • PO_4^{3-}	• BOD_5 • COD

3. INTEGRATED ANALYSIS FRAMEWORK

OPI (Organic Pollution Index)	WQI (Water Quality Index)	PCA (Principal Component Analysis)
Evaluates organic pollution level	Assesses overall water quality	Identifies key drivers and sources of water quality variation
Indicators: BOD_5, COD	Output: WQI score	Variance explained: 92%

Combined interpretation of water quality status and sources

4. KEY FINDINGS

Aïn Segleb (S1)
- Stable water quality
- Low organic pollution
- Moderate mineralization

Aïn Siporex (S2)
- High seasonal variability
- Increased organic load (summer–autumn)
- Higher anthropogenic pressure

OPI
Low organic pollution at both sites

WQI
Good water quality at both sites, slight seasonal deterioration at S2

PCA (92% variance explained)
- Mineralization processes
- Anthropogenic inputs
- Seasonal variability

92%

5. PCA RESULTS – KEY DRIVERS (92% VARIANCE EXPLAINED)

Factor Plot (PCA biplot)

Interpretation of Factors

Mineralization Processes (Ca^{2+}, Mg^{2+}, HCO_3^-, EC, TDS)

Anthropogenic Inputs (BOD_5, COD, Nutrients)

Seasonal Variability (Temperature, Hydrology, Dilution)

6. OVERALL CONCLUSION

Aïn Segleb (S1) shows more stable hydrochemical conditions, while Aïn Siporex (S2) is more affected by seasonal anthropogenic influences. The integrated use of OPI, WQI and PCA provides a **robust and transferable framework** for seasonal water quality assessment and supports sustainable management of freshwater resources in northeastern Algeria.

Seasonal Monitoring: Spring, Summer, Autumn, Winter

Parameters Analyzed: Physicochemical, Major Ions, Nutrients, Organic Indicators

Integrated Tools: OPI (Organic Pollution Index) WQI (Water Quality Index) PCA (Principal Component Analysis)

Study Area: Aïn Segleb (S1) Aïn Siporex (S2) El Kala, NE Algeria

This study fills a gap in regional literature by integrating seasonal monitoring, indices and multivariate analysis for a comprehensive assessment.

Abstract

This study investigates the seasonal variability of surface water quality in two spring systems, Aïn Segleb (S1) and Aïn Siporex (S2), located in northeastern Algeria. Seasonal sampling (spring, summer, autumn, and winter) was conducted to evaluate physicochemical parameters, major ions, nutrients, and organic pollution indicators (BOD_5 and COD).

Water quality was assessed using the Organic Pollution Index (IPO), Water Quality Index (WQI), and Principal Component Analysis (PCA) to identify the main factors controlling water quality variation.

The results showed clear spatial and seasonal differences between the two sites. Aïn Segleb exhibited relatively stable water quality with moderate mineralization and consistently low organic pollution throughout the year. In contrast, Aïn Siporex showed higher temporal variability, with increased organic loads during summer and autumn, suggesting stronger anthropogenic pressure.

IPO results indicated generally low organic pollution at both sites, while WQI classified the water as overall good quality, with slight seasonal deterioration at S2. PCA explained 92% of the total variance and highlighted mineralization processes, anthropogenic inputs, and seasonal effects as the main drivers of water quality variation.

Overall, Aïn Segleb presented more stable hydrochemical conditions, whereas Aïn Siporex was more affected by seasonal anthropogenic influences. These findings emphasize the importance of continuous seasonal monitoring for sustainable management and protection of freshwater resources in northeastern Algeria.

Keywords: Surface water quality, Seasonal variation Ain Segleb, Ain Siporex, Physico-chemical parameters, Organic pollution index, Water quality index, Principal component analysis.

1. Introduction

Water is a fundamental natural resource essential for sustaining life and supporting human activities. It plays a central role in domestic, agricultural, and industrial sectors, making it highly vulnerable to various forms of pollution. As a result, water resources often act as receptors for physical, chemical, and biological contaminants, and may serve as vectors for waterborne diseases (Laoufi *et al.,* 2025). Ensuring access to safe drinking water, defined by appropriate physicochemical, microbiological, and organoleptic standards, remains a major global challenge (Salamani *et al.,* 2024).

Despite its essential role, water pollution continues to cause significant health risks, particularly in developing countries, where millions of deaths are linked to contaminated water sources (El Marmara et *al.,* 2024). Water intended for human consumption must meet strict quality criteria, including clarity, absence of odor and harmful substances, and complete absence of pathogenic microorganisms (Lalaoui et *al.,* 2024).

Currently, water quality is increasing pressure due to rapid population growth, urbanization, and expanding industrial and agricultural activities. The degradation of water quality has become as critical as water scarcity itself (Moussaoui et *al.,* 2025). Anthropogenic activities, including agricultural runoff, wastewater discharge, and improper waste management, are major contributors to water contamination (Syed et *al.,* 2025).

In Algeria, water resources are becoming increasingly limited, intensifying competition between agriculture, industry, and domestic use (Mebarki *et al.,* 2024). Over the past decades, the uncontrolled discharge of agricultural, industrial, and domestic effluents has significantly contributed to the degradation of both surface and groundwater quality.

The wilaya of El Tarf is particularly known for its abundance of natural springs and water resources. However, despite this richness, many of these springs remain underutilized or poorly managed. Inadequate protection measures, lack of monitoring, and exposure to anthropogenic pollution sources have led to the deterioration of water quality, limiting their potential use.

Although several studies have investigated groundwater quality in Algeria and North Africa, most of them are based on single-season sampling, limited physicochemical parameters, or descriptive approaches. Integrated studies combining seasonal monitoring, pollution indices, and multivariate statistical analysis remain scarce, particularly for spring water systems.

In this context, the novelty of the present study lies in: (i) the integration of seasonal monitoring covering four seasons, (ii) the combined application of Organic Pollution Index (IPO), Water Quality Index (WQI), and Principal Component Analysis (PCA), and (iii) the comparative assessment of two hydrogeologically contrasting spring systems. This comprehensive approach allows a deeper understanding of the interactions between natural processes (lithology, hydrochemistry) and anthropogenic pressures on water quality.

This study therefore aims to assess the seasonal variability of surface water quality in two spring systems (Aïn Segleb and Aïn Siporex) in northeastern Algeria by analyzing physicochemical parameters, hydrochemical facies, and organic pollution indicators, in order to identify the key factors controlling water quality and to support sustainable water resource management.

2. Material and methods

2.1. Study area

The two studied water sources (Ain Siporex and Ain Segleb) are in northern El Traf Province, Northeastern Algeria. Source Ain Siporex (S2) is in Oum Teboul at 36°53.576′N 08°33.017′E and source Ain Segleb (S1) is in Souarkh at 36°53.576′N08°33.017′E. The study area is part of El Kala National Park, is located in the extreme northeast of Algeria, It is limited: In the North, by the Mediterranean Sea. In the South, by the foothills of the Medjerda mountains. To the East, by the Algerian-Tunisian border. To the West, by the end of the alluvial plain of Annaba (Figure 1).

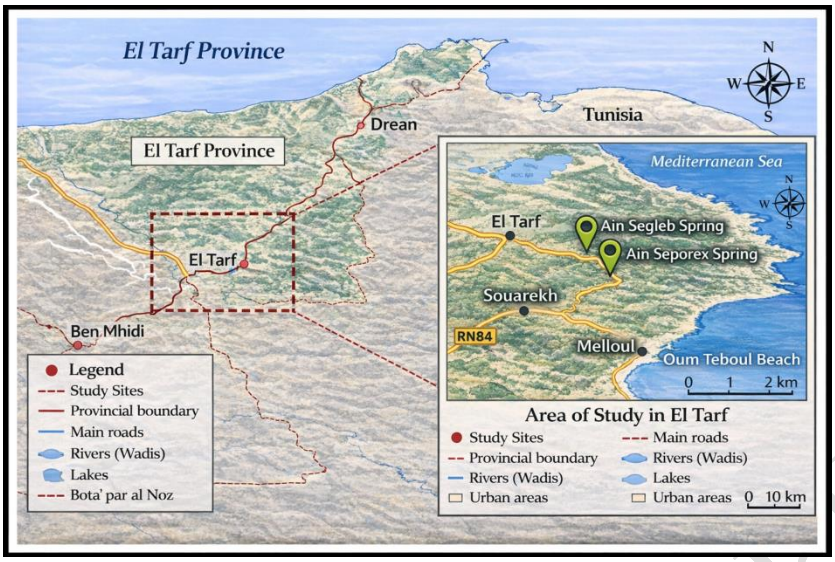


Figure 1. Localisation of the study area

2.2. Sampling and analysis methods

The choice of sampling sites was determined by their exposure to various pollutants. Sampling was carried out in situ during the four seasons of 2024, with three samples taken per site, at two different locations (Figure 1). Samples were collected in sterile glass bottles for bacteriological analyses and in polyethylene bottles for physicochemical analyses, after being rinsed at least three times with the sampling water. After bottling and labeling, the samples were placed in a cooler at 4°C to maintain their temperature. Temperature (T°), hydrogen potential (pH), electrical conductivity (EC), salinity, total dissolved solids (TDS) and turbidity, were measured in situ using a multi-parameter field instrument (type Hanna Hi 8519N). The monitoring of physico-chemical parameters is carried out in the laboratory at El Tarf University using standardised methods. These parameters are: Total alkalimetric titre (TAC), calcium (Ca^{+2}), magnesium (Mg^{+2}), potassium (K^{+}), sodium (Na^{+}), chloride (Cl^{-}), total chlorine (Cl_2), ammonium (NH_4^{+}), nitrate (NO_3^{-}), nitrite (NO_2^{-}), orthophosphate (PO_4^{-3}), Biological Oxygen Demand (BOD_5 and COD).

2.3. Organic Pollution Index (OPI)

For evaluation of organic pollution, we employed the Organic Pollution Index (IPO) to evaluate the organic load in the river. The fundamental principle of the IPO is to categorize the values of pollutants into five classes. The underlying calculation principle is to divide the values of the four pollutants were categorized into five classes. The class numbers for each parameter were then determined based on the values obtained in the study, with the average data from (Table 1) being used for this purpose. The classification of organic parameters is a subject of considerable interest. In accordance with the five quality classes that correspond to standard colors (Boukich *et al.,* 2025).

Table 1. Grid of organic pollution index classes OPI and degrees of pollution (Leclercq, 2001).

Parameters Classes	**NH_4^+ (mg/l)**	**BOD_5 (mg/l)**	**PO_4^{3-}(µg/l)**	**NO_2^- (µg/l)**	**Average of classes (OPI)**	**Level of organi pollution**
5	<0,1	<2	<15	<5	4,6-5,0	**Nothing Pollution**
4	0,1-0,9	2,1-5	16-75	6 – 10	4,0-4,5	**Low Pollution**
3	1-2,4	5,1-10	76-250	11 – 50	3,0-3,9	**Moderate Pollution**
2	2,5-6	10,1-15	251-900	51 – 150	2,0-2,9	**Strong Pollution**
1	>6	>15	>900	>150	1,0-1,9	**Very strong Pollution**

Water Quality Index (WQI) Methodology

The Water Quality Index (WQI) was applied to provide an integrated evaluation of surface water quality at the investigated sites. The index was calculated using a set of key physicochemical variables namely pH, electrical conductivity (EC), salinity, dissolved oxygen (DO), total dissolved solids (TDS), and major ions chosen for their recognized relevance in characterizing water quality conditions (Salamani et *al.,* 2024). Each parameter was assigned a specific weight reflecting its relative contribution to overall water quality. A quality rating was then determined for each variable by comparing the measured concentration with its corresponding ideal value and permissible standard. Individual sub-indices were obtained by multiplying the assigned weight by the respective quality rating, and the final WQI value was derived from the summation of all sub-indices, following the approach described by Al Baghdadi et *al.,* (2019).

The Water Quality Index (WQI) was calculated using the following equation:

$$\mathbf{WQI = \Sigma\, SI_i}$$

where:

- **SI_i** is the sub-index of the *i-th parameter*

- $\mathbf{SI_i = W_i \times Q_i}$
- $\mathbf{W_i}$ is the relative weight of each parameter
- $\mathbf{Q_i}$ is the quality rating of each parameter
- **n** is the number of parameters

The WQI values were classified into five categories**:** Excellent (0–25), Good (26–50), Poor (51–75), Very Poor (76–100), and Unsuitable for drinking (>100)**,** providing a clear evaluation of water quality across stations and seasons.

2.4. Principal Component Analysis (PCA)

Principal component analysis (PCA) was applied to the normalized dataset in order to explore relationships among physicochemical variables and to identify the main spatial gradients differentiating the studied sites. Prior to PCA, all variables were standardized to eliminate the effect of different measurement units. PCA was performed on the correlation matrix, and only components with eigenvalues > 1 were considered for interpretation. The first two principal components (PC1 and PC2) explained the majority of the total variance, indicating that most of the observed variability can be summarized by a reduced number of underlying environmental factors, as previously reported by Samake *et al.,* (2025).

The PC1 axis, interpreted as a mineralization and pollution gradient, showed strong positive loadings for electrical conductivity (EC), chlorides (Cl^-), sulfates (SO_4^{2-}), and to a lesser extent nitrates (NO_3^-). This component reflects the influence of water mineralization processes associated with both natural geological background and anthropogenic inputs, including soil leaching, agricultural activities, and domestic wastewater discharge.

The PC2 axis, interpreted as an organic and trophic pollution gradient, was mainly associated with biological oxygen demand (BOD_5), phosphates (PO_4^{3-}), and ammonium (NH_4^+). This component reflects recent organic pollution inputs and varying degrees of eutrophication in the studied aquatic environments.

2.5. Bacteriological study

Microbiological analyses were performed following the standard methods described by Rodier (2009). In addition, complementary procedures described by Babalola *et al.,* (2024) were also applied. Water samples were collected aseptically in sterile 500 mL glass bottles with ground-glass stoppers, ensuring minimal contamination during sampling and leaving a small air space to allow homogenization prior to analysis.

The bacteriological quality of water was assessed through the enumeration of indicator microorganisms, including total viable bacteria, total coliforms, fecal coliforms (FC), fecal streptococci (FS), sulfite-reducing Clostridia (CSR), and Salmonella spp. These indicators were selected due to their relevance in assessing fecal contamination and potential health risks.

Bacteriological analyses were carried out using the membrane filtration technique (0.45 µm). Selective culture media and incubation conditions were applied according to the targeted microorganisms. Total bacteria were enumerated at 22°C and 37°C, while elevated incubation temperatures were used to distinguish fecal coliforms from total coliforms. Fecal streptococci were enumerated on Slanetz and Bartley agar, as described in previous studies.

All microbial counts were expressed as colony-forming units per 100 mL (CFU/100 mL). The methodological approach ensured consistency across all samples and allowed reliable comparison of microbiological water quality.

3. Data processing

All analyses were performed in triplicate using independent measurements. Data were expressed as mean ± standard deviation (SD). Prior to statistical analysis, data were checked for consistency and normality where applicable. This approach was used to ensure the reliability and reproducibility of the results.

4. Results and Discussion

4.1. Physico-chemical characterisation of the source waters.

The results of water quality parameters of Ain Segleb and Ain Siporex are presented in Table 2. The seasonal analysis of the physico-chemical parameters measured at the two sampling stations (S1 and S2) reveals clear spatio-temporal variations reflecting both natural processes and anthropogenic pressures within the study area.

Temperature

The results indicate a clear seasonal pattern in water temperature, with higher values recorded during summer (approximately 19–20 °C) and lower values observed in winter (approximately 11–12 °C). This variability is primarily associated with regional climatic conditions. Seasonal temperature fluctuations play a key role in regulating dissolved oxygen solubility, microbial activity, and the kinetics of biochemical processes in aquatic environments.

At both sampling stations, water temperature exhibited similar temporal trends, suggesting that the two sites are mainly controlled by the same regional climatic regime rather than by local disturbances.

Water temperature is considered an important quality parameter for waters intended for human consumption, as it strongly influences consumer perception and acceptability (Laoufi, 2025). In natural aquatic systems, temperature is governed by multiple factors, including geographical location, seasonal changes, water depth, color, and volume, as well as potential inputs from industrial and domestic discharges (Laoufi et al., 2025; Moussaoui et *al.,* 2025).

Potential of hydrogen (pH)

The pH parameter reflects the acid–base status of water through the activity of hydrogen ions and typically ranges from 0 to 14. In the present study, pH values indicated slightly alkaline conditions at S1 (Aïn Segleb), with values close to 8, whereas S2 (Aïn Siporex) exhibited neutral to slightly acidic conditions, with values around 7. The relatively higher pH observed at S1 may be related to the geological context of the area, particularly the presence of carbonate-rich formations, which enhance the buffering capacity of the water and promote moderate mineralization.

Overall, all recorded pH values remained within the range generally accepted for natural freshwater environments, suggesting the absence of notable acidic or alkaline disturbances, in agreement with previous findings reported by Boumerdassi et *al.,* (2023).

Across the study area, pH variations were limited, with minimum and maximum values of 7.06 at the Aïn Siporex spring and 8.08 at the Aïn Segleb spring, respectively. These results are consistent with those reported for groundwater and spring waters in similar Algerian regions, including the studies conducted by Saibi (2013) in the Saida area, as well as more recent investigations by Laoufi (2025), Salamani (2024), and Mebarki (2024).

Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

Electrical conductivity (EC) and total dissolved solids (TDS) reveal marked spatial variability between the two sampling stations. Station S1 is characterized by a higher degree of mineralization, in agreement with the elevated concentrations of major dissolved cations, particularly Ca^{2+} and Mg^{2+}. Seasonal variations follow a classical hydrological pattern, with increased concentrations during the summer period as a consequence of enhanced evaporation, and lower values in winter due to dilution by rainfall. In contrast, station S2 exhibits lower mineral contents, indicating a less mineralized hydrogeochemical setting.

The highest electrical conductivity values were recorded at S2 (Aïn Siporex), ranging from 460 to 500 µS/cm, whereas lower values were observed at S1 (Aïn Segleb), between 350 and 410 µS/cm. These results confirm that the Aïn Siporex spring is more mineralized and consequently richer in dissolved salts.

Electrical conductivity reflects the presence and mobility of dissolved ions within the aquatic environment and is primarily controlled by both the nature and concentration of these ions (Sekiou et *al.,* 2025; Foughalia et *al.,* 2025). Total dissolved solids constitute an important parameter influencing water palatability and plant growth (Valipour et *al.,* 2014; Dass et *al.,* 2025). In the present study, TDS concentrations remained well below the guideline value of 1200 mg/L recommended by the World Health Organization, with measured values ranging from 183.1 to 200 mg/L (Table 2). The seasonal pattern of total mineralization closely mirrored that of electrical conductivity, reflecting their strong interdependence.

Turbidity values remained low throughout the study period, which is characteristic of waters with limited suspended particulate matter. Slightly higher turbidity levels were recorded during the winter season, likely associated with surface runoff and the transport of fine particles. Turbidity represents the reduction in water transparency caused by suspended materials such as clay, silt, finely divided organic matter, plankton, and other microscopic organisms (Khatri et *al.,* 2015; Bourquia et *al.,* 2024). The generally low turbidity observed suggests efficient natural settling processes and minimal erosion within the catchment areas surrounding the sampling sites (Guilal et *al.,* 2018).

Chemical Parameters of Source Waters

Calcium (Ca^{2+})

The average concentration of calcium (Ca^{2+}) in our samples varies between 150 and 240mg/L (Table 2) and its content varies essentially according to the nature of the terrain traversed (Madyouni *et al.,* 2023). The results obtained in the source of Ain Segleb are higher than those of the Algerian standards (JORA, 2011) which set a maximum value of 200 mg/L.

Magnesium (Mg^{2+})

Magnisium is an essential element for growth (50% in bones) and for the production of certain hormones**.** The measurements of our samples gave a magnesium concentration varying between 40.8 and 55.2mg/l (Table 01). These values are in agreement with the Algerian standard which set a maximum value of 150mg/l. Similar results were found by Lakhdari (2025).

Sodium (Na^{+}) is a vital element that participates in essential functions. Sodium concentrations varied from 26 (Ain Segleb) and 33mg/l (Ain Siporex)**,** and are in agreement with the Algerian standard. On the other hand our results represent higher values than those elaborated by El Behairy (2025), Mebarki (2014) and Lgourna (2013)

Potassium (K+)

According to Ayad and Kahoul (2017) (Kadari *et al.,* 2013), potassium (K+) plays an essential role in humans including the transmission of nerve impulses. The results obtained vary proportionally between 1.2 and 2.3mg/L fall below Algerian standards (Table 02). Our results are close to the results found by Singla (2014), however our results are lower than the results obtained by Semerjian (2011).

Chloride (Cl^-)

According to Mvongo (2025); the extremely varied chloride contents of water are mainly related to the nature of the terrain crossed. Water almost always contains chlorides but in highly variable proportions; their content generally increases with the degree of mineralization of the water. Chloride concentrations varied between 22 and 35 mg/L and are well below Algerian standards (500 mg/L), indicating acceptable levels for water potability.

Nitrate (NO_3^-)

Nitrate levels were moderate at S1 and comparatively low at S2. The elevated values at S1 may indicate diffuse agricultural inputs or shallow groundwater influence. All concentrations remain below the WHO guideline limit (50 mg/L). NO_3^- concentrations in Ain Siporex (S2) ranging from 17 to 26 mg/L and in Ain Sègleb (S2) rang from 6 to 12 mg/L. S1 shows a more pronounced anthropogenic impact, probably due to the agricultural fertilizers and wastewater infiltration (Habchaoui *et al.,* 2025).

Nitrite (NO_2^-)

High nitrite levels correspond to the reduction of nitrate to nitrite by sulfite-reducing anaerobes. They can also be related to the bacterial oxidation of ammonia (Hamma *et al.,* 2025). According to Table 2; the results obtained are negligible and vary between 0.002 and 0.008mg/L. These values are lower than the Algerian standards (JORA, 2011) and which set 0.1mg/L as a maximum value.

Ammonium (NH_4^+)

Ammonium has no appreciable effect on consumer health, but its presence in water is a confirmed indicator of pollution according to (Boumerdassi *et al.,* 2023). Ammonium in water usually reflects an incomplete degradation process of organic matter. It comes from the reaction of minerals containing iron with nitrates. The results obtained do not show a significant difference between the two sites and vary between 0.03 and 0.15mg/l (Table 02) and are below the maximum limit of 0.5mg/l set by the Algerian standards.

Orthophosphate (PO_4^{-3})

Phosphate in drinking water systems prevents corrosion and keeps harmful substances out. However, high levels can foster microorganisms and algae, leading to eutrophication (Achour *et al.,* 2002). Phosphate concentrations varied from 0.01 and 0.05mg/l (Table 01) remained below the 0.5 mg/L permissible limit.

Biological Oxygen Demand (BOD_5)

Biochemical Oxygen Demand over five days (BOD_5) reflects the amount of dissolved oxygen required for the microbial degradation of biodegradable organic matter in water under controlled conditions (20 °C for 5 days). In the present study, BOD_5 values of 0.6 mg O_2 L^{-1} at Aïn Segleb and 2.4 mg O_2 L^{-1} at Aïn Siporex were recorded.

These low concentrations indicate a limited presence of biodegradable organic matter at both sampling sites. According to the guideline values established by the World Health Organization (WHO) and the Algerian standards (JORA), the measured BOD_5 levels correspond to waters of good quality.

Chemical Oxygen Demand (COD)

Chemical oxygen demand (COD) represents the amount of oxygen required to chemically oxidize organic matter present in water, including compounds that are not readily biodegradable by microorganisms. As such, COD is widely used as an indicator of overall organic pollution in aquatic environments (Babalola et *al.,* 2024).

The results obtained in this study reveal consistently elevated COD values across all seasons, ranging from 32 mg O_2/L at Aïn Segleb to 60 mg O_2/L at Aïn Siporex. When compared with drinking water quality standards, these concentrations indicate that the waters from the investigated springs fall within fair to poor quality classes, respectively. The observed organic load is likely associated with the influence of surrounding agricultural practices and urban wastewater discharges in the vicinity of both spring systems.

Table 2: Seasonal variations of Hydrochemical Parameters **(Mean ± SD)**

Spring	Parameter	T (°C)	pH	CE (µS/cm)	TDS (mg/L)	Turb (NTU)	Ca++ (mg/L)	Mg (mg/L)	NO3 (mg/L)	Cl- (mg/L)	BOD_5 (mg O_2/L)	COD (mg O2/L)	CAT (F°)	HT (°C)	K+ (mg/L)	Na+ (mg/L)	Cl2 (mg/L)	NH_4^+ (mg/L)	NO_2^- (mg/L)	PO_4^{3-} (mg/L)
Ain Segleb (S1)	**Spring**	15.03 ± 0.31	8.06 ± 0.04	475.00 ± 5.00	201.67 ± 3.51	1.60 ± 0.10	241.67 ± 3.51	55.43 ± 1.27	20.00 ± 1.00	35.00 ± 1.00	0.70 ± 0.10	31.00 ± 1.00	13.1 ± 2.14	420 ± 29.15	1.2 ± 0.25	26 ± 1.83	0.86 ± 0.11	0.15 ± 0.03	0.08 ± 0.02	0.05 ± 0.01
	Summer	19.67 ± 0.45	8.15 ± 0.03	500.00 ± 5.00	212.33 ± 2.52	1.30 ± 0.10	250.00 ± 2.00	58.00 ± 1.00	17.00 ± 1.00	37.00 ± 1.00	1.00 ± 0.10	35.00 ± 1.00	10.0 ± 2.06	380 ± 29.15	1.8 ± 0.25	30 ± 1.83	0.70 ± 0.11	0.12 ± 0.03	0.06 ± 0.02	0.04 ± 0.01
	Autumn	16.97 ± 0.42	7.99 ± 0.04	461.67 ± 7.64	190.00 ± 5.00	1.80 ± 0.10	235.00 ± 5.00	53.00 ± 1.00	23.00 ± 1.00	33.00 ± 1.00	0.80 ± 0.10	32.00 ± 1.00	9.5 ± 2.08	365 ± 29.15	1.7 ± 0.25	29 ± 1.83	0.65 ± 0.11	0.10 ± 0.03	0.05 ± 0.02	0.03 ± 0.01
	Winter	12.03 ± 0.25	8.18 ± 0.03	445.00 ± 5.00	180.00 ± 2.00	2.13 ± 0.15	227.67 ± 2.52	50.00 ± 1.00	26.00 ± 1.00	31.00 ± 1.00	0.50 ± 0.10	28.00 ± 1.00	8.0 ± 2.12	350 ± 29.15	1.5 ± 0.25	28 ± 1.83	0.60 ± 0.11	0.09 ± 0.03	0.04 ± 0.02	0.03 ± 0.01
Ain Siporex (S2)	**Spring**	14.80 ± 0.20	7.02 ± 0.03	385.00 ± 5.00	182.33 ± 2.52	0.50 ± 0.03	150.00 ± 2.00	40.27 ± 0.75	8.00 ± 1.00	22.00 ± 1.00	2.23 ± 0.15	58.33 ± 1.53	5.8 ± 2.02	310 ± 20.82	2.3 ± 0.21	33 ± 1.83	0.18 ± 0.08	0.03 ± 0.01	0.02 ± 0.01	0.01 ± 0.01
	Summer	18.70 ± 0.30	7.11 ± 0.04	410.00 ± 5.00	192.33 ± 2.52	0.40 ± 0.02	156.33 ± 1.53	42.00 ± 1.00	6.00 ± 1.00	24.00 ± 1.00	2.63 ± 0.15	63.33 ± 1.53	9.0 ± 2.05	360 ± 20.82	1.9 ± 0.21	31 ± 1.83	0.35 ± 0.08	0.06 ± 0.01	0.04 ± 0.01	0.02 ± 0.01
	Autumn	16.13 ± 0.31	6.98 ± 0.03	371.67 ± 7.64	174.33 ± 4.04	0.56 ± 0.03	145.00 ± 3.00	38.00 ± 1.00	10.00 ± 1.00	20.00 ± 1.00	2.30 ± 0.10	59.33 ± 1.53	8.5 ± 2.04	345 ± 20.82	2.0 ± 0.21	30 ± 1.83	0.30 ± 0.08	0.05 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
	Winter	11.47 ± 0.25	7.18 ± 0.03	355.00 ± 5.00	165.33 ± 2.52	0.68 ± 0.03	140.00 ± 2.00	36.00 ± 1.00	12.00 ± 1.00	18.00 ± 1.00	1.90 ± 0.10	55.00 ± 1.00	7.0 ± 2.00	330 ± 20.82	1.8 ± 0.21	29 ± 1.83	0.25 ± 0.08	0.04 ± 0.01	0.03 ± 0.01	0.01 ± 0.01

The physicochemical parameters measured at both stations showed low standard deviations (SD) in all seasons, indicating good analytical precision and temporal stability of groundwater quality. Most parameters showed low seasonal dispersion, reflecting a relatively homogeneous hydrochemical system.

Parameters such as pH, turbidity, ammonium, nitrites, and orthophosphates exhibited particularly low variability, suggesting minimal anthropogenic disturbance and stable natural conditions (Boadi *et al.,* 2023).

A marked seasonal variation was observed for temperature, conductivity, total dissolved solids (TDS), hardness (HT), calcium, and magnesium at both stations. These parameters showed higher values in spring and summer, followed by a gradual decrease in autumn and winter, which can be statistically associated with: evaporation during warm periods, reduced dilution, and increased water-rock interaction. Nutrients such as nitrates (NO_3^-) showed moderate seasonal variability, with higher concentrations in autumn and winter at station S1, suggesting possible surface leaching or agricultural influence. However, the values remained well below the limits recommended by the WHO.

Statistically, station S1 consistently showed higher average values for conductivity, TDS, hardness, calcium, magnesium, nitrates, and chlorides than station S2. This suggests more mineralized groundwater at S1, likely related to the local lithology and a longer residence time.

Conversely, station S2 exhibited higher BOD_5 and COD values, indicating a relatively higher organic load. Despite this, the organic pollution indicators remained within acceptable limits, and no critical deterioration was observed.

4.2. Evaluation of the organic pollution index (OPI)

The spatial and seasonal variations of the Organic Pollution Index (OPI) were analyzed across the two monitoring stations of Ain Sigleb (S1) and Ain Siporex (S2) in the El Tarf region (Table 3 and Figure 2). The OPI values recorded at these stations are 4.25, indicating an overall water quality that is good. These values fall into the class, corresponding to low organic pollution according to the reference classification. The values of this index are explained by the very low values of ammonium, nitrite and phosphate reflecting more favorable hydrodynamic conditions and less accumulation of organic matter (Karadeniz *et al.,* 2024).

The results obtained for station S1 in Aïn Segleb show low BOD_5 values (0.5–1.0 mg O_2/L) across all seasons, indicating a low load of biodegradable organic matter. The COD values, although moderate (28–35 mg O_2/L), remain compatible with water that is minimally impacted by significant organic discharges (Table 3 and Figure 2).

Table 3. Evaluation of the organic pollution index (OPI)

Season	IPO / S1 (Ain Segleb)	Class	IPO / S2 (Ain Siporex)	Class
Spring	~1.2	**Low pollution**	~2.3	**Moderate pollution**
Summer	~1.5	**Low pollution**	~2.6	**Moderate pollution**
Autumn	~1.3	**Low pollution**	~2.4	**Moderate pollution**
Winter	~1.1	**Very low pollution**	~2.1	**Low to moderate**

The measured concentrations of ammonium (NH_4^+), nitrites (NO_2^-), and orthophosphates (PO_4^{3-}) were consistently low and remained below levels commonly associated with marked organic contamination. This pattern reflects a satisfactory self-purification capacity of the aquatic environment and suggests the absence of direct domestic or agricultural inputs (Table 3; Figure 3).

The Organic Pollution Index (IPO) calculated for this station categorizes the water as non-polluted to slightly polluted. A modest increase in organic load was observed during the summer and autumn periods, which can be attributed to higher temperatures enhancing biological processes, combined with reduced flow conditions that promote the relative accumulation of organic matter.

Overall, the Aïn Segleb spring demonstrates good organic water quality, typical of spring systems subjected to limited anthropogenic influence.

In contrast, station S2 is characterized by noticeably higher BOD_5 values (1.9–2.63 mg O_2 L^{-1}), accompanied by elevated COD levels (55–63 mg O_2 L^{-1}). These results indicate a greater organic load and a higher contribution of oxidizable organic substances.

Although the concentrations of NH_4^+, NO_2^-, and PO_4^{3-} remain relatively low, they are consistently higher than those observed at S1, suggesting a diffuse anthropogenic influence, likely related to: nearby agricultural activities; nutrient-enriched surface runoff; or infiltration of diluted domestic wastewater (Hazzab *et al.,* 2011).

The IPO thus classifies the waters of station S2 in the moderately polluted category, with a maximum of organic pollution observed during the summer period, a period characterized by reduced flows and an intensification of biochemical processes (Table 3 and Figure 2).

This station therefore exhibits a degraded organic quality compared to S1, although it remains at levels that do not indicate severe pollution. The comparison between the two stations highlights: better organic quality at Aïn Segleb (S1), greater vulnerability of the Aïn Siporex source (S2) to organic inputs.

On a seasonal level, the IPO reveals a summer increase in organic pollution, common to both stations, and a winter improvement, linked to the dilution of pollutants by rainfall (Jatoi *et al.,* 2018).

The analysis of the Organic Pollution Index indicates that station S1 (Aïn Segleb) is characterized by water that is slightly polluted to unpolluted, reflecting a good ecological state; on the other hand, station S2 (Aïn Siporex) exhibits moderate organic pollution, requiring regular monitoring to prevent any future degradation.

These results confirm the relevance of the IPO as a rapid diagnostic tool for the organic quality of spring waters and highlight the importance of managing anthropogenic activities in the studied watersheds (Saibi *et al.,* 2013) and (Jurczynski *et al.,* 2024).

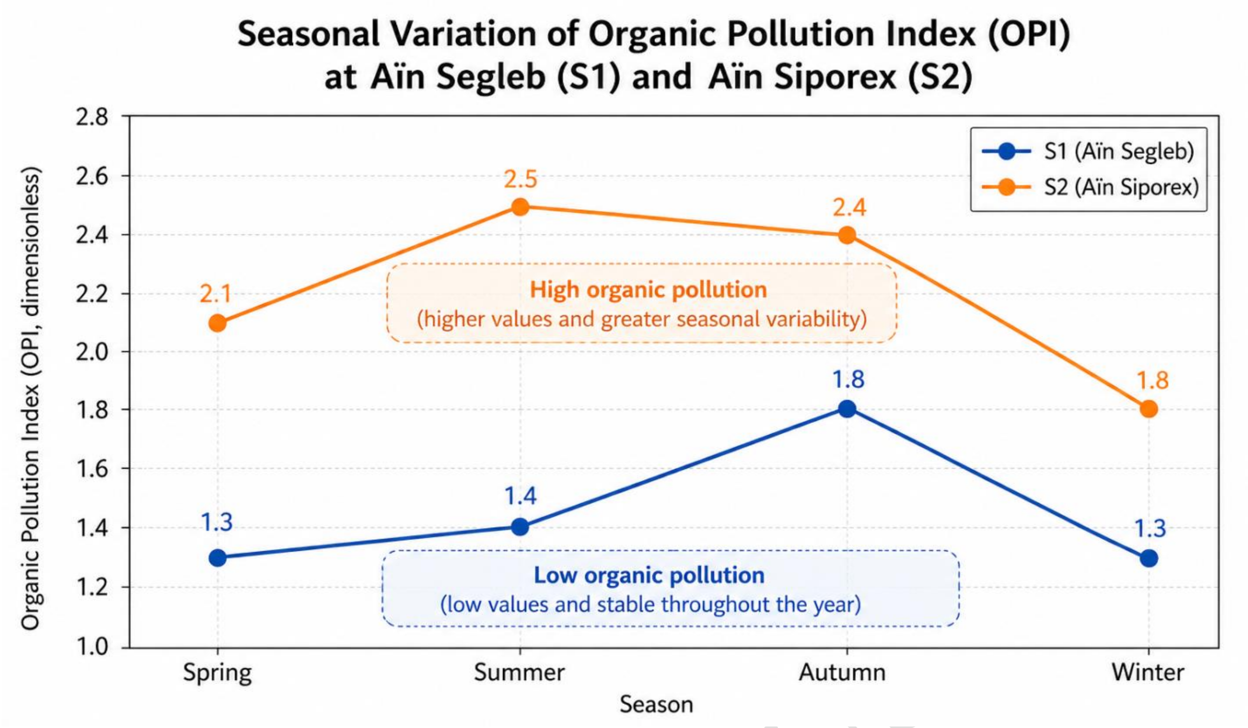


Figure 2. Seasonal variation of of the Organic Pollution Index (OPI) at Aïn Segleb (S1) and Aïn Siporex (S2). S1 showslow and stable organic pollution throughout the year, whereas S2 exhibits higher values and greater seasonal variability, particularly in summer an autumn.

The seasonal Organic Pollution Index (IPO) values indicate low organic pollution at both sites throughout the year. Site S1 shows slightly higher IPO values during spring, likely related to surface runoff and nutrient inputs, while Site S2 exhibits stable and lower IPO values, reflecting limited anthropogenic influence and good water quality (Laoufi *et al.,* 2025).

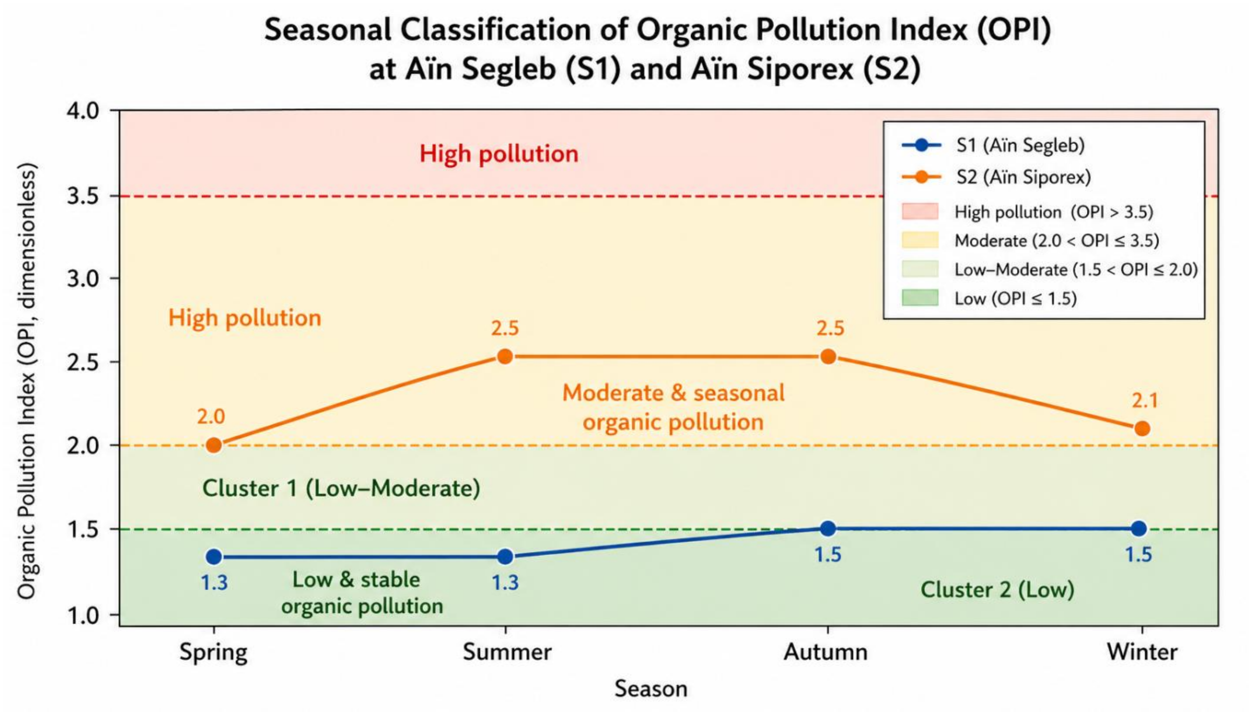


Figure 3. Seasonal classification of the organic pollution index (OPI) at Aïn Segleb (S1) and Aïn Siporex (S2). OPI values are grouped into four quality classes: High pollution (OPI>3.5), Moderate (2.0<OPI≤3.5), Low-Moderate (1.5<OPI≤2.0), and Low (OPI≤1.5). S1 shows low and stable organique pollution, whereas S2 exhibits moderate and seasonal organique pollution

Water Quality Index (WQI)

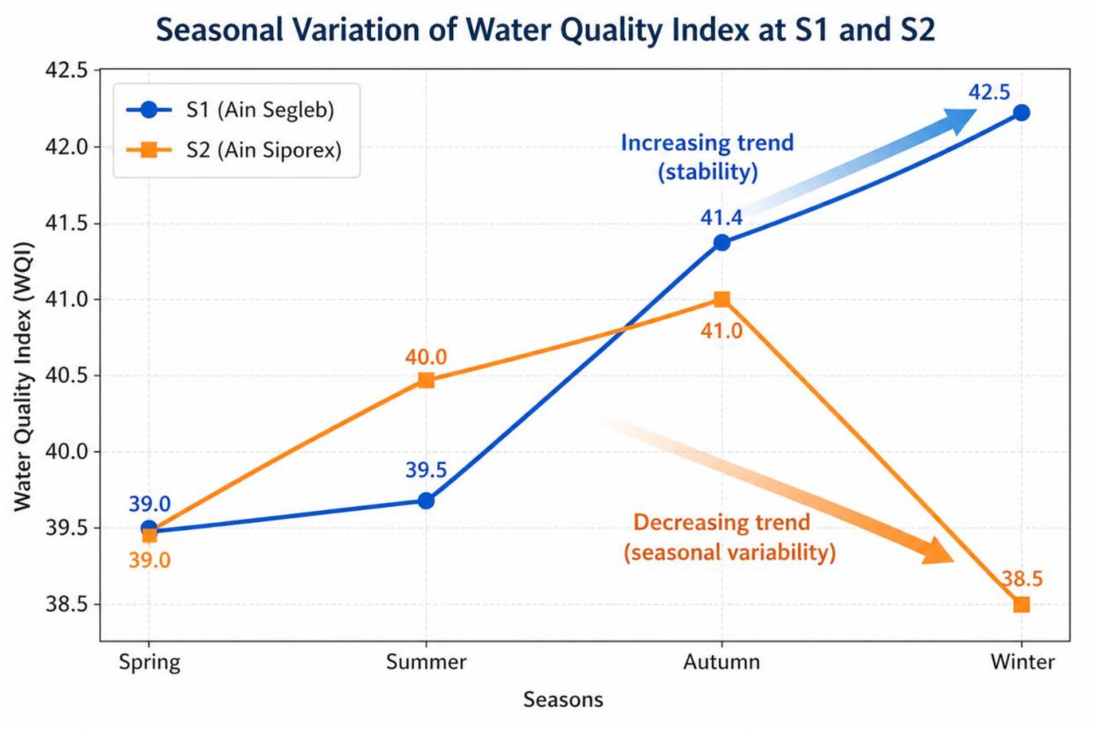


Figure 4. Seasonal Water Quality Index (WQI) at Aïn Segleb (S1) and Aïn Siporex (S2).

All WQI values for S1 and S2 indicate excellent water quality (Figure 4), with a slight degradation in autumn and winter for S1 and in summer for S2 (probably related to higher BOD_5). The figure 4 illustrates the seasonal variation of the Water Quality Index (WQI) at the two groundwater sampling stations, S1 (Ain Segleb) and S2 (Ain Siporex). Overall, WQI values at both stations remain below 50 throughout the year, indicating excellent water quality according to WHO-based classification.

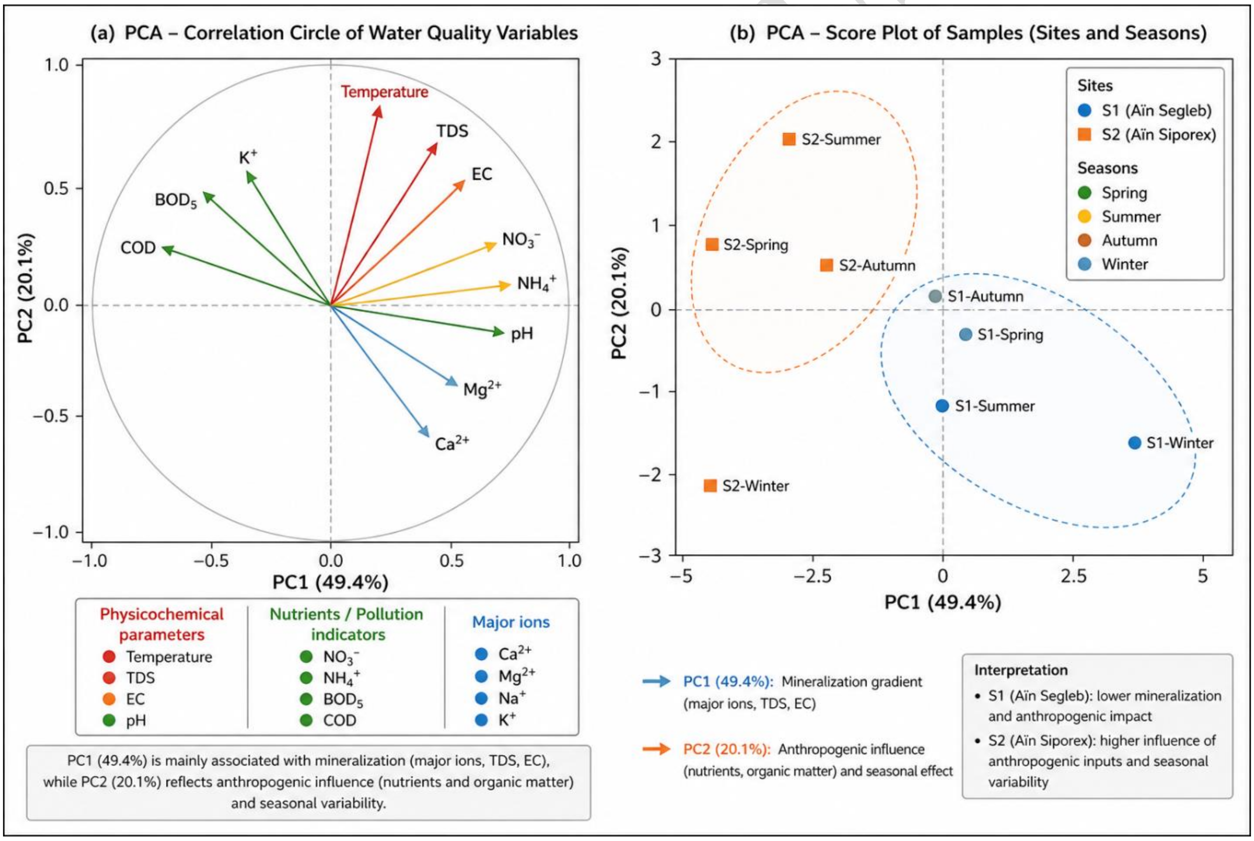
At station S1, the WQI shows a gradual increase from spring to winter, with the lowest value recorded in spring and the highest in winter (Salamani**,** *et al.,* 2024). This trend suggests a slight seasonal influence on groundwater quality, possibly related to increased mineral dissolution and reduced dilution during the colder and wetter seasons. However, the observed variations are minor and do not indicate any significant degradation of water quality (Bourquia *et al.,* 2024).

In contrast, station S2 exhibits a different seasonal pattern, with the highest WQI value observed during summer and lower values during spring and winter. The summer increase in WQI at this station may be attributed to higher biological activity and a moderate rise in organic matter, as reflected by parameters such as BOD_5. Despite this seasonal fluctuation, water quality remains within the excellent category throughout the year.

Comparatively, station S1 displays slightly higher WQI values than station S2 during autumn and winter, whereas station S2 records higher WQI values during summer. These differences highlight the influence of local hydrogeological conditions and seasonal processes on groundwater quality (Bourquia *et al.,* 2024).

Overall, the figure demonstrates that groundwater quality at both stations is stable and suitable for drinking purposes across all seasons, with only minor seasonal variations that do not compromise water safety.

4.3. Principal Component Analysis (PCA)



PC1 (49.4%) is mainly associated with mineralization (major ions, TDS, EC), while PC2 (20.1%) reflects anthropogenic influence (nutrients and organic matter) and seasonal variability.

→ PC1 (49.4%): Mineralization gradient (major ions, TDS, EC)

→ PC2 (20.1%): Anthropogenic influence (nutrients, organic matter) and seasonal effect

Interpretation

- S1 (Aïn Segleb): lower mineralization and anthropogenic impact
- S2 (Aïn Siporex): higher influence of anthropogenic inputs and seasonal variability

Figure 5. PCA biplot showing the projection of sampling sites (individuals) and physicochemical variables on the first two principal components (PC1 and PC2) Aïn Segleb (S1) and Aïn Siporex (S2).

Principal Component Analysis performed on all physicochemical, major ions, nutrients, and organic parameters shows that the first two components explain 92.0% of the total variance (Benyoussef, *et al.,* 2024). PC1; accounting for 75.6%, is strongly associated with EC, TDS, major cations, nitrate, BOD_5, and COD, representing a mineralization and anthropogenic pollution gradient. Samples from Site S1 plot on the positive side of PC1, indicating higher mineral and nutrient loads, whereas Site S2 samples cluster on the negative side, reflecting better water quality and lower anthropogenic influence. PC2 mainly reflects seasonal and thermal effects (Figure 5).

This study provides a comparative seasonal assessment of two spring systems using an integrated IPO–WQI–PCA approach. Beyond the methodological framework, its novelty lies in highlighting contrasting hydrochemical responses under similar climatic conditions but differing local pressures. This dual-site design offers new insights into spatial–temporal variability and improves understanding of natural versus anthropogenic controls on spring water quality.

4.4. Bacteriological analysis of source water

The results obtained are presented below (Figure 6). According to Algerian regulations (JORA, 2011), water intended for human consumption should not contain total and faecal coliforms in 100ml. Our results confirm the presence of total and faecal coliforms in Ain Segleb, on the other hand the water of the source of Ain Siporex confirms an absence of total and faecal coliforms (Total germs; Ain Segleb (S1)= 1473CFU/100ml and Ain Siporex (S2)= 80CFU/100ml). The results obtained are comparable to those reported by Singla and *al.,* (2014) in India. This contamination is due to free airborne germs that are in direct contact with unprotected sources. The high concentrations of total coliforms, faecal coliforms and faecal streptococci suggest the possible existence of the wastewater discharge upstream of these two points. According to Hébert and Légaré (2000), the content of pollutants regularly discharged into a watercourse decreases and is diluted in a larger volume of water following rainfall. Rainfall can act as a diluting agent for bacterial contamination (Nitin *et al.,* 2018).

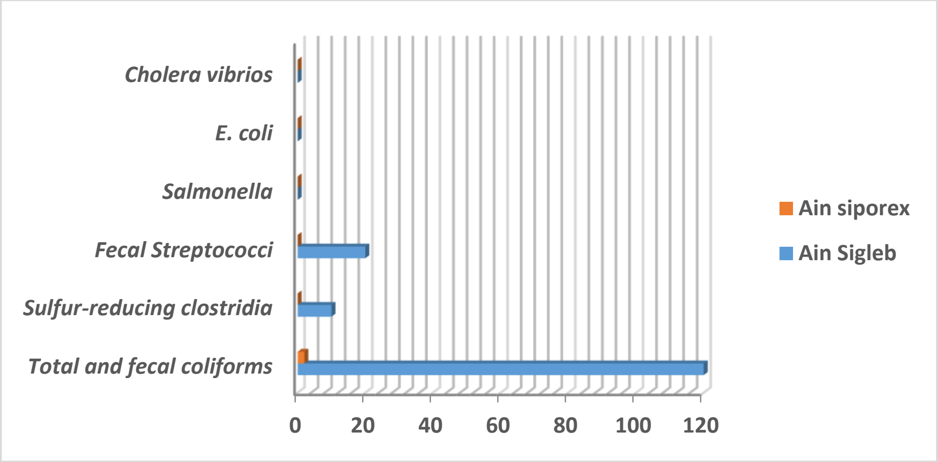


Figure 6. *Spatial variation of bacterial loads of water* in *Aïn Segleb (S1) and Aïn Siporex (S2).*

The key findings can be summarized as follows:

The EC and TDS values were consistently higher at S1 (EC: 445–500 µS/cm; TDS: 180–212 mg/L) compared to S2 (EC: 355–410 µS/cm; TDS: 165–192 mg/L), indicating stronger mineral enrichment at S1. Both sites were dominated by a Ca–Mg–HCO_3 hydrochemical facies, while S2 showed a seasonal shift toward a Na–HCO_3 facies, suggesting active ion-exchange processes.

Regarding organic pollution, IPO values ranged from 1.25 to 2.00, indicating generally low contamination levels. Slightly higher values were recorded at S1 during spring and summer. In parallel, the WQI classified water quality as "good" at both sites, with marginally better conditions at S2. However, the IPO appeared more sensitive to short-term fluctuations in organic pollution.

The multivariate analysis further clarified these patterns. PCA explained 92% of the total variance, with the first component (75.6%) strongly associated with mineralization and anthropogenic influence, as indicated by high loadings of EC, TDS, major ions, nitrate, BOD_5, and COD. The second component reflected seasonal variability and temperature effects. The spatial distribution along PCA axes highlighted higher mineral and nutrient loads at S1, while S2 exhibited greater hydrochemical stability.

Despite generally good physicochemical quality, coliform bacteria were detected in 100% of samples, revealing a significant sanitary risk for irrigation and livestock use.

These findings highlight the importance of regular seasonal monitoring to track variations in both mineral and organic pollution. They also suggest that microbiological and molecular analyses should be integrated in future studies to better identify contamination sources and assess health risks. In addition, long-term monitoring would allow better characterization of interannual variability and extreme climatic events, while hydrogeochemical modeling and machine learning approaches could improve prediction of water quality evolution. Expanding investigations to additional sites and aquifers, as well as considering land use impacts such as agriculture and urbanization, would further support regional vulnerability assessment and mitigation strategies.

In northeastern Algeria, previous studies on groundwater quality have generally focused on mineralization processes without considering seasonal variability or integrating multiple indices. For example, Bouderbala (2016) emphasized hydrochemical processes but did not include seasonal dynamics or combined approaches. In contrast, the present study provides a comparative seasonal assessment of two springs (Aïn Segleb and Aïn Siporex), revealing clear spatial and temporal heterogeneity. Aïn Segleb showed relatively stable and low organic pollution conditions, whereas Aïn Siporex exhibited higher seasonal variability and increased organic load, particularly during summer and autumn.

Similarly, Kherici-Bousnoubra and Kherici (2014) highlighted anthropogenic impacts and nitrate contamination using conventional methods, but their approach remained limited to univariate analyses. Here, the integration of IPO, WQI, and PCA provides a more comprehensive framework for identifying pollution sources and characterizing organic contamination. In Tunisia, studies such as Kammoun et al. (2018) and Jarraya-Horriche et al. (2017) applied WQI mainly for classification purposes, but without detailed interpretation of controlling processes. In comparison, PCA in this study, explaining 92% of the variance, clearly distinguishes geogenic, seasonal, and anthropogenic influences, improving interpretative depth.

Seasonal variability, often overlooked in regional studies such as Belkhiri et *al.,* (2011), is explicitly addressed here. Higher BOD_5 and COD values during warm seasons at S2 indicate increased anthropogenic pressure, whereas S1 remains more stable and less impacted.

Overall, the originality of this work lies in the comparative analysis of two contrasting spring systems, the integration of IPO, WQI, and PCA, and the explicit consideration of seasonal variability. This combined approach provides a more comprehensive and dynamic assessment of water quality in northeastern Algeria (Sivakumar et *et al.,* 2025).

Previous studies in North Africa and the Mediterranean (e.g., Bouderbala et *et al.,* 2016; Kherici-Bousnoubra and Kherici, 2014) have mainly relied on descriptive or single-method approaches, while Tunisian works (Kammoun et *et al.,* 2018; Jarraya-Horriche et *et al.,* 2017) focused primarily on WQI classification without multivariate interpretation. By contrast, the present study integrates multiple indices and PCA, allowing a more robust understanding of hydrochemical processes and pollution sources.

Furthermore, seasonal variability remains insufficiently addressed in many regional studies. Its inclusion here represents a significant improvement, particularly for semi-arid environments where temporal fluctuations strongly influence water quality. Overall, the combined IPO–WQI–PCA approach provides a more holistic and transferable framework for groundwater assessment in Mediterranean and semi-arid regions (El Azhari et *et al.,* 2022; Hammoumi et *et al.,* 2024; Lakhdari et *et al.,* 2025).

In conclusion, the integration of hydrochemical indices, multivariate statistics, and seasonal monitoring provides a robust framework for groundwater quality assessment in northeastern

Algeria, supporting more informed and sustainable water resource management. However, the study is limited to two spring sites and seasonal sampling, which may not capture interannual variability or extreme events. Uncertainties associated with IPO, WQI, and PCA calculations may introduce methodological bias, and microbial analyses were restricted to coliforms, suggesting the need for broader microbial and molecular investigations (Balasubramanian et *et al.,* 2025). Finally, the approach may require adaptation for hydrogeologically different or highly impacted environments, highlighting the importance of long-term monitoring (Ramasamy et *et al.,* 2025).

Overall, this study provides a novel contribution by integrating seasonal dynamics, dual water quality indices, and PCA-based source identification, offering a more comprehensive and dynamic understanding of spring water quality in Mediterranean environments.

5. Conclusion

This study provides a seasonal assessment of groundwater quality at two spring sites, Aïn Segleb (S1) and Aïn Siporex (S2), using an integrated approach combining physicochemical characterization, hydrochemical facies, pollution indices (IPO, WQI), and PCA. The results indicate generally low to moderate mineralization, with consistently higher EC and TDS at S1, suggesting a stronger influence of surface processes compared to S2.

Hydrochemical facies were dominated by Ca–Mg–HCO_3, while seasonal evolution toward Na–HCO_3 at S2 suggests ion-exchange processes and longer groundwater residence time. Although organic pollution remained low according to IPO, slight seasonal increases at S1 indicate localized anthropogenic influence. WQI results confirmed overall good chemical quality for both sites.

Multivariate analysis (PCA), explaining 92% of the total variance, clearly differentiated sites and seasons and highlighted mineralization processes and anthropogenic pressure as the main controlling factors. Despite generally acceptable physicochemical conditions, the persistent presence of coliform bacteria indicates ongoing microbiological contamination, representing the main water quality concern and limiting safe domestic use.

From a practical perspective, these findings highlight the need to prioritize microbiological monitoring alongside physicochemical assessments in spring water management programs. In particular, protection measures should focus on controlling local contamination sources near S1, where anthropogenic influence appears more pronounced. The combined use of IPO, WQI, and PCA proved to be a robust framework for interpreting water quality variability and can be applied in similar Mediterranean and semi-arid hydrogeological contexts.

Overall, while the groundwater shows generally favorable chemical quality, microbiological contamination remains a critical issue. This underscores the necessity of integrated monitoring strategies combining hydrochemical, microbiological, and land-use assessments to support sustainable groundwater management in northeastern Algeria. Future studies should focus on long-term monitoring and predictive modeling to better understand contamination dynamics and improve water resource protection strategies.

From a management perspective, the findings highlight the need for regular monitoring programs combining physicochemical and microbiological parameters. Particular attention should be given to site S1, where anthropogenic influence is more pronounced. The integration of WQI, IPO, and PCA provides a practical decision-support tool for water resource managers to identify vulnerable areas and prioritize protection measures in spring water systems.

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