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Impact of Physico-Chemical Parameters on the Spatial Distribution of Phytoplankton in Beni Haroun Dam (Mila, Northeastern Algeria)

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ABSTRACT

This study examined the spatial distribution of physicochemical parameters and phytoplankton diversity in the waters of the Beni Haroun Dam (Mila, Northeastern Algeria). Twenty sampling stations were analyzed for various parameters, including nutrients (PO_4, NH_4, NO_2, NO_3, SiO_4), salinity, as well as water quality indicators (electrical conductivity, TDS, pH, temperature, and turbidity). The results revealed significant spatial variability of the parameters. Nutrient concentrations and other parameters varied, with phosphate (PO_4) levels ranging from 0.01 to 0.72 mg/L and ammonium (NH_4) from 0.02 to 0.29 mg/L. Phytoplankton diversity was assessed at the genus level, revealing a rich community dominated by phyla such as Cyanobacteria, Dinoflagellata, and Chlorophyta. The most abundant genera were Oscillatoria, Anabaena, and Ceratium. Stations S20, S7, and S5 showed higher diversity, with higher concentrations of nutrients and sodium, while stations S16 and S17 exhibited lower diversity. The study highlights the impact of environmental factors, such as nutrient availability and temperature, on phytoplankton distribution, providing insights for water management and ecosystem monitoring.

INTRODUCTION

Water is an essential resource and a fundamental pillar of life and ecosystems. It plays a critical role biologically, economically, and socially, supporting vital processes, regulating ecological cycles, and sustaining various human activities. These include providing nourishment, serving as a medicinal resource, acting as an industrial raw material, supplying energy, supporting agriculture, and facilitating transportation **(Costanza *et al.*, 1997; Gleick, 1998; Gerin *et al.*, 2003)**. Despite its importance, human activities have led to the overexploitation, contamination, and pollution of this vital resource, making access to sufficient quantities of high-quality water increasingly difficult **(Postel *et al.*, 1996)**. Water scarcity, compounded by growing demand driven by population growth and the intensification of industrial, agricultural, and livestock activities, has led to the construction of reservoirs. These infrastructures are essential for meeting society's current and future needs **(Schmitz, 1995; Loucks *et al.*, 2017)**.

Dams and reservoirs are critical infrastructures for water, particularly for drinking, agricultural irrigation, and energy production. Artificial aquatic ecosystems create unique environments where interactions between physico-chemical, biological, and hydrological parameters differ significantly from those in natural ecosystems. These environments require careful management to maintain ecological balance while meeting human needs **(Poff *et al.*, 1997; Gleick, 1998; WCD, 2000)**.

Since the early 19th century, algae have been recognized as bio-monitors and bio-indicators of human disturbances **(Dokulil, 2003; Eastwood *et al.*, 2023)**. Phytoplankton, which includes planktonic algae, is a key primary producer in aquatic ecosystems and forms the foundation of the food chain **(Hötzel & Croome, 1999)**. Due to their short life cycles, these algae respond quickly to environmental changes, making them valuable water quality indicators essential for resource management and pollution control **(Paerl *et al.*, 2001; Wu *et al.*, 2014)**.

Phytoplankton is highly responsive to changes in environmental factors, including water's physico-chemical parameters, such as temperature, pH, salinity, and concentrations of nutrients like phosphates, nitrates, and silicates **(Hecky & Kilham, 1988; Reynolds, 2006)**. These parameters directly influence the composition, density, and distribution of phytoplankton communities. Increased nutrient concentrations, such as phosphates and nitrates, can stimulate the growth of certain phytoplankton species, leading to algal blooms **(Anderson *et al.*, 2002; Smith, 2003)**. In contrast, stressful conditions, such as extreme pH or high salinity, can reduce phytoplankton diversity by favoring tolerant species and excluding others **(Horne & Goldman, 1994; Smayda, 1997)**. Therefore, studying the interactions between physico-chemical parameters and phytoplankton communities is crucial for assessing water quality. Phytoplankton plays a key role in the primary productivity of aquatic ecosystems and serves as a sensitive biological indicator of environmental changes **(Wetzel, 2001; Reynolds, 2006)**.

The Beni Haroun Dam, located in the Mila region of northeastern Algeria, plays a pivotal role in both agriculture and drinking water supply. However, its functionality makes it susceptible to the potential impacts of nearby agricultural activities, especially the use of pesticides and fertilizers, which can lead to water pollution. This study aims to assess the ecological status of the dam by analyzing the spatial distribution of physicochemical water parameters, such as nutrients, conductivity, and pH, as well as examining the distribution and diversity of phytoplankton taxa. We aim to identify signs of pollution related to agricultural practices by comparing nutrient concentrations with changes in phytoplankton composition. By exploring the relationships between environmental conditions and phytoplankton, this study seeks to understand how these factors influence the aquatic ecosystem and to propose recommendations for sustainable water resource management focused on preserving water quality and biodiversity in the dam.

MATERIALS AND METHODS

1. Study area

Mila Province, located in northeastern Algeria, lies approximately 470 meters above sea level and is situated about 35 kilometers from the Mediterranean Sea. It forms part of the eastern region of the Tell Atlas. The region enjoys a Mediterranean climate, characterized by hot, dry summers and mild winters. The landscape is diverse, with high mountains to the north, valleys and hills in the central areas, and plains to the south. Agriculture is the primary economic activity, with significant cultivation of cereal and forage crops, as well as arboriculture in the mountainous zones. Livestock farming also plays an important role. Mila benefits from substantial water resources, including both surface and groundwater, supported by infrastructures such as the Beni Haroun Dam. Although forest cover is limited, it contributes to controlling soil erosion **(ANDI, 2002)**.

This study was conducted at the Beni Haroun Dam, the largest hydraulic structure in Algeria. It is part of a comprehensive program for surface water mobilization and transfer, developed by the Algerian government to address the country's significant hydrological imbalances **(Mebarki, 2005; Benayache, 2014)**. Located downstream from the confluence of the Rhumel and Endja Rivers (Fig. 1), in the northeastern part of Mila Province, the dam is about 40 kilometers north of Constantine and an equivalent distance from the mouth of the Oued Kébir River in Jijel Province. This gravity dam, constructed using Roller-Compacted Concrete (RCC), began filling in 2002 and has a storage capacity of up to 1,000 million cubic meters, with a useful volume of 732 hm^3 between elevations of 172 and 200 meters. The dam currently holds 435 million cubic meters of water, with an average depth of 24 meters, calculated based on the ratio between storage capacity and surface area **(Kerdoud, 2006)**. The Beni Haroun Dam plays a vital role in regulating the region's annual water supply and significantly contributes to water resource management in the area **(ANBT, 2000; Mebarki, 2009; Boulaiche & Arous, 2015; Teffaha & Kihal, 2016)**.

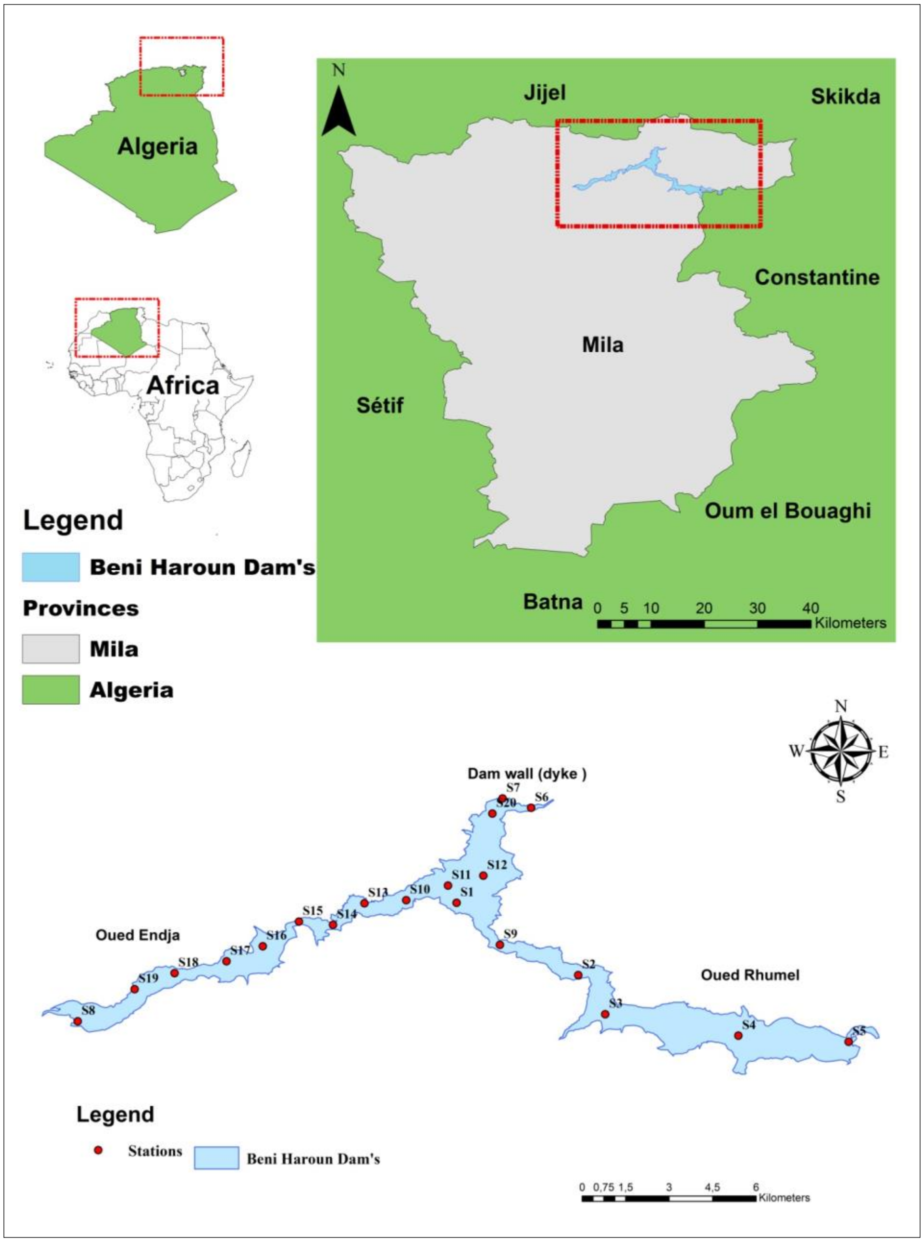

Fig. 1. Map of the study area and sampling site locations

2. Water, phytoplankton sampling, and analytical methods

Samples were collected from December 2023 to April 2024. Sampling stations were selected randomly to ensure coverage of the entire reservoir surface. Twenty stations were sampled using a boat. At each station, two samples were collected in parallel: one for physicochemical parameters and the other for phytoplankton identification (biological model).

In situ measurements of parameters such as Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH, Salinity (Sal), Temperature (Tem), and Turbidity (Tur) were performed using the multiparameter probe WTW 197i. Approximately 2 liters of dam water were collected for nutrient analysis. These samples were stored in polyethylene bottles, frozen immediately, and processed within two days of collection. Water samples intended for nutrient analysis were filtered through Whatman GF/C 0.5 µm glass filters.

Hydrological parameters, including Ammonium (NH_4), Phosphate (PO_4), Nitrite (NO_2), Nitrate (NO_3), Dissolved Inorganic Nitrogen (DIN: $NO_3 + NO_2 + NH_4$), Silicate (SiO_4), Sulfate (SO_4), Chloride (Cl), Sodium Chloride (NaCl), and Sodium (Na), were determined using standard colorimetric methods **(Rodier, 1984, 1996; AFNOR, 1994)**. All plastic bottles used for water sampling were thoroughly washed and rinsed first with distilled water, then with reservoir water at each station prior to use. Water samples were collected following standardized procedures **(Rodier, 1984, 1996; AFNOR, 1994)**.

Phytoplankton samples were collected at each station using a 5 µm plankton net. The filtrate (the liquid passing through the net) was recovered and preserved in opaque bottles with the addition of Lugol's iodine solution. This step was essential for preserving phytoplankton and enabling further analysis **(Verlecar & Desai, 2004)**. In the laboratory, optical microscopy was used for phytoplankton identification. The filtrate was refrigerated until microscopic observation **(Booth & Horner, 1997; Callieri & Stockner, 2002)**. The microscope remains a fundamental tool for identifying phytoplankton taxa, mainly based on morphological characteristics **(Tomas, 1997)**.

Taxonomic identification depends on careful examination of these characteristics, although challenges may arise if cells are damaged during handling. Some taxa are particularly difficult to identify using optical microscopy due to their small size or lack of distinct features **(El Hourany, 2019)**. Considering the objectives of this study, identification was limited to the genus level. An optical microscope equipped with a screen was used to facilitate identification, allowing for better visualization and detailed examination of morphological features. Identification was based on the keys provided by Bellinger & Sigee (2011) in *Freshwater Algae: Identification and Use as Bioindicators*, along with the global database AlgaeBase.

For spatial analysis, ArcGIS 10.8 was used to perform kriging mapping, a geostatistical method for estimating the spatial distribution of variables based on measurements from various locations **(Isaaks & Srivastava, 1989)**. Kriging relies on spatial correlation, where values closer in space tend to be more similar **(Cressie, 1990)**. It is widely used for assessing water and air quality indices. Studies have demonstrated that kriging techniques, such as ordinary kriging (OK), are effective for estimating and mapping water quality indices based on hydrochemical parameters **(Azawi & Saleh, 2021; Mohsin *et al.*, 2023)**.

As an interpolation method, kriging enables precise modeling of variable distributions by generating detailed environmental parameter maps **(Journel & Huijbregts, 1978)**. It accounts not only for measured values but also for spatial distances and variability between sampling points **(Wackernagel, 2003)**. Kriging is preferred for its ability to produce unbiased estimates with minimized error variance, making it more effective than methods like inverse distance weighting or moving averages, especially for groundwater quality assessment **(Al-Mashagbah *et al.*, 2012)**.

By addressing sparse data, kriging provides a comprehensive view of spatial distributions, making it a valuable tool in ecology, hydrology, and environmental sciences **(Chilès & Delfiner, 2012)**.

RESULTS

1. Physicochemical parameters of water samples

The results obtained for the water quality parameters of the Beni-Haroun Dam showed generally good water quality, although variations were observed between stations. These variations may be due to seasonal, local, or anthropogenic factors.

Table 1. Physicochemical parameters of water samples

Site	PO_4	NH_4	NO_2	NO_3	DIN	SiO_4	SO_4	Cl	NaCl	Na	EC	TDS	pH	Sal	Tem	Tur
S1	0,01	0,22	0,07	0,26	0,59	0,1	130	209	342	136	1415	755	8,34	0,7	25,4	6,03
S2	0,08	0,1	0,55	0,52	1,59	0,1	133	213	351	138	1396	744	7,79	0,7	25,3	10,5
S3	0,01	0,15	0,24	0,27	0,77	0,14	116	213	351	138	1543	818	8,16	0,7	25,2	6,84
S4	0,01	0,29	0,21	0,28	0,77	0,09	126	195	322	127	1698	906	8,22	0,8	25,1	4,81
S5	0,01	0,24	0,16	0,24	0,65	0,1	110	302	498	196	1702	904	8,12	0,8	25,3	4,96
S6	0,01	0,18	0,15	0,22	0,59	0,09	145	195	322	127	1489	794	7,99	0,7	25,4	6,42
S7	0,01	0,02	0,16	0,22	0,59	0,1	126	284	468	184	1570	838	8,26	0,8	25,4	3,9
S8	0,01	0,02	0,16	0,34	0,83	0,08	120	249	410	161	1536	816	8,17	0,8	25,4	3,38
S9	0,01	0,18	0,02	0,23	0,48	0,12	108	231	381	150	1934	944	8,13	0,9	25,4	7,66
S10	0,01	0,09	0,19	0,24	0,67	0,12	120	238	392	154	1852	841	8,11	0,9	25,4	8,76
S11	0,01	0,15	0,34	0,34	1,02	0,13	133	249	410	161	1990	926	8,1	0,8	25,3	8,38
S12	0,07	0,16	0,08	0,13	0,35	0,12	138	213	351	138	1559	834	7,63	0,8	25,1	3,6
S13	0,02	0,04	0,23	0,28	0,57	3,29	175	746	1229	483	964	1057	8,5	0,5	13,9	5,5
S14	0,22	0,06	0,38	0,38	0,9	2,98	280	657	1082	426	950	1047	8,08	0,5	14	7,42
S15	0,72	0,09	0,36	0,4	0,93	2,94	190	604	995	391	955	1032	8,22	0,5	15,5	6,95
S16	0,02	0,18	0,3	0,68	1,09	0,49	480	976	1609	633	987	1066	8,8	0,5	19,8	24,2
S17	0,03	0,21	1,26	0,87	2,83	0,19	57	1065	1755	690	1043	1128	9,14	0,5	24,2	101
S18	0,02	0,12	0,14	0,3	0,54	0,89	45	852	1404	552	928	1012	8,8	0,5	25	6,03
S19	0,03	0,23	0,31	0,39	1	7,79	170	220	363	143	1028	1114	8,6	0,5	22,1	13,4
S20	0,03	0,09	0,18	0,52	0,69	7,65	280	249	410	161	1255	1360	8,3	0,7	23,3	18,6
Min	**0,01**	**0,02**	**0,02**	**0,13**	**0,35**	**0,08**	**45**	**195**	**322**	**127**	**928**	**744**	**7,63**	**0,5**	**13,9**	**3,38**
Max	**0,72**	**0,29**	**1,26**	**0,87**	**2,83**	**7,79**	**480**	**1065**	**1755**	**690**	**1990**	**1360**	**9,14**	**0,9**	**25,4**	**101**
Mean	**0,09**	**0,14**	**0,31**	**0,37**	**0,94**	**1,61**	**169**	**428**	**706**	**278**	**1396**	**956**	**8,28**	**0,68**	**22,8**	**16,5**

Phosphate (PO_4) concentrations ranged from 0.01 to 0.72 mg/L, with an average of 0.09 mg/L (Table 1). These relatively low values suggest that there is no significant eutrophication pressure in the dam. Although elevated phosphate concentrations can trigger algal blooms, the current levels do not indicate an immediate risk of this phenomenon.

Ammonium (NH_4) concentrations ranged from 0.02 to 0.29 mg/L, with an average of 0.14 mg/L. As an indicator of organic pollution, ammonium levels were generally low, indicating limited contamination by organic matter. However, a localized peak of 0.29 mg/L may reflect slight pollution at specific stations.

Nitrite (NO_2) concentrations ranged from 0.02 to 1.26 mg/L, with an average of 0.31 mg/L (Tab. 01). Although nitrites are toxic at high concentrations, most values remained low, suggesting effective management of nitrogen pollution in the catchment area. Nevertheless, the 1.26 mg/L peak warrants closer observation.

Nitrate (NO_3) concentrations varied between 0.13 and 0.87 mg/L, with an average of 0.37 mg/L. These moderate values are typical of water bodies influenced by agricultural fertilizers. While nitrates can degrade water quality when present in excess, the levels observed remain within acceptable limits.

Dissolved Inorganic Nitrogen (DIN), calculated as the sum of NO_3, NO_2, and NH_4, ranged from 0.35 to 2.83 mg/L, with an average of 0.94 mg/L (Table 1). Higher DIN values in certain stations may reflect localized nitrogen enrichment, although the overall concentrations are still considered acceptable for dam waters.

Silicate (SiO_4) concentrations ranged from 0.08 to 7.79 mg/L, with an average of 1.61 mg/L. Silicate is essential for the development of certain algae, particularly diatoms. The data indicate no excessive silicate inputs, although natural seasonal variability likely influences distribution.

Sulfate (SO_4) concentrations ranged from 45 to 480 mg/L, with an average of 169 mg/L. While variations were observed, even the highest values were not alarming. However, elevated sulfate levels may suggest industrial or agricultural inputs, warranting periodic monitoring.

Chloride (Cl) concentrations ranged from 195 to 1065 mg/L, and NaCl from 322 to 1755 mg/L (Table 1). The maximum values suggest both natural and anthropogenic inputs. These levels remain within tolerable ranges and do not appear to significantly affect overall water salinity.

Sodium (Na) concentrations ranged from 127 to 690 mg/L, with an average of 278 mg/L. Elevated sodium may originate from agricultural or industrial sources. Although current levels are not critical, continued monitoring is advised due to local variability.

Electrical Conductivity (EC) ranged from 928 to 1990 µS/cm, averaging 1396 µS/cm. This reflects moderate salinity linked to dissolved ions. These values are acceptable but indicate some spatial differences in mineral content.

Total Dissolved Solids (TDS) ranged from 744 to 1360 mg/L, with an average of 956 mg/L. These results fall within a typical range, suggesting the water does not contain harmful levels of dissolved substances.

pH values ranged from 7.63 to 9.14, with an average of 8.28 (Table 1). This slightly alkaline condition is typical for reservoirs and supports aquatic ecosystem stability. No anomalies were detected.

Salinity (Sal) ranged from 0.5 to 0.9 PSU, averaging 0.68 PSU. These values confirm the freshwater nature of the reservoir, with minimal spatial variation and no observed impact on water quality.

Temperature varied from 13.9 to 25.5°C, with an average of 22.8°C. While relatively warm, these temperatures are below critical thresholds. Nevertheless, monitoring during hotter months is essential, as elevated temperatures can promote algal proliferation.

Turbidity (Tur) showed high variability, ranging from 3.38 to 101 NTU, with an average of 16.5 NTU (Table 1). Elevated turbidity in certain stations may be due to sedimentation, physical disturbances, or external inputs such as waste or agricultural runoff.

Overall, the results suggest generally good water quality, with moderate variations likely influenced by seasonal, natural, or anthropogenic factors. Nutrient concentrations (nitrates, ammonium, phosphates) reflect moderate levels of organic and mineral pollution. Conductivity, TDS, and salinity are within acceptable limits. However, high turbidity and nutrient enrichment in some areas highlight the need for continuous monitoring to prevent eutrophication and maintain ecological balance.

4. Spatial distribution of physicochemical parameters in the Beni Haroun Dam

Spatial distribution maps reveal heterogeneous patterns of water quality parameters across the Beni Haroun reservoir. Elevated phosphate levels along the western shore near Oued Endja point to a localized pollution source, possibly linked to agricultural runoff. Conversely, the eastern side (Oued Rhumel) shows the lowest phosphate levels, with intermediate concentrations in the reservoir's center.

Ammonium concentrations appear more randomly distributed. High values in the east (Oued Rhumel) suggest potential domestic or agricultural inputs, while lower concentrations occur in the west (Oued Endja) and near the dam (Fig. 2).

Nitrite and nitrate follow similar spatial trends. High concentrations on the western side (Oued Endja), intermediate levels near the dam, and lower values in the east (Oued Rhumel) reflect different pollution sources across the catchment.

DIN ($NO_2 + NO_3 + NH_4$) displays marked spatial heterogeneity. The highest levels are found near Oued Endja, indicating a substantial nutrient load from this tributary. In contrast, the dam and the upstream section of Oued Rhumel show lower concentrations, suggesting either nutrient dilution or fewer pollution sources in these zones. This disparity underscores the varying influences of the two tributaries on reservoir water quality.

Silicate concentrations mirror the DIN gradient, with elevated levels in the west and lower values in the east, potentially linked to geological features or sediment input. Central areas and regions near the dam show intermediate values, suggesting mixing of waters from both tributaries (Fig. 2).

Sulfate also follows a similar spatial trend, with higher concentrations generally located in the west. However, the distribution does not perfectly overlap with other parameters, indicating that additional hydrological or chemical factors may influence sulfate levels.

Chloride levels show the highest concentrations in the west (Oued Endja), with minimum values in the reservoir center and east (Oued Rhumel), suggesting dilution and fewer chloride sources in these areas.

Sodium chloride (NaCl) and sodium (Na) maps reflect comparable patterns: high concentrations in the west, moderate values near the dam, and low concentrations in the east and center of the eastern shore, reinforcing the influence of local inputs (Fig. 2).

Electrical Conductivity (EC) shows a distinct pattern, with peak values in the east (Oued Rhumel) and reservoir center, and lower values in the west (Oued Endja) and near the dam. This may suggest varying ion concentrations from different inflows (Fig. 3).

TDS distribution aligns with that of other parameters, with maximum levels in the west (Oued Endja), minimum levels in the east (Oued Rhumel), and intermediate values near the dam and central reservoir.

pH shows significant variation. The highest values are observed in the west (Oued Endja), the lowest at the center of the eastern shore, and intermediate values near the dam and in the east (Fig. 3). These differences likely reflect mineral inputs or localized discharges.

Salinity presents a heterogeneous gradient, with high values in the center, east, and west, and lower concentrations on the western shore. This may indicate localized salt inputs and varying hydrological processes.

Temperature varies across the reservoir, peaking in the center, southern section, and near the dam, with cooler values in the west and intermediate readings in the east (Fig. 3). These differences emphasize the influence of local environmental factors.

Turbidity is highest on the western side (Oued Endja), lowest on the eastern side (Oued Rhumel), and moderate in the central zone. This distribution likely results from sediment input and anthropogenic disturbances, such as agriculture and runoff.

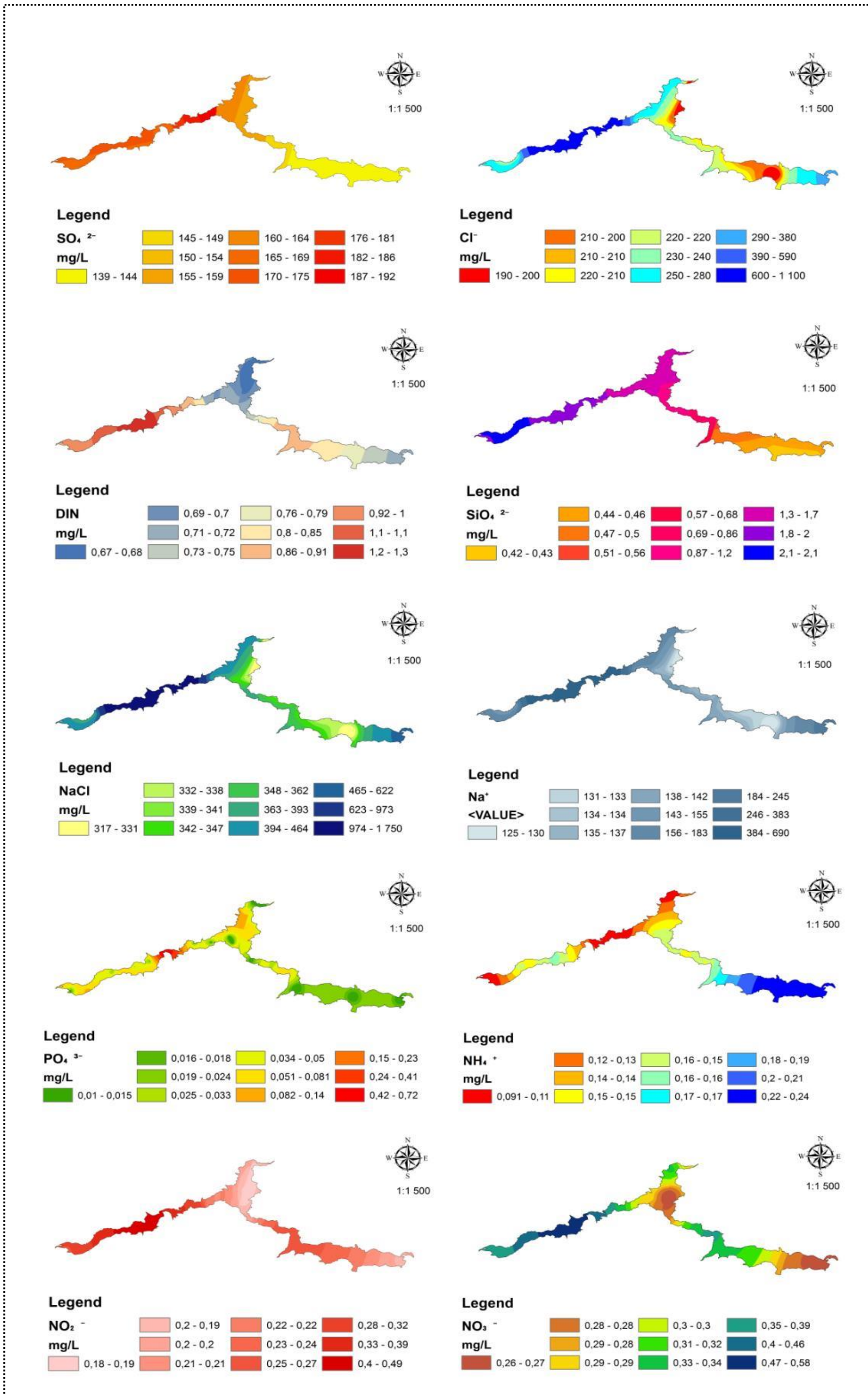

Fig. 2. Results from interpolations of chemical parameters in the Beni Haroun Dam

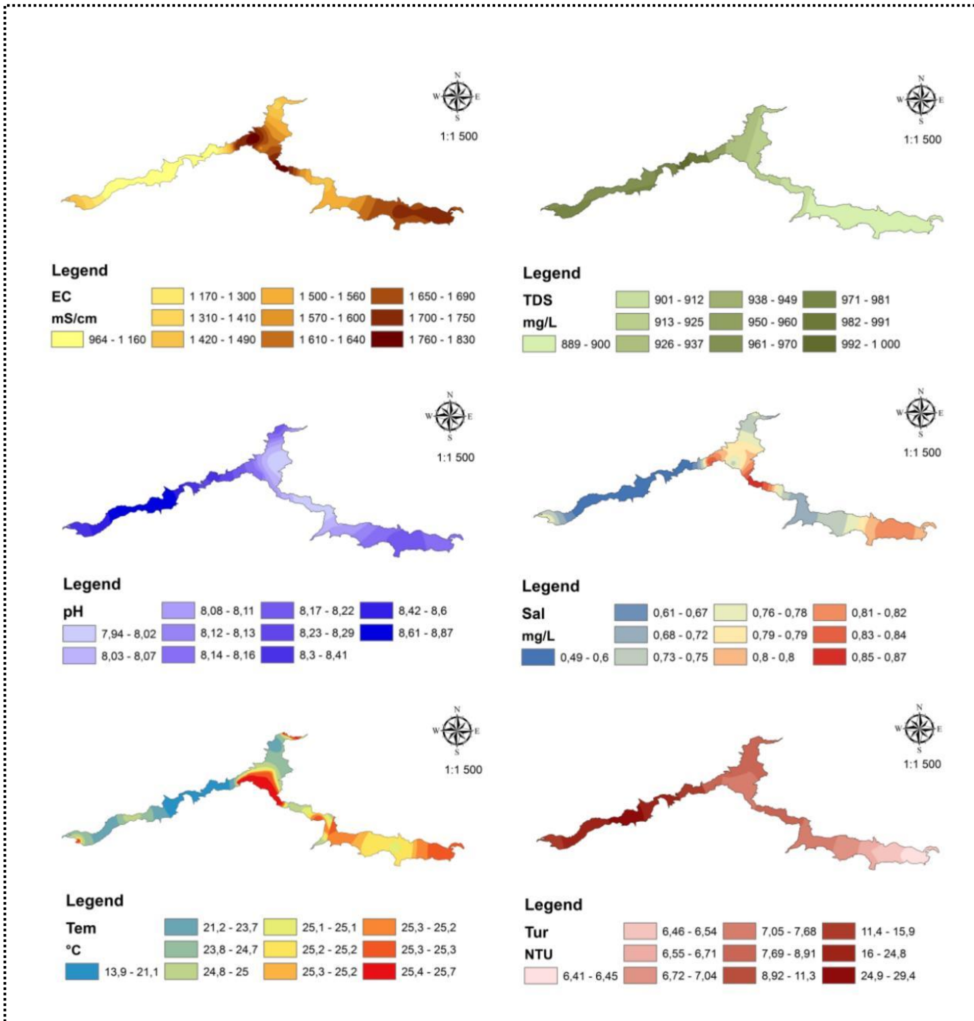

Fig. 3. Results from interpolations of physical parameters in the Beni Haroun Dam

3. Phytoplankton community

The qualitative study of the phytoplankton at Beni Haroun Dam allowed us to identify 43 taxa belonging to 32 families distributed across the following phyla: Cyanobacteria, Dinoflagellata, Heterokontophyta, Ciliophora, Chlorophyta, and Euglenophyta (Table 3).

Table 2. Taxonomic list of phytoplankton inventoried at Beni Haroun Dam

Phylum	Class	Order	Family	Genus
Cyanobacteria	Cyanophyceae	Oscillatoires	Oscillatoriacées	Oscillatoria
		Nostocales	Nostocacées	Nostoc
			Aphanizomenonacées	Anabaena
		Chroocoques	Microcystacées	Mérismopédie
				Microcystis
		Pseudanabaenales	Pseudanabaenaceae	Pseudanabaena
		Chroococcales	Chroococcaceae	Chroococcus
Dinoflagellata	Dinophyceae	Gonyaulacales	Cératiacées	Cératium
		Prorocentrales	Prorocentraceae	Prorocentrum
Heterocontophyta	Bacillariophyceae	Surirellales	Surirellacées	Cymatopleur
		Naviculales	Naviculacées	Gyrosigma
				Navicule
			Pleurosigmatacées	Pleurosigma
		Thalassiophysales	Catenulaceae	Amphora
		Bacillariales	Bacillariaceae	Bacillaria
				Nitzschia
				Sigmatella
		Cymbellales	Gomphonemataceae	Gomphonema
		Fragilariales	Fragilariaceae	Synedra
				Synedra
	Coscinodiscophyceae	Coscinodiscales	Coscinodiscacées	Coscinodiscus
		Mélosirales	Mélosiracées	Mélosira
	Mediophyceae	Stephanodiscales	Stéphanodiscacées	Cyclotelle
				Stephanodiscus
		Thalassiosirales	Thalassiosiraceae	Thalassiosira
Ciliophora	Oligohymenophorea	Sessilida	Vorticellidae	Vorticella
Chlorophyta	Trebouxiophyceae	Chlorellales	Chlorellacées	Actinastrum
			Oocystacées	Oocystis
	Ulvophyceae	Ulotrichales	Ulotrichaceae	Ulothrix
	Zygnematophyceae	Desmidiales	Clostériacées	Clostérium
				Clostérium
			Desmidiaceae	Staurastrum
		Spirogyrales	Spirogyraceae	Spirogyra

		Zygnematales	Zygnemataceae	Zygnema
	Chlorophyceae	Sphaeropleales	Characiacées	Characium
			Hydrodictyaceae	Pediastrum
				Pediastrum
				Pseudopediastrum
			Scenedesmaceae	Scenedesmus
				Cœlastre
		Chlamydomonas	Volvocacées	Eudorine
Euglenophyta	Euglenophyceae	Euglenales	Euglenaceae	Euglena
				Trachelomonas

The analysis of phytoplankton richness by phylum reveals a clear predominance of Heterokontophyta, which accounts for 37.21% (16 genera) of the total recorded genera. This is closely followed by Chlorophyta, representing 34.88% (15 genera). Cyanobacteria contribute 16.28% (7 genera), while Dinoflagellata and Euglenophyta each represent 4.65% (2 genera). Ciliophora, with only 2.33% (1 genus), is the least represented group (Table 3). This distribution highlights the dominance of diatoms and green algae in the Beni Haroun Dam ecosystem, with other phyla contributing to the community's overall biodiversity, albeit to a lesser extent.

An analysis of class-level richness further emphasizes this trend. Bacillariophyceae (diatoms) is the most diverse class, representing 25.58% (11 genera) of the recorded taxa. Cyanophyceae and Chlorophyceae follow, each comprising 16.28% (7 genera). Zygnematophyceae accounts for 11.63% (5 genera), and Mediophyceae makes up 6.98% (3 genera). Other classes—including Dinophyceae, Coscinodiscophyceae, Trebouxiophyceae, and Euglenophyceae—each contribute 4.65% (2 genera), while Oligohymenophorea and Ulvophyceae are the least represented, with 2.33% (1 genus) each. These results underscore the ecological importance of diatoms (Bacillariophyceae) and green algae (Chlorophyceae and Cyanophyceae), which dominate the phytoplankton community, while the presence of less abundant classes still enhances overall diversity (Table 3).

4. Spatial distribution of phytoplankton species richness

The spatial distribution of phytoplankton species richness across the 20 sampling stations reveals considerable variability. Station S20, located at the dam's embankment (dyke), exhibits the highest species richness, with 27 identified taxa, suggesting optimal conditions for phytoplankton growth and high ecological productivity. Stations S7 (also near the dam) and S5 (to the east near Oued Rhumel) follow, with 21 and 18 species, respectively, indicating similarly favorable conditions (Fig. 4).

In contrast, Stations S16 and S17, both located in the middle of the Oued Endja arm (west), recorded the lowest species richness, with only 6 taxa each. This low diversity may be attributed to ecological stress or less favorable environmental conditions. Other stations, such as S4, S9 (central-eastern region), and S10 (central-west), also show reduced diversity, with 9 species each, indicating areas with more uniform or constrained phytoplankton communities (Figure 04).

This spatial pattern suggests that phytoplankton diversity in the reservoir is influenced by local environmental factors. Stations with higher diversity—such as S20, S7, and S5—tend to be associated with elevated levels of nutrients, sodium, pH, and total dissolved solids (TDS). These conditions are generally conducive to phytoplankton development and support a more diverse community.

Conversely, stations with lower diversity—such as S16 and S17—are characterized by lower nutrient concentrations and higher electrical conductivity, suggesting less favorable growth conditions. Additionally, temperature appears to be an influencing factor, with warmer stations correlating with increased species richness, highlighting the role of thermal conditions in shaping community structure.

In summary, the spatial heterogeneity in phytoplankton richness across the Beni Haroun Dam reflects the combined influence of physico-chemical parameters, nutrient availability, and local hydrological conditions, emphasizing the need for continued monitoring to support biodiversity and maintain water quality.

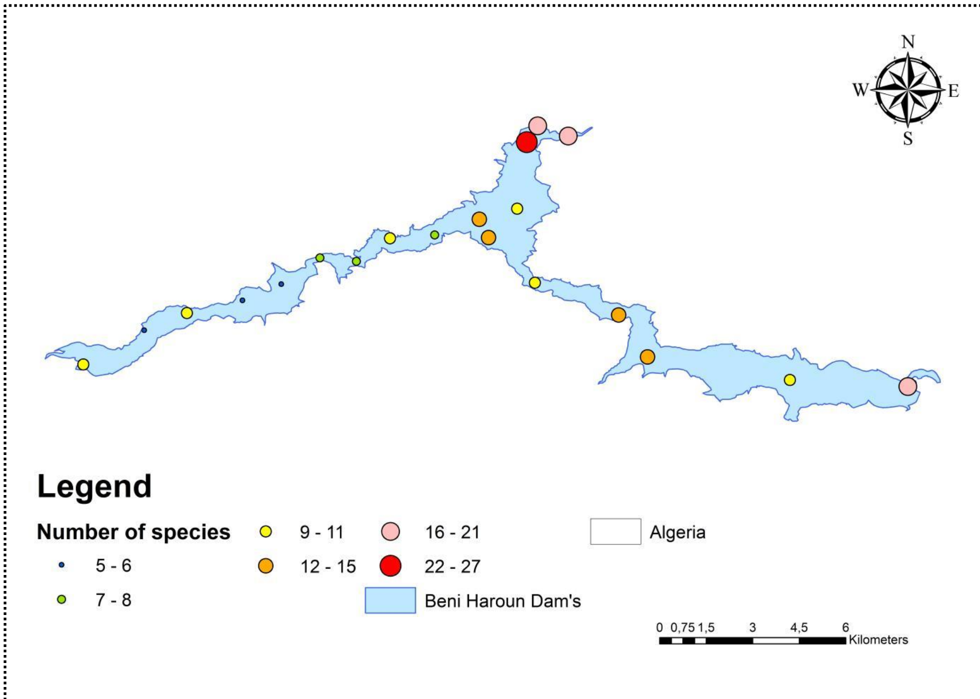

Fig. 4. The spatial distribution of species richness (number of species) in the Beni Haroun Dam

DISCUSSION

The spatial distribution of physicochemical parameters and phytoplankton in the Beni Haroun Dam provides critical insights into both water quality and the ecological health of its aquatic ecosystem **(Yilmaz, 2019; Cheraghpour-Ahmadmahmoodi, 2024; Kunpradid, 2024)**. The study reveals generally favorable water quality conditions, though with localized variations influenced by seasonal, natural, and anthropogenic factors. These variations are important considerations for long-term ecosystem sustainability and effective management of the dam.

In terms of physicochemical quality, phosphate (PO_4) concentrations ranged from 0.01 to 0.72 mg/L, with an average of 0.09 mg/L, indicating a low risk of eutrophication **(Abdelali *et al.*, 2018; Tadesse *et al.*, 2024)**. This is further supported by the relatively low ammonium (NH_4) concentrations (0.02–0.29 mg/L) and generally acceptable nitrite (NO_2) levels. However, peak values of 1.26 mg/L for NO_2 and 0.29 mg/L for NH_4 at specific stations warrant targeted monitoring for potential localized pollution sources **(Makhloogh *et al.*, 2017; Avilés & Niell, 2007; Bouchareb *et al.*, 2024)**.

Similarly, nitrate (NO_3) concentrations (0.13–0.87 mg/L) and dissolved inorganic nitrogen (DIN) (0.35–2.83 mg/L) reflect moderate inputs likely linked to agricultural runoff, but remain within acceptable thresholds for freshwater systems **(Yang *et al.*, 2024; Xu *et al.*, 2024)**. Silicate

(SiO_4) concentrations (0.08–7.79 mg/L) suggest suitable conditions for diatom growth, with no indication of over-enrichment **(Umiatun *et al.*, 2017; Amenorfenyo *et al.*, 2024; Bouchareb *et al.*, 2024)**.

Other parameters, such as sulfate (SO_4) and chloride (Cl), though variable, remain within safe levels. However, elevated sodium (Na) levels (127–690 mg/L) in certain areas suggest possible agricultural or industrial sources that could alter water chemistry. While electrical conductivity (EC) was relatively high at some stations, salinity levels remained within acceptable limits for freshwater ecosystems **(Bouderbala *et al.*, 2016; Karjalainen *et al.*, 2023)**.

A notable concern is the wide variability in turbidity, with values reaching as high as 101 NTU. Such high turbidity levels can significantly reduce light penetration, impairing photosynthesis and aquatic productivity **(Nunes *et al.*, 2022; Lin *et al.*, 2024)**. These peaks likely result from sedimentation or anthropogenic disturbances such as agriculture and waste discharge, emphasizing the need for focused monitoring of affected areas.

Regarding biological indicators, the phytoplankton community exhibited high diversity, with 43 taxa across 32 families. The community is dominated by Heterokontophyta (diatoms) and Chlorophyta (green algae), reflecting the nutrient and silicate availability within the reservoir. The high representation of Bacillariophyceae, in particular, highlights the key role of silicate in sustaining primary production **(Znachor *et al.*, 2013; Shanthi *et al.*, 2014; Zhigila *et al.*, 2022; Lv *et al.*, 2024)**.

Species such as *Navicula* sp., *Coelastrum* sp., and *Merismopedia* sp. were found in 65% and 55% of the stations, respectively, suggesting high adaptability to the dam's environmental conditions. Conversely, less frequent taxa like *Euglena* sp., *Pseudanabaena* sp., and *Vorticella* sp. (present in only 15% of stations) likely indicate narrower ecological tolerances or specific habitat preferences **(Nguetsop *et al.*, 2008; Czerwik-Marcinkowska *et al.*, 2011; Gökçe, 2016)**.

Of particular interest is the consistent presence of *Anabaena sp.* and *Ceratium sp.*, both associated with harmful algal blooms (HABs) **(Grogan *et al.*, 2023)**. While no current signs of eutrophication were detected, these taxa may serve as early indicators of potential nutrient imbalances or future water quality shifts. The widespread occurrence of *Navicula sp.* in 65% of stations suggests its potential as a bioindicator due to its resilience to environmental fluctuations **(Messyasz & Treska, 2019; Blanco, 2024)**.

By integrating the data on physicochemical parameters and phytoplankton diversity, this study provides a holistic view of the ecological status of the Beni Haroun Dam **(Zang *et al.*, 2024)**. Low concentrations of phosphates, nitrates, and ammonium support the conclusion that eutrophication is not currently a threat, a finding consistent with the observed community structure of phytoplankton. However, local peaks in ammonium, nitrite, and turbidity suggest the presence of spatially confined pressures likely stemming from agricultural runoff or domestic waste inputs.

These disturbances could influence community dynamics, favoring more tolerant phytoplankton species and potentially altering the ecological balance over time. Given the sensitivity of phytoplankton to environmental change, they are effective indicators of shifts in ecosystem health.

It is therefore strongly recommended that long-term monitoring be conducted for both physicochemical variables and phytoplankton composition. Particular attention should be paid to stations with high turbidity and nutrient enrichment, as these could serve as early warning signs of ecological degradation **(Essa *et al.*, 2024; Tekebayeva *et al.*, 2024)**.

Future research should also focus on:

- Seasonal variability in water quality and community composition.
- Microbial interactions and their role in ecosystem dynamics.
- The influence of land-use practices on localized water quality.

Such efforts will contribute to more informed management strategies, ensuring the preservation of water quality and biodiversity in the Beni Haroun Dam for the long term.

CONCLUSION

This study underscores the critical importance of monitoring both physico-chemical parameters and phytoplankton diversity to evaluate the ecological health of the Beni Haroun Dam. Although overall water quality remains favorable, localized anomalies—particularly in ammonium, nitrite, turbidity, and sodium concentrations—highlight the influence of seasonal, natural, and anthropogenic factors. The phytoplankton community, largely dominated by diatoms and green algae, reflects a generally healthy aquatic ecosystem. However, the presence of species associated with harmful algal blooms (HABs) raises concerns about potential shifts in water quality under changing environmental conditions.

These findings emphasize the need for continuous and targeted monitoring, particularly in zones exhibiting elevated turbidity and nutrient concentrations. Such proactive monitoring can serve as an early warning system for ecological disturbances, enabling timely and effective management interventions. To support the long-term sustainability of the dam's ecosystem, further research should investigate seasonal dynamics, land-use patterns, and the cumulative impact of local human activities. This will enhance the foundation for evidence-based water management and contribute to the preservation of water quality and biodiversity in the region.

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