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Physicochemical quality and metal pollution of Tabalak pond water (Ramsar site, Niger): Spatio-temporal dynamics and impacts on aquatic organisms

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ABSTRACT
Objective: The present study aimed to evaluate the spatio-temporal assessment disturbances in water quality due to anthropogenic activities around Tabalak pond, based on physicochemical characteristics and metal pollution.
Methodology and Results: The physico-chemical variables such as temperature (T°), electrical conductivity (EC), total dissolved solids (TDS), pH and dissolved oxygen (DO) were measured in situ, while total suspended solids (TSS), Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, NO_2^-, NH_4^+, P, and trace metal elements (Pb, Zn, Cu, Fe and Cd) were determined in laboratory. it appears form the results that there was no significant difference in water quality among sampling stations. However, a significant seasonal variation influenced temperature, pH, dissolved oxygen, Ca^{2+}, Mg^{2+}, Na^+, K^+ and total nitrogen ($P < 0.05$) was revealed. High mineralization was detected in hot season. Concentrations of nutrients: NO_3^- (1.2–1.6 mg·L^{-1}), NO_2^- (1.4–1.6 mg·L^{-1}), NH_4^+ (1.3–1.6 mg·L^{-1}) and P (16–19.9 mg·L^{-1}), exceeded guideline values to protect aquatic life. High values were also recorded for Pb (25.98–43.80 µg·L^{-1}), Zn (8.13–10.76 µg·L^{-1}), Cu (3.4 µg·L^{-1} at Fallé), and Fe (541.25 µg·L^{-1} at Sillalé). If this trend is maintained, local biodiversity may be severely threatened.
Conclusion and applications of results: The results of this study showed the necessity to implement an integrated management approach to preserve the ecosystem services provided by this water body to local populations. An integrated management strategy combining regular physico-chemical monitoring, reducing of pollutant inputs, establishment of vegetated buffer zones, and control of anthropogenic pressures is essential.
Keywords: Tabalak pond; Ramsar site; physicochemical parameters; metal pollution; aquatic organisms

INTRODUCTION

Wetlands are characterized by high biological diversity and provide essential ecological and socio-economic functions, particularly in regulating hydrological regimes and supplying scientific and recreational resources (Perennou *et al.,* 2012). In Niger, wetlands include floodplains, ponds, dallols, depressions, and oasis systems of the Aïr Mountains. Fourteen of these wetlands are designated as Ramsar sites, covering more than seven million hectares, largely composed of surface waters (CNEDD, 2011; Ramsar, 2025). Since the severe droughts of the 1970s, Niger's natural resources have undergone continuous degradation due to deforestation, fishing activities, inappropriate agricultural practices, and increasing climatic variability. These pressures have profoundly altered the hydrological functioning of wetlands (CNEDD, 2011; Adamou *et al.,* 2015). Wetlands receive domestic and industrial effluents, as well as runoff enriched with fertilizers and other contaminants. These inputs increase organic matter and nutrient loads (nitrogen and phosphorus), deteriorate physicochemical and microbiological water quality, reduce dissolved oxygen concentrations, and promote eutrophication processes (Bassirou *et al.,* 2009; Amadou *et al.,* 2012). Furthermore, several studies have reported contamination of lakes and ponds by trace metals and pesticides, raising concerns about ecological integrity and human uses of these aquatic systems (Adamou *et al.,* 2015; Youchaou Tawaye *et al.,* 2021; Hassane *et al.,* 2022). Tabalak pond represents a typical example of a threatened Ramsar wetland. Despite its ecological and socio-economic importance, research conducted on this site remains limited. Some studies have focused on climate risks and sustainable management strategies without providing detailed analytical data (UNDP & IISD, 2013), while others have addressed fisheries management through socio-economic surveys and field observations without direct ecological measurements (Mahamadou, 2015). Previous water quality assessments were restricted to the water column, lacked seasonal resolution, and did not include sediment analyses (Adamou *et al.,* 2015). This scientific data gap highlights the need for a more integrated and comprehensive assessment. Therefore, the present study aims to evaluate anthropogenic impacts on Tabalak pond water quality through a spatio-temporal analysis of physicochemical parameters and metal pollution.

MATERIAL AND METHODS

Description of the Study Area: Tabalak pond is located approximately 50 km from Tahoua, Niger. It consists of three interconnected basins Sillalé, Fallé, and Kéhéhé, extending over 12 to 15 km from west to east. The pond exhibits strong seasonal variability, with a surface area ranging from 50 to 1,000 ha. Its maximum depth is about 2 m, and its storage capacity exceeds 30 million m³. Fishing is one of the main economic activities around the pond and represents a major source of income for local communities. Fish production was estimated at 307.6 tonnes in 2008, while cumulative catches between 2006 and 2015 reached approximately 1,742.297 tonnes. The dominant fish species are *Lates niloticus (Nile perch), Clarias gariepinus (Catfish), Bagrus bayad (Bayad catfish), and Oreochromis niloticus (Nile tilapia)* (Mahamadou, 2015). The study area is characterized by a Sahelian-Saharan climate with two distinct seasons: a long dry season lasting about eight months (October-May), subdivided into a cool period (November-February) and a hot period (March-May), and a short rainy season (June-September). Rainfall is highly irregular and ranges annually between 200 and 500 mm. Air temperatures vary from 8–10 °C during the cool dry season to above 40 °C during the hot dry season (UNDP and IISD, 2013; FDR, 2018).

Data Collection: Water samples were collected three seasons (cool season, hot season, and rainy season) from three stations (Kéhéhé, Fallé, and Sillalé). In each season, data were sampled two times, resulting in a total of six (6) sampling campaigns of 18 samples. This sampling strategy was designed to capture both hydrological and climatic seasonal variability (Soro *et al.,* 2021). The approach allowed the assessment of seasonal effects, spatial variability, and their interaction on the measured parameters.

Sampling Strategy: Water and sediment samples were collected at both littoral zones and pelagic points (Figure 1). At each station, three (3) individual samples were collected at identical locations for all matrices and subsequently pooled to form composite samples. Water samples were collected with sampling bottles within the first 25 cm of the water column, while sediment samples (approximately 500 g) were taken at 5 cm from the pond bottom. Collected water samples were then stored in 500 mL polyethylene bottles and transported under refrigerated conditions in an ice-filled cooler to the laboratory. Sediment samples were placed in plastic bags, transported to the laboratory, and air-dried at ambient laboratory temperature prior analysis.

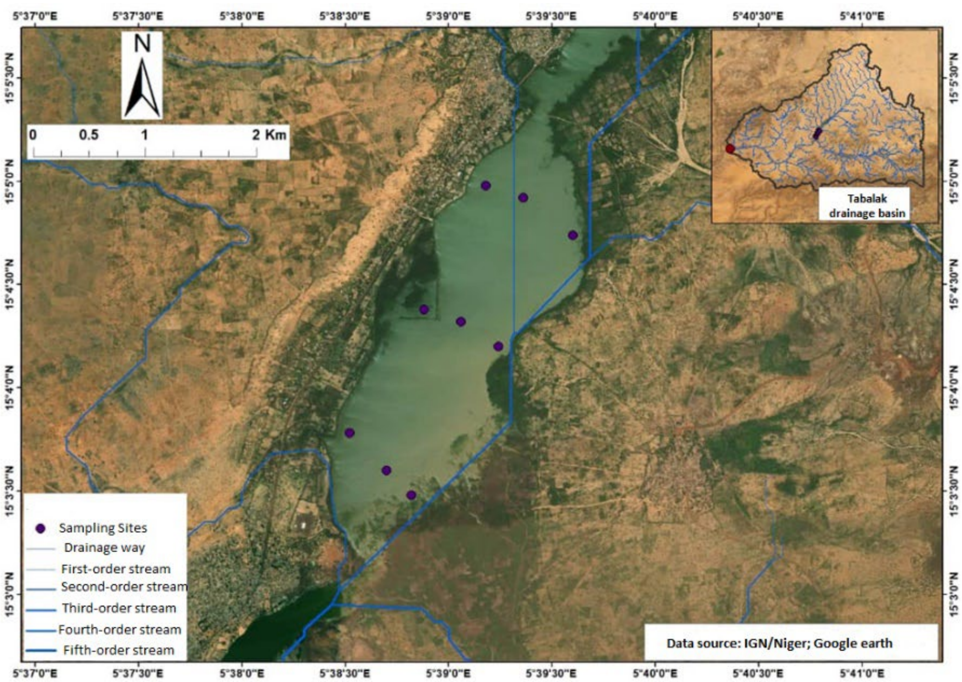

Figure 1. Location of the sampling sites

Determination of Physicochemical Parameters of Water : The water physicochemical characteristics such as temperature (T°), electrical conductivity (EC), and total dissolved solids (TDS) were recorded using a Hanna HI-9812-5 multiparameter, while Dissolved oxygen (DO) was measured using a YSI ODO 200 dissolved oxygen meter in situ. Laboratory analysis was focused on total suspended solids (TSS), chlorides (Cl^-), sulphates (SO_4^{2-}), bicarbonates (HCO_3^-), carbonates (CO_3^{2-}), nitrates (NO_3^-), nitrites (NO_2^-), ammonium (NH_4^+), phosphorus (P), as well as trace metals elements: lead (Pb), zinc (Zn), copper (Cu), iron (Fe), and cadmium (Cd), following standardized procedures Rodier (2009). For this purpose, Total suspended solids (TSS) were determined by filtration through pre-weighed Whatman filter paper, followed by drying of the residues in an oven at 105 °C for 1 hour, cooling for 30 minutes, and repeating the process until a constant weight was obtained while Carbonates and bicarbonates levels were quantified by titrimetric methods using phenolphthalein and methyl orange indicators, respectively. On another hand, Nitrates, nitrites, ammonium, and sulphates concentrations were measured by spectrophotometric (Spectro colorimetric) methods while chlorides were determined using the Mohr titration method.

Determination of Trace Metal Elements in Sediments : The trace metal elements (TMEs) such as Pb, Zn, Cu, Fe, and Cd were quantified by flame atomic absorption spectrophotometry (FAAS) after filtration of water samples. (Rodier, 2009). The determination of trace metal elements both in water and sediment matrices was conducted during a single sampling campaign.

Data Processing and Statistical Analysis : Water physicochemical parameters were tested for normality (Shapiro-Wilk) and homogeneity of variances (Bartlett) prior to statistical analysis. Seasonal and spatial effects were assessed using one-way ANOVA or the Kruskal-Wallis test when assumptions were not met, followed by appropriate post hoc tests (Tukey HSD or pairwise Wilcoxon). Principal component analysis (PCA) was used to explore relationships among variables and patterns related to season and station. Analyses were performed in R (v4.2.1), while descriptive statistics were calculated in Microsoft Excel 2021. Mean concentrations were compared with international guideline values for aquatic life protection (Table 1 and 2).

Table 1: Internationally accepted guideline values for protection of aquatic organisms (water)

Parameters	International standards (CCME, USEPA, WHO, OECD)	WFD (EU) standards	References
pH	6.5 – 9.0 (general, tolerance range)	6 – 9 (Bathing water Directive guidance and ecological guidance)	CCME (1999), USEPA (2009), WFE
Temperature	< 30 °C to prevent thermal stress	No fixed threshold; ΔT ≤ 1.5 °C between discharge and receiving water body	CCME (1999), WFD Annex V
Disolved Oxygen (DO)	> 5 mg·L⁻¹ (good ecological status)	≥ 5 mg·L⁻¹ (rivers), ≥ 4 mg/L (lakes)	USEPA (1986), WHO (2017), WFD
Electrical Conductivity (EC)	< 300 µS/cm desirable ; > 500 µS/cm indicated stress	No direct standard (used as an indicator of eutrophication/salinity)	MERI (2007), WFD
Chlorides (Cl^-)	≤ 120 mg·L⁻¹ (chronic), ≤ 640 mg·L⁻¹ (acute exposure)	No specific EQS (monitored in sensitive areas)	CCME (2011), WFD
Nitrates (NO_3^-)	≤ 2 mg·L⁻¹ (eutrophication prevention), ≤ 10 mg·L⁻¹ (toxicity threshold)	≤ 50 mg·L⁻¹ (Nitrates directive 91/676/EEC)	WHO (2017), CCME (2007), WFD
Nitrites (NO_2^-)	≤ 0.06 mg·L⁻¹ (chronic exposure)	≤ 0.1 mg·L⁻¹ (guideline value)	CCME (2007), WFD
Ammonia (NH_4^+ / NH_3)	≤ 0.05 mg·L⁻¹ (un-ionized NH_3)	≤ 0.2 mg·L⁻¹ (freshwaters supporting salmonid species)	USEPA (2013), WFD annex V
Phosphates (PO_4^{3-})	≤ 0.1 mg·L⁻¹ (eutrophication prevention)	No single threshold; water body-specific (good status generally ≤ 0.05–0.2 mg·L⁻¹)	OECD (1982), WFD annex V
Total nitrogen	0.5 – 1.8 mg·L⁻¹		USEPA (2022)
Total phosphorus		> 0.05 mg·L⁻¹et ≤ 0.2 mg·L⁻¹ (good ecological status range)	
Cadmium (Cd)	≤ 0.001 mg·L⁻¹ (freshwater)	Annual EQS : 0.08–0.25 mg·L⁻¹hardness-dependent)	CCME (2007), Directive 2013/39/EU
Lead (Pb)	≤ 0.007 mg·L⁻¹	Annual EQS :1.2 µg·L⁻¹	WHO (2017), Directive 2013/39/EU

Copper (Cu)	≤ 0.002 mg·L⁻¹	Annual EQS: 1–10 µg·L⁻¹ (bioavailability-adjusted)	CCME (2007), Directive 2013/39/EU
Zinc (Zn)	≤ 0.03 mg·L⁻¹	Annual EQS: 7.8 µg·L⁻¹ (Hardness-adjusted	CCME (2007), Directive 2013/39/EU
Iron (Fe)	≤ 0.3 mg·L⁻¹ (WHO drinking water guideline ecological indicator)	No specific EQS	WHO (2017)

Table 2: Internationally accepted guideline values for protection of aquatic organisms (sediment)

Metal	**Threshold (Lowest Effect Level, LEL)**	**Threshold (Severe Effect Level, SEL)**
Cadmium (Cd)	0.6 mg/kg	10 mg/kg
Copper (Cu)	16 mg/kg	110 mg/kg
Lead (Pb)	31 mg/kg	250 mg/kg
Zinc (Zn)	120 mg/kg	820 mg/kg
Iron (%) (Fe)	2 %	4 % (equivalent to 20 000 – 40 000 mg/kg dry weight)

RESULTS

Seasonal Variation of Physicochemical Parameters of Water : The mean values of measured physicochemical parameters during this study are presented in Table 3.

Table 3: Seasonal variation of physicochemical parameters

Parameters	Cold season	Hot season	Rainy season	p-value	sign. p<(0.05)
pH	7.3 ±0.4ab	7.5 ±0.4b	6.9 ±0.1a	0.025	*
EC µS/cm	268 ±33.5	244.8 ±14.2	276 ±13.1	0.06	
TDS mg·L⁻¹	137,2 ±17.3	143,5 ±45.6	124.8 ±14,4	0.413	
Temp °C	19.1 ±1.0b	27.4 ±2.6a	26.9 ±0.3a	0.0017	**
DO	-	8.7 ±0,4a	5.5 ±0.8b	0.016	*
TSS mg·L⁻¹	57.9 ±19.7	61.0 ±49.3	66.1 ±3.0	0.227	
Ca^{2+} mg·L⁻¹	84.3 ±10.4ab	71.6 ±11.3b	86.8 ±5.7a	0.0239	*
Mg^{2+} mg·L⁻¹	24.8 ±9.9a	18.6 ±5.0a	45.2 ±4.3b	1.79.10-5	***
Na^{+} mg·L⁻¹	22.5 ±2.4b	32.1 ±4.8a	34.0 ±5.1a	0.0006	***
K^{+} mg·L⁻¹	40.5 ±8.8b	41.4 ±9.7ab	50.9 ±1.7a	0.031	*
Cl^{-} mg·L⁻¹	84.7 ±78.3	19.2 ±2.3	52.1 ±12.5	0.148	
SO_4^{2-} mg·L⁻¹	10.4 ±3.0	10.9 ±0.5	11.1 ±1.1	0.982	
CO_3^{-} mg·L⁻¹	81.5 ±7.8	122.1 ±7.8	143.7 ±6.6	0.111	
NO_3^{-} mg·L⁻¹	1.6 ±0.1	1.26 ±0.3	1.5 ±0.09	0.092	
NO_2^{-} mg·L⁻¹	1.6 ±0.6	1.4 ±0.3	1.6 ±0.1	0.53	
NH_4^{+}mg·L⁻¹	1.4 ±0.2	1.4 ±0.5	1.4 ±0.2	0.634	
N mg·L⁻¹	0.36 ±0.32ab	0.53 ±0.05b	0.95 ±0.36a	0.027	*
P mg·L⁻¹	16.0 ±9.2	17.8 ±4.3	19.9 ±1.5	0.994	

The results indicated that several physicochemical parameters of the water (pH, temperature, dissolved oxygen, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and total nitrogen) had significant seasonal variations (p-value < 0.05). Water pH remained close to neutrality, and changed from 6.9 to 7.5 during respectively in the rainy season and the hot season during the study period. Water temperature was low during the cool season (19.1 °C) and high during the hot season (27.4 °C) and the rainy season (26.9 °C). Dissolved oxygen concentrations were high during the cool season (8.7 mg·L⁻¹) and low during the rainy season (5.5 mg·L⁻¹). Calcium concentrations were high during the rainy season (86.8 mg·L⁻¹) and low during the hot season (71.6 mg·L⁻¹). Magnesium showed very low concentrations during the hot season (18.6 mg·L⁻¹) and markedly high values during the rainy season (45.2 mg·L⁻¹). Sodium concentrations were high during the hot season (32.1 mg·L⁻¹) and the rainy season (34.0 mg·L⁻¹) compared to the cool season (22.5 mg·L⁻¹). Potassium concentrations were relatively stable between the cool season (40.5 mg·L⁻¹) and the hot season (41.4 mg·L⁻¹), but increased markedly during the rainy season (59.9 mg·L⁻¹). Total nitrogen concentrations were high during the rainy season (0.9 mg·L⁻¹) than during the cool (0.4 mg·L⁻¹) and hot (0.5 mg·L⁻¹) seasons. In contrast, the remaining parameters have not shown statistically significant seasonal differences. Although some seasonal trends were observed for total suspended solids (TSS; 57.9–66.1 mg·L⁻¹), carbonates (CO_3^{2-}; 81.5–143.7 mg·L⁻¹), electrical conductivity (EC; 257.8–269.5 µS·cm⁻¹), chlorides (Cl^{-}; 47–54 mg·L⁻¹), nitrates (NO_3^-; 1.4–1.5 mg·L⁻¹), nitrites (NO_2^-; 1.4–1.6 mg·L⁻¹), and phosphorus (P; 16.0–19.9 mg·L⁻¹). When compared with guideline values, concentrations of NO_2^-, NH_4^+, total phosphorus, and total nitrogen exceeded water quality standards for the protection of aquatic organisms. In contrast, pH, EC, temperature, dissolved oxygen, chlorides, and nitrates remained within acceptable limits.

Spatial Variation of Physicochemical Parameters Among Stations : The table 4 presents the mean values of physicochemical parameters of Tabalak pond water according to sampling stations. High mean pH, temperature and NO_2^- values were measured respectively at Kéhéké, and Sillalé stations while the low values of EC, DO and P were recorded respectively at Sillalé, Fallé Kéhéké stations.

Table 4: Spatial variation of physicochemical parameters mean values.

	Kéhéké	**Fallé**	**Sillalé**	**p-value**	**sign. p<(0.05)**
pH	7.18 ±0.4	7.3 ±0.4	7.2 ±0.4	0.073	
EC µS/cm	259.8 ±14.9	269.5 ±23.4	257.8 ±35.9	0.713	
T D S mg·L⁻¹	135.8 ±9.3	146.7 ±45.9	123 ±16.0	0.292	
Temperature	23.9 ±5.2	24.9 ±4.0	25.3 ±5.2	0.929	
DO mg·L⁻¹	7.1 ±2.7	6.5 ±0	6.7 ±2.5	0.849	
TSS mg·L⁻¹	72.8 ±45.8	56.7 ±15.0	55.5 ±16.8	0.849	
Ca^{2+} mg·L⁻¹	79.15 ±11.0	82.1 ±13.1	81.4 ±11.4	0.902	
Mg^{2+} mg·L⁻¹	27.3 ±12.9	31.3 ±12.6	29.9 ±16.5	0.885	
Na^+ mg·L⁻¹	26.0 ±2.8	29.9 ±6.8	32.6 ±8.1	0.223	
K^+ mg·L⁻¹	41.6 ±9.3	43.0 ±8.5	48.3 ±8.0	0.391	
Cl^- mg·L⁻¹	47.3 ±52.5	54.4 ±53.2	54.3 ±56.8	0.989	
SO_4^{2-} mg·L⁻¹	11.1 ±1.8	10.8 ±2.1	10.5 ±1.8	0.867	
CO_3^- mg·L⁻¹	116.2 ±50.8	113.3 ±50.8	117.9 ±52.7	0.859	
NO_3^- mg·L⁻¹	1.5 ±0.1	1.4 ±0.2	1.4 ±0.4	0.651	
NO_2^- mg·L⁻¹	1.4 ±0.5	1.5 ±0.3	1.6 ±0.3	0.648	
NH_4^+ mg·L⁻¹	1.3 ±0.2	1.3 ±0.2	1.6 ±0.4	0.286	
N mg·L⁻¹	0.6 ±0.3	0.6 ±0.4	0.7 ±0.4	0.744	
P mg·L⁻¹	17.3 ±7.0	18.4 ±5.6	18.1 ±5.8	0.896	

The analysis of these results indicates that there are no statistically significant differences among the three stations for measured physicochemical parameters (p-value ≥ 5%). Indeed, all parameters reflect generally homogeneous water quality across the sampling stations. On the other hand, concentrations of NO_2^-, NH_4^+, total phosphorus, and total nitrogen exceed guideline values for the protection and survival of aquatic organisms. In contrast, pH, electrical conductivity, temperature, dissolved oxygen, chlorides, and nitrates remain within acceptable limits at all stations.

Multivariate correlations among parameters and their grouping by season and station: A principal component analysis (PCA) was performed to examine the relationship between the sampling stations and measured predictor variables (physicochemical parameters) in the water body in accordance of seasonality (Figure 2).

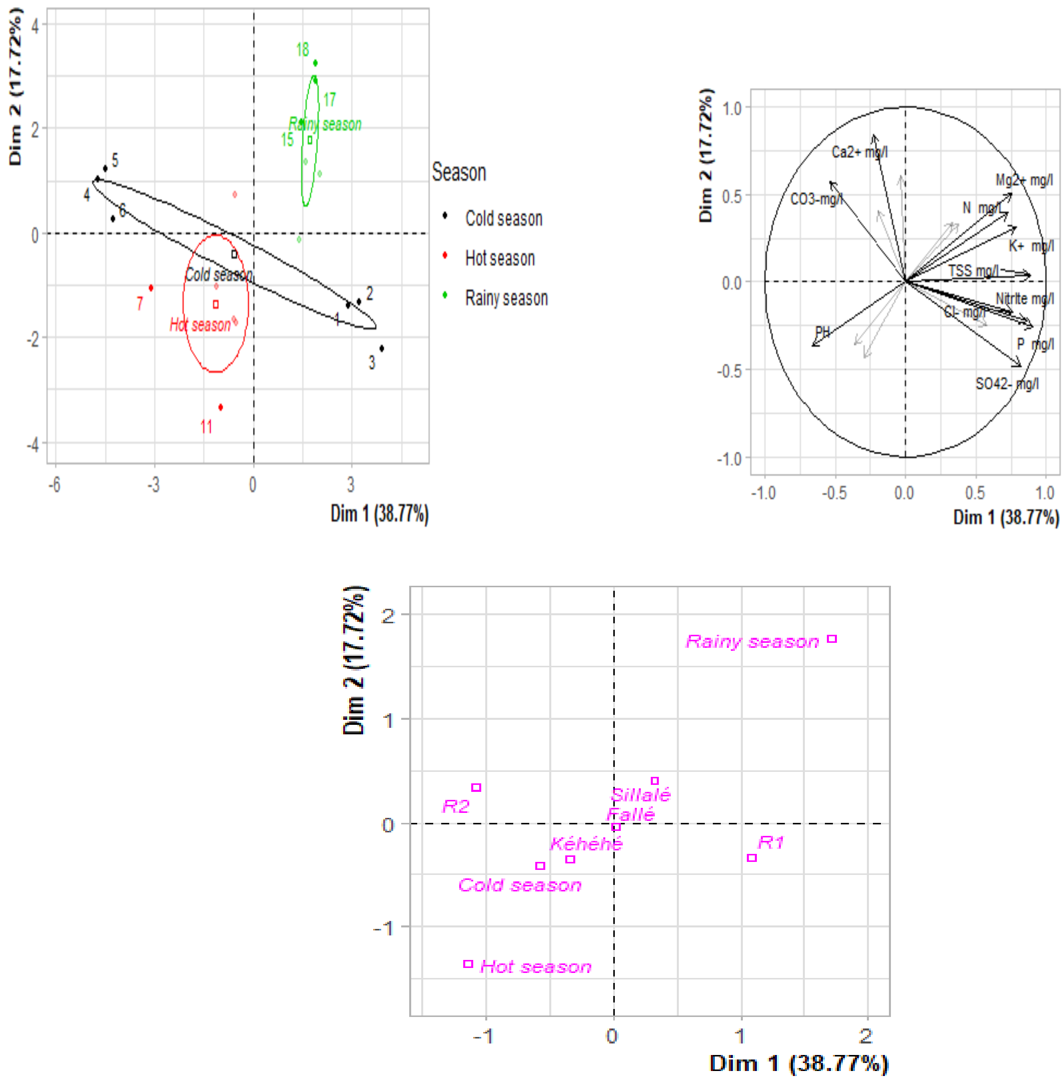

Figure 2. Principal Component Analysis PCA of physicochemical parameters

The principal component analysis (PCA) showed that the first two axes explained 56.49% of the total variance. Axis 1 (38.77%) represented a mineralization and nutrient gradient, separating waters enriched in Cl^-, NO_2^-, SO_4^{2-}, phosphorus, and suspended solids from more alkaline waters with higher pH. Axis 2 (17.72%) was mainly associated with Na^+, Mg^{2+}, and total nitrogen. Seasonal projection indicated a clear seasonal pattern, with low mineralization during the rainy season, high mineralization in the hot season, and intermediate conditions in the cool season. Spatial variability between stations (Kéhéhé, Sillalé, and Fallé) remained limited.

Variation of Trace Metal Elements in the Water and sediment Matrix : The Tables 5 and 6 present the concentrations of trace metal elements in the water and sediment matrices of Tabalak pond respectively. Analysis of these tables highlights the presence of all investigated trace metal elements; lead (Pb), zinc (Zn), copper (Cu), iron (Fe), and cadmium (Cd) both in water and sediment samples at all sampling stations.

Table 5: levels of trace metal elements in water

TME	Station		
	Kéhéhé	Fallé	Sillalé
Pb (µg/l)	25.98	43.80	38.22
Zn (µg/l)	8.44	8.13	10.76
Cu (µg/l)	1.10	3.47	1.56
Fe (µg/l)	160.84	208.88	541.25
Cd (µg/l)	5.23	4.13	4.28

Trace Metal Elements (TMEs), Pb: Lead; Zn: Zinc; Cu: Copper; Fe: Iron; Cd: Cadmium.

The measured concentrations in water ranged from 25.98 to 43.80 $\mu g \cdot L^{-1}$ for Pb, 8.13 to 10.76 $\mu g \cdot L^{-1}$ for Zn, 1.10 to 3.47 $\mu g \cdot L^{-1}$ for Cu, 160.84 to 541.25 $\mu g \cdot L^{-1}$ for Fe, and 4.13 to 5.23 $\mu g \cdot L^{-1}$ for Cd.

Table 6: levels of trace metal elements in sediment

TME	Stations		
	Kéhéhé	Fallé	Sillalé
Pb (mg/kg)	0.88	0.71	0.80
Zn (mg/kg)	2.05	1.32	1.32
Cu (mg/kg)	0.89	0.62	0.63
Fe (mg/kg)	114.62	46.83	67.22
Cd (mg/kg)	0.02	0.02	0.01

The concentrations of metallic trace elements in the sediments ranged from 0.71 to 0.80 mg/kg for Pb, 1.32 to 2.05 mg/kg for Zn, 0.62 to 0.89 mg/kg for Cu, 46.83 to 114.62mg/kg for Fe and 0.01 to 0.02 mg/kg for Cd.

DISCUSSION

The analysis of water from the Tabalak pond reveals a predominantly seasonal variability of physico-chemical parameters, whereas spatial variability among sampling stations remains low, indicating a relative homogeneity of the water body. This homogeneity may result from wind-induced mixing that promotes convective movements, as well as from relatively uniform land use within the watershed, which is largely dominated by agricultural activities. The observed characteristics confirm that seasonal hydrological dynamics constitute the principal driver structuring water quality. The pH values range from 6.9 to 7.5 across seasons and from 7.1 to 7.3 among stations, indicating overall neutral conditions with a slight alkaline tendency. A decrease in pH during the rainy season is observed, likely attributable to dilution by rainwater and inputs of organic matter, as reported by Chapman (1996) and Tfiel *et al.* (2018). The measured values remain within the recommended standards for the protection of aquatic life. Although they partially differ from those reported by Adamou *et al.* (2015), who documented more pronounced variability with alternating acidic and alkaline trends, they are consistent with the findings of Chahboune *et al.* (2011) and Mama *et al.* (2011) in comparable hydrological contexts. Electrical conductivity, ranging from 244.8 to 276 µS/cm across seasons and from 257.8 to 269.5 µS/cm among stations, reflects moderate mineralization of the waters. These values remain well below the critical threshold of 1500 µS/cm indicated by Monney *et al.*

(2016) and therefore suggest ionic concentrations compatible with aquatic life. Total dissolved solids exhibit a similar pattern, with values between 124.8 and 143.5 mg/L. Seasonal fluctuations are explained by the combined effects of evaporation during the hot season and runoff inputs during the rainy season, in agreement with the observations of Cormier *et al.* (2018), Stober *et al.* (2023), and Hade (2003). Differences compared to the results of Adamou *et al.* (2015) may be attributed to distinct hydrological conditions or to changes in anthropogenic practices within the watershed. Water temperature varies from 19.1 to 27.4 °C, with lower values recorded during the cool dry season and higher values during the hot and rainy seasons. This pattern follows ambient thermal dynamics and solar radiation intensity. As emphasized by Jain *et al.* (2021), temperature strongly influences reaction kinetics and dissolved oxygen solubility. Dissolved oxygen concentrations show significant seasonal variation, with higher levels during the cool season and lower levels during the rainy season. This trend is consistent with greater oxygen solubility at lower temperatures and increased consumption associated with organic matter decomposition during the rainy period, as described by Allan and Castillo (2007) and Buhungu *et al.* (2018). Nevertheless, the values remain within the acceptable standards reported by Abboudi *et al.* (2014). Major ions such as Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} exhibit significant increases during the rainy season, reflecting soil leaching and agricultural inputs, consistent with the findings of Wetzel (2001) and Meybeck (2003). Nitrogen compounds, derived from the nitrification process described by UNEP/MAP/MEDPOL (2004), remain statistically stable across seasons and stations; however, nitrite and ammonium concentrations exceed recommended standards. The potential transformation of NH_4^{+} into NH_3, a toxic form, represents a risk for aquatic organisms, as highlighted by Koudénoukpo (2017). Total phosphorus shows a marked increase during the rainy season, reaching concentrations far above the admissible threshold of 0.5 mg/L reported by Agblonon Houelome (2016), thereby suggesting substantial agricultural inputs. Principal component analysis confirms that water quality variability is primarily governed by seasonality. The first axis contrasts waters enriched in chlorides, nitrites, sulfates, and phosphorus, indicating probable anthropogenic influence linked to agricultural runoff, as described by Sun *et al.* (2022), with more alkaline and weakly mineralized waters potentially influenced by dilution, in accordance with Liu *et al.* (2023). The second axis highlights an ionic gradient distinguishing water enriched in alkaline salts and total nitrogen from those dominated by other nutrients, a pattern comparable to that observed in tropical and semi-arid systems by Hammoumi *et al.* (2024) and Umwali *et al.* (2021). The positioning of seasons on the factorial plane reflects the combined effects of dilution during the rainy period and concentration through evaporation during the hot season, consistent with Ouyang (2006), Hamdhani *et al.* (2023), and Begum *et al.* (2023). The clustering of stations further confirms relative spatial homogeneity. Trace metals constitute the main source of concern. Several exceedances of guideline values are observed for lead, zinc, copper, and iron, indicating water contamination likely associated with agricultural inputs, as suggested by Ouattara *et al.* (2018). Although current concentrations are lower than those reported by Adamou *et al.* (2015), these discrepancies may be explained by changes in agricultural practices, enhanced seasonal dilution, or methodological differences. Heavy metals pose significant ecotoxicological risks due to their capacity for bioaccumulation and biomagnification, as emphasized by Ouattara *et al.* (2021) and Martinez-Haro *et al.* (2022). Iron may reduce water transparency and affect photosynthesis, according to Viollier *et al.* (2000), while lead can accumulate in fish tissues, inducing oxidative stress and physiological alterations, as demonstrated by Chouahda and Soltani (2009), Lee *et al.* (2019), and Srivastav *et al.* (2024). Zinc and copper, although essential at low concentrations, become toxic at elevated levels.

CONCLUSION AND APPLICATION OF RESULTS

The results revealed a strongly structure governed by seasonality and ionic composition, with periods of high mineralization during the hot seasons in contrast to the rainy season characterized by the dilution of dissolved ions. This seasonal pattern is typical of aquatic systems in semi-arid tropical regions and constitutes a key indicator of the ecological functioning of this environment. Several measured parameters (NO_3^-, NO_2^-, $NH_4^+$and P; Pb, Zn, Cu and Fe for TME) exceed established guideline limits, thereby indicating a degradation of water quality. Indeed, the Tabalak pond is highly threatened by eutrophication, as well as contamination by trace metal elements (Pb, Zn, Cu, and Fe). This situation without a continuous monitoring program could be disastrous for local biodiversity and, leading potentially to fish mortality and deterioration of water quality, hence the necessity to implement an integrated management approach to preserve the ecosystem services provided by this water body to local populations. A regular environmental monitoring program focusing on physico-chemical parameters and metal contaminants is strongly recommended in order to better understand seasonal variations and anticipate periods of degradation. In parallel, management strategies such as reducing pollutant inputs, establishing of vegetated buffer zones, and the controlling anthropogenic activities should be implemented.

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