



Spatio-temporal variation of water physicochemical parameters in Lake Toho (Southern Benin)

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Abstract. Lake Toho is one of the important freshwater ecosystem in southern Benin, under intense human activities. This study aims to assess the spatial and temporal variations of water physicochemical parameters in Lake Toho. A total of 54 water samples were taken during three campaigns at 6 stations from February to June 2024. Water depth and Secchi Disk Depth (SDD) were recorded in situ using a Secchi disk. Turbidity was determined using a turbidimeter. Parameters such as temperature, pH, dissolved oxygen, oxygen saturation, salinity, Electrical Conductivity (EC), and Total Dissolved Solids (TDS) were measured using a probe multiparameter. Nutrient concentrations were quantified using specific reagents and a spectrophotometer. Analyses of variance revealed spatial and temporal significant variations ($p < 0.05$) for water depth (1.71–2.24 m), SDD (21.33–26.44 cm), pH (7.06–7.68), temperature (30.4–32.25 °C) and suspended solids (22.56–27.22 mg L⁻¹). EC (470.56–508.72 μ S cm⁻¹), salinity (0.22–0.24 PSU), nitrate (7.29–10.66 mg L⁻¹), ammonium (0.18–0.28 mg L⁻¹) and orthophosphate (0.08–0.13 mg L⁻¹) were showed only very significant variation between months ($p < 0.001$). Significant correlations ($p < 0.001$) were observed between SDD and turbidity, between nitrate and pH, water depth, salinity, EC and TDS. The nutrient enrichment observed in this lake could be responsible for organic pollution, likely driven by anthropogenic inputs. This study constitutes a preliminary assessment of the ecosystem, and further investigations are needed to better understand its biogeochemical functioning and the nature of the disturbances affecting it.

1 Introduction

Freshwater systems play an essential role in regulating the local climate, supporting agriculture and livestock farming, domestic uses, and particularly production of drinking water for human consumption. This resource, a strategic global issue, requires management aligned with a sustainable development perspective (Abdelkarim, 2020). However, freshwater ecosystems are among the most threatened environments (Ayele and Atlabachew, 2021). These aquatic environments frequently serve as receptacles for organic pollutants from human activities, such as household waste, and urban and agricultural runoff. These inputs disrupt their functioning and lead to a loss of biodiversity (Lévêque, 1997).

In Benin, population growth in recent years has led to rapid urbanization of aquatic ecosystem basins (Gbaguidi et al., 2020). Lake Toho, the largest freshwater body in southern Benin, is a vital resource for local communities, providing water and fish products (Montcho et al., 2015). Once one of the country most productive water bodies, it recorded fish catches of up to 603.60 t yr⁻¹ (Montcho et al., 2015). Today, however, the lake is suffering the adverse effects of surrounding human activities and inadequate waste management, altering its ecological characteristics (Hounkpèvi et al., 2024). Lake Toho receives discharges from domestic, agricultural, and fishing activities, the main sources of pollution responsible for biodiversity loss (Gbaguidi et al., 2020). The pres-

tures exerted on this ecosystem include organic pollution, the presence of heavy metals, and the use of chemical fertilizers and pesticides. These substances, transported by rainfall runoff, modify the physicochemical composition of the water and influence the abundance of living species (Montcho et al., 2015; Adite et al., 2017; Gbaguidi et al., 2020).

Lake Toho has experienced several episodes of mass fish mortality, notably in 2012, 2018, and 2021, resulting in significant economic losses and impacting biodiversity, notably ichthyological diversity. Although some recovery of aquatic life was observed after these episodes, persistent pollution remains a major threat to this ecosystem. This study aims to characterize the spatial and temporal variation of water physicochemical quality in Lake Toho following these disasters. It aims to provide useful information to the managers for a better preservation of this fragile ecosystem.

2 Materials and methods

2.1 Study environment

Lake Toho is situated in southwestern Benin at Mono Department. It extends between $6^{\circ}35'$ and $6^{\circ}40'$ North latitude during low water period and between $1^{\circ}45'$ and $1^{\circ}50'$ East longitude during high water period (Adandedjan et al., 2018). The Lake covers an area of 9.6 km^2 during low water period and 15 km^2 during high water period. It receives water from Adiko and Akpatohoun Rivers. The Sazué Valley, to the south, serves as a discharge point during high-water periods, while the Akpacohadji Valley acts as both a tributary and outlet. Lake Toho watershed covers an area of 374 km^2 (Adandedjan et al., 2018). Lake Toho is under sub-equatorial climate, characterized by four (04) successive seasons: a long rainy season (mid-March to mid-July), a short dry season (mid-July to mid-September), a short rainy season (mid-September to mid-November) and a long dry season (mid-November to mid-March). Annual rainfall is around 1167.2 mm . Average annual totals range from 850 to 1150 mm (Montcho et al., 2015). Average monthly temperatures range from 27 to 31°C and relative humidity from 55% to 95% . The main human activities polluting the lake are agriculture, fishing and fish farming (PADPPA, 2008). Lake Toho is surrounded by grassy vegetation, ferns, plantations and agricultural and market crops, dominated by maize, manioc and legumes (Adandedjan et al., 2018; Hounkpèvi et al., 2024).

2.2 Sampling stations selection

Six (06) sampling stations, each comprising 3 substations, were selected to characterize the spatial variations of water physicochemical quality of Lake Toho (Fig. 1). Sampling station selection was based on multiple criteria, including accessibility, the presence or absence of urban settlements, agricultural activity, and riparian vegetation. These charac-

teristics provided a basis for refining the spatial assessment of water quality in the lake.

2.3 Sampling

Water samples were collected bimonthly from February to June 2024. In situ measurements of physicochemical were carried out between 06:30 and 10:30 a.m. (West Africa Time, UTC+1). Secchi Disk Depth (SDD) and water depth were measured using a Secchi disk. A multi-parameter Model Hanna HI9829 was used to measure parameters such as pH, temperature, dissolved oxygen, salinity, Total Dissolved Solids (TDS), and Electrical Conductivity (EC). Turbidity was measured with a Model Eutech TN-100 turbidimeter. After measurements had been taken, water samples were collected at each station in 1.5 L plastic bottles, which were rinsed before use. These Samples were stored in a cool box at 4°C and transported to laboratory. Analyses of nutrient parameters such as nitrite, nitrate, ammonium, and orthophosphate were carried out before 48 h after sampling using a molecular absorption spectrophotometer Hach DR6000 with Nitriver 3, Nitriver 5, Nesler Reagent, and Phosver 3 respectively (Rodier et al., 2009). Suspended solids (SS) were measured using also the same spectrophotometer.

2.4 Statistical analysis

The descriptive statistics for all variables were determined by calculating the mean and standard deviation by station and month. The data were then subjected to the Shapiro-Wilk normality test and Bartlett variance homogeneity test, in order to decide which mean comparison test use. The correlation matrix between physicochemical parameters was determined using Spearman method. To obtain a better assignment of the parameters to their group, a Principal Component Analysis was finally performed on the mean values of the different groups obtained after classification. All statistical analyses were carried out using R software version 4.2.2.

3 Results

3.1 Spatial variation of water physicochemical parameters in Lake Toho

The mean values of the water physicochemical parameters and the results of statistical tests are presented in Table 1. SDD ranged between $21.33 \pm 4.06 \text{ cm}$ in ST1 and $26.44 \pm 3.36 \text{ cm}$ in ST6. The mean values of pH varied from 7.06 ± 0.42 in ST1 to 7.68 ± 0.19 in ST4. The water depth was included between $1.71 \pm 0.24 \text{ m}$ (ST2) and $2.24 \pm 0.57 \text{ m}$ (ST6). The mean values for turbidity varied from $23.79 \pm 2.97 \text{ NTU}$ in ST5 to $33.72 \pm 4.72 \text{ NTU}$ in ST1. Water temperature ranged between $30.4 \pm 0.57^{\circ}\text{C}$ in ST1 to $32.25 \pm 0.86^{\circ}\text{C}$ in ST6. Suspended solids was included between $22.56 \pm 2.13 \text{ mg L}^{-1}$ in ST6 and $27.22 \pm 4.82 \text{ mg L}^{-1}$

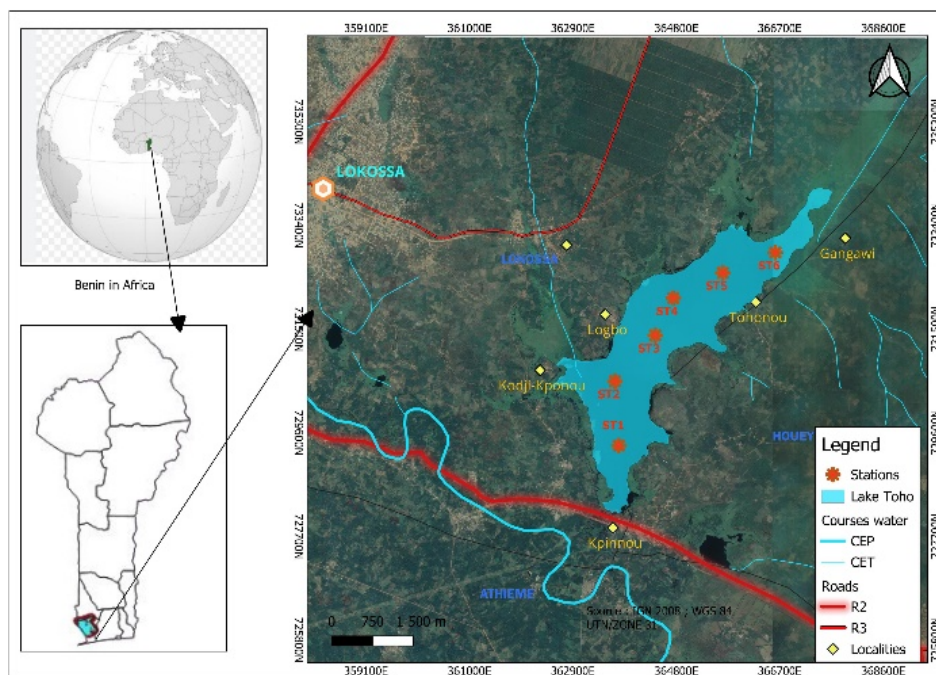


Figure 1. Map of Lake Toho showing the location of sampling stations.

in ST2. Dissolved oxygen and oxygen saturation varied from $2.72 \pm 0.98 \text{ mg L}^{-1}$ and $36.88 \pm 12.7 \%$ in ST1 to $3.89 \pm 1.25 \text{ mg L}^{-1}$ and $52.31 \pm 16.66 \%$ respectively. EC ranged between $482 \pm 18.8 \mu\text{S cm}^{-1}$ in ST1 to $508.3 \pm 36.4 \mu\text{S cm}^{-1}$ in ST6. Also, Total Solids Dissolved (TDS) was included between $242.4 \pm 9.15 \text{ mg L}^{-1}$ in ST1 and $256.9 \pm 31.95 \text{ mg L}^{-1}$ in ST6. The parameters such as nitrate (8.84 ± 1.32 to $9.06 \pm 1.63 \text{ mg L}^{-1}$), nitrite (0.03 ± 0 to $0.04 \pm 0 \text{ mg L}^{-1}$), ammonium (0.20 ± 0.05 to $0.24 \pm 0.09 \text{ mg L}^{-1}$) and orthophosphate (0.10 ± 0.03 to 0.13 ± 0.04) were varied between stations 1 and 6.

The parameters such as SDD, water depth, turbidity, pH, temperature, and SS were showed significant variation ($p < 0.05$) between sampling stations. There was no significant ($p > 0.05$) between sampling stations for dissolved oxygen, oxygen saturation, salinity, TDS, EC, nitrite, nitrate, ammonium, and orthophosphate.

3.2 Temporal variation of water physicochemical parameters in Lake Toho

The results of water physicochemical parameters are presented in Table 2. Maximum mean values for water depth ($2.15 \pm 0.46 \text{ m}$), SDD ($28.72 \pm 1.96 \text{ cm}$), temperature ($32.53 \pm 0.83 ^\circ\text{C}$), SS ($27.61 \pm 4.45 \text{ mg L}^{-1}$) and orthophosphate ($0.13 \pm 0.03 \text{ mg L}^{-1}$) were recorded during February. In April, high values were obtained for dissolved oxygen ($3.63 \pm 1.14 \text{ mg L}^{-1}$), oxygen saturation ($49.44 \pm 16.04 \%$), salinity ($0.24 \pm 0.01 \text{ mg L}^{-1}$), TDS ($255.3 \pm 7.66 \text{ mg L}^{-1}$), and EC ($508.72 \pm 17.19 \mu\text{S cm}^{-1}$). On the other hand,

turbidity ($30.33 \pm 5.79 \text{ NTU}$), pH (7.73 ± 0.23), nitrite ($0.037 \pm 0.01 \text{ mg L}^{-1}$), nitrate ($10.66 \pm 0.53 \text{ mg L}^{-1}$) and ammonium ($0.28 \pm 0.05 \text{ mg L}^{-1}$) recorded their maximums during June. Analysis of variation between sampling months revealed that water depth, SDD, pH, temperature, salinity, EC, nitrate, ammonium and orthophosphate showed significant differences ($p < 0.05$). Dissolved oxygen, oxygen saturation, and nitrite did not show any significant differences between the months.

3.3 Relationship between water physicochemical parameters in Lake Toho

The correlation matrix between the physicochemical water parameters of Lake Toho is presented in Table 3. The results reveal that temperature was positively and significantly ($p < 0.01$) correlated with TDS, water depth, dissolved oxygen, and oxygen saturation, while it was negatively correlated with turbidity. Furthermore, EC was positively correlated with salinity and TDS, which were negatively correlated ($p < 0.01$) with pH. There is also a high positive correlation between nitrate and pH, while a high negative and significant correlation ($p < 0.01$) exists between this variable and parameters such as salinity, EC, TDS, and temperature. Ammonium was negatively correlated with TDS, oxygen dissolved, oxygen saturation, temperature, salinity, EC, SS and nitrate. Finally, orthophosphate was positively correlated with SDD, water depth, SS and nitrate.

Table 1. Variation of water physicochemical parameters across sampling stations in Lake Toho between February and June 2024. Letters a, b, and c indicate significant differences between means according to the post-hoc Tukey test ($p < 0.05$).

Parameters	ST1	ST2	ST3	ST4	ST5	ST6	Sig.
Water depth (m)	1.91 ^{ab} ± 37.3	1.71 ^a ± 24.50	1.80 ^{ab} ± 27.45	1.89 ^{ab} ± 32.35	2.01 ^{ab} ± 28.14	2.24 ^b ± 57.45	*
SDD (cm)	21.33 ^a ± 4.06	24.3 ^{ab} ± 4.36	23.4 ^{ab} ± 2.92	25 ^{ab} ± 3.12	26.44 ^b ± 2.55	26.44 ^b ± 3.36	*
Turbidity (NTU)	33.72 ^a ± 4.72	32.82 ^a ± 4.88	29.90 ^{ab} ± 4.94	28.8 ^{ac} ± 3.04	23.79 ^c ± 2.97	24.6 ^{bc} ± 1.83	***
pH	7.06 ^a ± 0.42	7.35 ^{ab} ± 0.43	7.43 ^{ab} ± 0.44	7.68 ^b ± 0.19	7.49 ^{ab} ± 0.1	7.65 ^b ± 0.21	**
OD (mg L ⁻¹)	2.72 ^a ± 0.98	3.34 ^a ± 0.72	3.08 ^a ± 0.58	3.23 ^a ± 0.44	3.87 ^a ± 1.43	3.89 ^a ± 1.25	ns
Saturation (%)	36.88 ^a ± 12.7	44.53 ^a ± 9.80	41.57 ^a ± 8.63	44.49 ^a ± 6.72	53.27 ^a ± 20.27	52.31 ^a ± 16.66	ns
Temperature (°C)	30.4 ^a ± 0.57	31.1 ^{ab} ± 1.20	31.20 ^{ab} ± 1.24	31.94 ^b ± 1.20	31.91 ^b ± 1.04	32.25 ^b ± 0.86	**
Salinity (g L ⁻¹)	0.23 ^a ± 0.01	0.23 ^a ± 0.014	0.23 ^a ± 0.01	0.23 ^a ± 0.01	0.23 ^a ± 0.01	0.23 ^a ± 0.01	ns
TDS (mg L ⁻¹)	242.4 ^a ± 9.15	249 ^a ± 13.28	248.4 ^a ± 13.57	243.8 ^a ± 8.07	256.1 ^a ± 31.95	246.4 ^a ± 8.4	ns
EC (µs cm ⁻¹)	482.4 ^a ± 18.8	497.7 ^a ± 26.9	488.7 ^a ± 23.72	487.3 ^a ± 15.76	489 ^a ± 15.24	508.3 ^a ± 36.40	ns
SS (mg L ⁻¹)	25.2 ^{ab} ± 3.90	27.22 ^a ± 4.82	25.8 ^{ab} ± 3.53	26.7 ^{ab} ± 2.74	25.4 ^{ab} ± 1.51	22.56 ^b ± 2.13	*
NO ₂ ⁻ (mg L ⁻¹)	0.04 ^a ± 0.00	0.038 ^a ± 0.00	0.04 ^a ± 0.00	0.035 ^a ± 0.00	0.036 ^a ± 0.00	0.037 ^a ± 0.00	ns
NO ₃ ⁻ (mg L ⁻¹)	8.84 ^a ± 1.32	9.056 ^a ± 1.63	9.08 ^a ± 1.63	8.98 ^a ± 1.77	8.98 ^a ± 1.49	8.92 ^a ± 1.096	ns
NH ₄ ⁺ (mg L ⁻¹)	0.22 ^a ± 0.04	0.22 ^a ± 0.04	0.20 ^a ± 0.05	0.21 ^a ± 0.04	0.23 ^a ± 0.07	0.24 ^a ± 0.09	ns
PO ₄ ³⁻ (mg L ⁻¹)	0.13 ^a ± 0.04	0.109 ^a ± 0.03	0.10 ^a ± 0.021	0.11 ^a ± 0.023	0.097 ^a ± 0.025	0.101 ^a ± 0.03	ns

SDD = Secchi Disk Depth; DO = Dissolved Oxygen; TDS = Total Dissolved Solids; SS = Suspended Solids; EC = Electrical Conductivity; NO₃⁻ = Nitrate; NO₂⁻ = Nitrite; NH₄⁺ = Ammonium; PO₄³⁻ = Orthophosphate; degree of significance: ns = no significant ($p > 5\%$); $p < 5\%$ (*); $p < 1\%$ (**); $p < 1\%$ (***).

Table 2. Variation of water physicochemical parameters in Lake Toho across months between February and June 2024. Letters a, b, and c indicate significant differences between means according to the post-hoc Tukey test ($p < 0.05$).

Parameters	February	April	June	Sig.
Water depth (m)	2.15 ^a ± 0.46	1.66 ^b ± 0.2	1.97 ^b ± 0.28	***
SDD (cm)	28.72 ^a ± 1.96	22.39 ^b ± 2.43	22.39 ^a ± 2.38	***
Turbidity (NTU)	27.52 ^a ± 3.51	29 ^a ± 6.13	30.33 ^a ± 5.79	ns
pH	7.41 ^a ± 0.28	7.19 ^a ± 0.39	7.73 ^b ± 0.23	***
DO (mg L ⁻¹)	3.42 ^a ± 1.12	3.63 ^a ± 1.14	3.01 ^a ± 0.65	ns
Saturation (%)	47 ^a ± 15	49.44 ^a ± 16.04	40.08 ^a ± 8.58	ns
Temperature (°C)	32.53 ^a ± 0.83	31.46 ^b ± 1.04	30.43 ^c ± 0.49	***
Salinity (g L ⁻¹)	0.23 ^a ± 0.00	0.24 ^b ± 0.01	0.22 ^c ± 0.00	***
TDS (mg L ⁻¹)	246.6 ^a ± 6.54	255.3 ^{ab} ± 7.66	241.22 ^b ± 24.63	*
EC (µs cm ⁻¹)	497.4 ^a ± 26.25	508.72 ^a ± 17.19	470.56 ^b ± 7.13	***
SS (mg L ⁻¹)	27.61 ^a ± 4.45	24.72 ^b ± 2.56	24.11 ^a ± 1.97	**
NO ₂ ⁻ (mg L ⁻¹)	0.04 ^a ± 0.00	0.04 ^a ± 0.00	0.04 ^a ± 0.00	ns
NO ₃ ⁻ (mg L ⁻¹)	8.98 ^a ± 0.13	7.29 ^b ± 0.37	10.66 ^c ± 0.53	***
NH ₄ ⁺ (mg L ⁻¹)	0.18 ^a ± 0.03	0.21 ^a ± 0.04	0.28 ^b ± 0.051	***
PO ₄ ³⁻ (mg L ⁻¹)	0.13 ^a ± 0.03	0.08 ^b ± 0.01	0.11 ^c ± 0.02	***

SDD = Secchi Disk Depth; DO = Dissolved Oxygen; TDS = Total Dissolved Solids; SS = Suspended Solids; EC = Electrical Conductivity; NO₃⁻ = Nitrate; NO₂⁻ = Nitrite; NH₄⁺ = Ammonium; PO₄³⁻ = Orthophosphate; degree of significance: ns = no significant ($p > 5\%$); $p < 5\%$ (*); $p < 1\%$ (**); $p < 1\%$ (***).

3.4 Principal component analysis and projection of physicochemical variables

The results of the principal component analysis (PCA) showed that 49.7 % of the variance of water physicochemical parameters is explained by two principal components (Fig. 2). The first principal component of the PCA (Dim1) explained 27.2 % of the variation of physicochemical parameters. This component explains better the variation of ni-

trate, EC, salinity, temperature and ammonium. The second principal component (Dim2) explained 22.5 %. It explains more variation of water depth, TDS, pH, temperature and orthophosphate. PCA ordination shows that Lake Toho was influenced during February by SDD, water depth, dissolved oxygen, oxygen saturation and orthophosphate (Fig. 3). During April, Lake Toho is characterized by high values of salinity, EC and TDS. These parameters contrast with variables

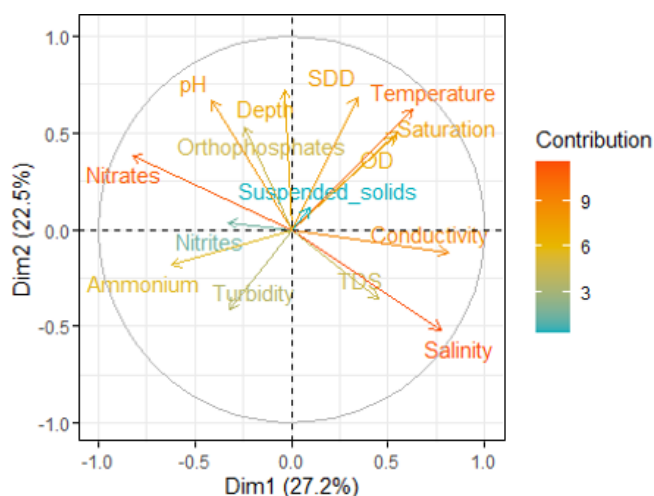


Figure 2. Principal component analysis of water physicochemical parameters at Lake Toho.

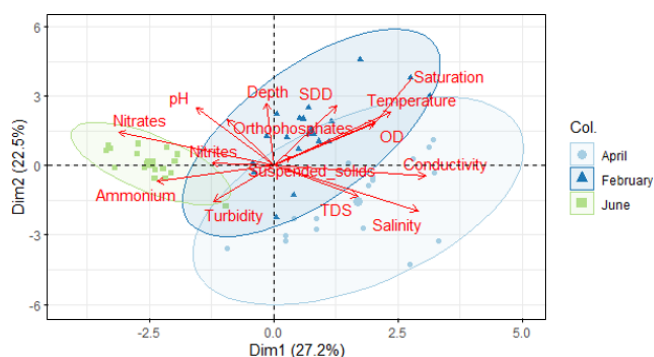


Figure 3. Projections of water physicochemical parameters on the first 2 axes across sampling months.

such as nitrite, nitrate, ammonium and turbidity obtained in June.

4 Discussion

The water physicochemical parameters of Lake Toho showed more significant variations between months than between the sampling stations. These results reveal that habitat conditions are homogeneous at the sampling stations in this study. The physicochemical characteristics observed are those of small, shallow tropical lakes, similar to those of Lake Bunyonyi in Uganda (Saturday et al., 2021) and Lakes Victoria and Baringo in Kenya (Ouma et al., 2016). These lakes generally display low spatial variability for parameters such as temperature and EC. Temporal variation of physicochemical parameters are often decisive in explaining variability in these ecosystems (Chouti et al., 2011; Alcocer et al., 2022). The fluctuations of physicochemical parameters values observed in this study can be attributed to the transition between the long dry season (February) and the long rainy season (June).

This explains the low values for SDD, salinity and EC in February, as well as the high turbidity values recorded in June, characterized by higher rainfall.

Water depth of Lake Toho during this study (1.17 and 3.05 m) differs slightly from the values reported by Adandedjan et al. (2018) in same ecosystem. The difference observed can be explained by the different hydrological periods considered. The lake can therefore be described as shallow, with no permanent stratification of the water column (Lévêque, 1997).

SDD (24.5 cm) is low compared to results observed by Lingfo et al. (2024) in Lake Nokoué and by Capo-Chichi et al. (2022) in Lake Toho-Todougba. It can be explained by high levels of turbidity and suspended matter (Dimon et al., 2014; Saturday et al., 2021). Indeed, in this lake, there are numerous anthropogenic activities such as intensive fishing, gravel mining and especially market gardening activities that regularly put suspended matter. In addition, the proliferation of algae contributes to a reduction SDD.

The pH values measured (6.57 and 7.95) reveal that the waters of Lake Toho are close to neutral and characterize the majority of surface waters and therefore do not indicate the acidity or basicity of the waters of Lake Toho. These results are in line with the variations observed by several authors such as Mama et al. (2011), Djihouessi et al. (2021), Capo-Chichi et al. (2022), Lingfo et al. (2024) in Lake Nokoué. The pH values are close to those reported for the same ecosystem (Gbaguidi et al., 2020; Hounkpèvi et al., 2024). These values are in line with WHO recommendations, which stipulate that pH of surface water should be between 5.5 and 8.5 (WHO, 2017).

Water temperature is an essential ecological factor, which strongly influence aquatic life. It affects gas solubility, dissociation of dissolved salts, pH and the rate of chemical reactions (Lingfo et al., 2024). The temperature recorded during our sampling correspond to those observed by Adandedjan et al. (2018) and Topanou et al. (2020) in this ecosystem. The favorite temperature to fish growth are generally situated between 24 and 35 °C (WHO, 2017).

Dissolved oxygen is a crucial parameter for aquatic ecology, essential for respiration of heterotrophic organisms and decomposition of organic matter by microorganisms (Ouma et al., 2016; Lingfo et al., 2024). Dissolved oxygen indicates the health of an aquatic ecosystem and, among other things, makes it possible to assess the quality of fish habitats. This parameter is an integral part of ecosystem metabolism. Fish and other animals consume it to maintain their metabolism (cellular respiration). The average dissolved oxygen in Lake Toho is 3.36 mg L⁻¹ during this study, which is comparable to values observed in other lakes of Benin (Dimon et al., 2014; Capo-Chichi et al., 2022; Lingfo et al., 2024). The EPA (2016) recommends a concentration of at least 5 mg L⁻¹ to maintain a healthy aquatic environment. Low dissolved oxygen concentration could indicate a high pollutant load or high temperature (Lingfo et al., 2024).

Table 3. Correlation matrix between water physicochemical parameters in Lake Toho from February and June 2024.

	SSD	Depth	Turb.	pH	OD	Sat.	Temp.	Sal.	TDS	EC	SS	NO ₃ ⁻	NO ₂ ⁻	NH ₄ ⁺	PO ₄ ³⁻
SSD	1														
Water Depth	0.44***	1													
Turb.	-0.49***	-0.27	1												
pH	0.19	0.33*	-0.25	1											
OD	0.18	0.26	-0.19	0.20	1										
Sat.	0.24	0.26	-0.21	0.20	0.97***	1									
Temp.	0.75***	0.30*	-0.50***	0.19	0.48***	0.53***	1								
Sal.	-0.05	-0.36**	-0.07	-0.64***	0.10	0.10	0.16	1							
TDS	0.06	-0.22	-0.23	-0.35**	-0.03	-0.04	0.04	0.54***	1						
EC	0.21	0.07	-0.17	-0.46***	0.36**	0.33*	0.35*	0.73***	0.38**	1					
SS	0.31*	-0.19	0.06	-0.02	-0.16	-0.12	0.29*	0.03	0.03	-0.02	1				
NO ₃ ⁻	0.03	0.32*	0.07	0.60***	-0.25	-0.26	-0.35*	-0.80***	-0.35**	-0.64***	-0.07	1			
NO ₂ ⁻	0.05	-0.09	0.08	0.17	-0.12	-0.13	-0.11	-0.27*	0.07	-0.22	0.04	0.28*	1		
NH ₄ ⁺	-0.38**	-0.04	0.01	0.21	-0.28*	-0.32*	-0.51***	-0.32*	-0.15	-0.37**	-0.28*	0.46***	0.22	1	
PO ₄ ³⁻	0.40**	0.50***	0.12	0.15	-0.05	-0.04	0.11	-0.41**	-0.29*	-0.17	0.32*	0.41**	0.03	-0.17	1

The degree of significance of correlations is marked by asterisks: $p < 5\%$ (*), $p < 1\%$ (**), and $p < 0.1\%$ (***). SSD = Transparency; Turb = Turbidity; pH = Hydrogen Potential; OD = Dissolved Oxygen; Sat = Saturation; Temp = Temperature; Sal = Salinity; TDS = Dissolved Solid Rate; Cond = Conductivity; SS = Suspended Solids; NO₃⁻ = Nitrate; NO₂⁻ = Nitrite; NH₄⁺ = Ammonium; PO₄³⁻ = Orthophosphate.

In addition, ammonia, often represented as ammonium ion (NH₄⁺), has high values of between 0.18 and 0.28 mg L⁻¹, compared to the limit value of 0.02 mg L⁻¹ (BE, 2012). The distribution of ammonium in an aquatic environment varies according to the level of productivity of the ecosystem and its degree of pollution by organic matter. Its presence in water is thought to result from the aerobic degradation of organic nitrogen, much of which comes from market gardening and agricultural activities (Hounkpèvi et al., 2024).

The nitrate concentrations (7.29 and 10.66 mg L⁻¹) exceed the international standard set at 0.02 mg L⁻¹ (BE, 2012). These high nitrate concentrations are primarily due to the presence of minerals resulting from agricultural activities, fish farms and household waste of all kinds discharged into the lake by runoff. As for nitrite, a value observed (0.04 mg L⁻¹) exceeds 0.02 mg L⁻¹ standard permitted in normal surface water. These high concentrations can affect the development of aquatic species, as water containing even low levels of nitrite can be considered suspect, even lethal, for fish. These levels can also be explained by the anaerobic conditions that exist in some areas, due to the abundance of macrophytes, and which promote the extensive nitrification of organic matter.

Orthophosphate result from bacterial degradation of organic phosphates from wastewater discharges such as metabolism, washing powders, food, chemical industries and fertilizer use. Assimilable by plants and photosynthetic organisms, they play a decisive role in eutrophication (BE, 2012). However, above a certain concentration and under favorable conditions, it can cause excessive growth of algae and aquatic plants (Djihouessi et al., 2021; Lingof et al., 2024). The values found in this study are higher than the permitted tolerances and therefore reflect excessive input from leaching and runoff from fertilized farmland.

The correlations observed among water physicochemical parameters are consistent with those reported in other tropical lake environments (Dimon et al., 2014; Capo-Chichi et al., 2022). Mineralization plays a key role in enriching the water with nutrients, which in turn promotes excessive algal growth and leads to the accumulation of salts and ions (Lingof et al., 2024). Furthermore, the results of PCA show an increasing of inorganic pollution during months sampling.

During the long rainy season and the short dry season, nutrient levels, especially nitrogen and phosphorus, become high (Capo-Chichi et al., 2022; Lingof et al., 2024). These nutrient are drained by run-off water loaded with leaching products from watersheds and by the arrival of continental waters, rich in organic matter. This creates organic pollution in the lake (Adandedjan et al., 2018). It is also linked to the excessive use of chemical fertilizers in farming activities around Lake Toho.

5 Conclusions

Lake Toho underwent significant temporal variation of water physicochemical parameters, while very few variables fluctuated spatially. The physicochemical conditions of Lake Toho are more or less homogeneous in sampling stations and reveal a progressive degradation of water quality across the months, due to significant point source organic pollution. This degradation is the result of emerging anthropogenic activities such as household waste, intensive fishing and, in particular, agriculture, whose cleaning products enrich the lake waters with nutrients and can lead to eutrophication. Effective management strategies must be implemented to reduce nutrient inputs from agriculture and livestock, which are threatening the stability of this sensitive ecosystem.

Code availability. Statistical analyses were performed using R software (version 4.2.2). Custom scripts are available upon request from the respective author, as they contain site-specific data that cannot be made public.

Data availability. Research data underlying this study are available from the corresponding author upon request. They are not publicly accessible due to local research agreements and confidentiality constraints.

Author contributions. MONCH contributed to sampling data, analysis data and first manuscript draft. RBL contributed to sampling data and analysis data, and YA supervised the work.

Competing interests. The contact author has declared that neither of the authors has any competing interests.

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References

- Abdelkarim, M. S.: Biomonitoring and bioassessment of running water quality in developing countries: a case study from Egypt, *Egyptian Journal of Aquatic Research*, 46, 313–324, <https://doi.org/10.1016/j.ejar.2020.11.003>, 2020.
- Adandedjan, D., Houelome, T. M. A., Montcho, A. S., Hounkpe, E., and Laleye, A. P.: Anthropogenic impacts on water quality and macroinvertebrates distribution of Toho Lake, South-West Benin, *Journal of Biodiversity and Environmental Sciences*, 13, 152–165, 2018.
- Adite, A., Tossavi, C. E., and Kakpo, D. B. E.: Biodiversity, length-weight patterns and condition factors of cichlid fishes (Perciformes: Cichlidae) in brackish water and freshwater lakes of the Mono River, Southern Benin, West Africa, *International Journal of Fauna and Biological Studies*, 4, 26–34, 2017.
- Alcocer, J., Merino-Ibarra, M., Ramírez-Zierold, J. A., Os-eguera, L. A., Cortés-Guzmán, D., Castillo-Sandoval, F. S., Guzmán-Arias, A. P., and Pérez-Ramírez, M. G.: Physicochemical Characteristics Lake Alchichica, *Limnology*, 101–142, https://doi.org/10.1007/978-3-030-79096-7_7, 2022.
- Ayele, H. S. and Atlabachew, M.: Review of characterization, factors, impacts, and solutions of Lake eutrophication: Lesson for lake Tana, Ethiopia, *Environmental Science and Pollution Research*, 28, 14233–14252, <https://doi.org/10.1007/s11356-020-12081-4>, 2021.
- Bruxelles Environnement (BE): Programmes de surveillance de l'état des eaux de la Région de Bruxelles-Capitale en application de l'Ordonnance Cadre Eau, <https://org.belgif.be/id/CbeRegisteredEntity/0236916956> (last access: 12 November 2025), 2012.
- Capo-Chichi, H. B. P., Adandedjan, D., Aglonon, H. M., and Laleye, P.: Physico-chimie et pollution organique du lac Nokoué au Sud du Bénin, *Journal of Applied Biosciences*, 170, 17752–17774, <https://www.ajol.info/index.php/jab/article/view/233264/220340> (last access: 12 November 2025), 2022.
- Chouti, W., Mama, D., Alassane, A., Changotade, O., Alapini, F., Boukari, M., Aminou, T., and Afouda, A.: Caractérisation physicochimique de la lagune de Porto- Novo (sud Bénin) et mise en relief de la pollution par le mercure, le cuivre et le zinc, *Journal of Applied Biosciences*, 43, 2882–2890, 2011.
- Dimon, F., Dovonou, F., Adjahossou, N., Chouti, W., Mama, D., Alassane, A., and Boukari, M.: Caractérisation physicochimique du lac Ahémé (Sud Bénin) et mise en relief de la pol-

- lution des sédiments par le plomb, le zinc et l'arsenic, *J. Soc. Ouest-Afr. Chim.*, 37, 36–42, 2014.
- Djihouessi, M. B., Tigo, B. A., and Aina, M. P.: The use of nutrient budget approach for informing eutrophication management in urbanised shallow coastal lakes: A case study from Lake Nokoué in Benin, *Ecohydrology and Hydrobiology*, 21, 341–353, <https://doi.org/10.1016/j.ecohyd.2020.11.003>, 2021.
- Environmental Protection Agency (EPA): National Recommended Water Quality Criteria – Aquatic Life Criteria Table, United States, <https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table> (last access: 7 November 2025), 2016.
- Gbaguidi, J. G., Topanou, N., Fatonbi, J., Moyo, E. A., Mama, D., and Aminou, T.: Contributions to the protection of a lentic system in the tropical region against chemical pollutions: A case study of “Toho Lake” in Southeastern Benin, West Africa, *Journal of Bioscience and Applied Research*, 6, 8–19, <https://doi.org/10.21608/jbaar.2020.115763>, 2020.
- Houunkpèvi, D. T. E., Chouti, W. K., Tometin, L., Fatombi, J. K., and Mama, D.: Influence of the water quality of Lake Toho located in the Mono department, southwest Benin, by glyphosate and metals (copper, zinc, lead, and cadmium), *Int. J. Res.*, 12, 42–51, <https://doi.org/10.21474/ijar01/19226>, 2024.
- Lévêque, C.: Biodiversity dynamics and conservation: The freshwater fish of tropical Africa, Cambridge University Press, Royaume Uni, 438, ISBN 0 521 57033 6, 1997.
- Lingofo, R. B., Chabi Kpera, M. O. N., Ewédje, E. L., Zébazé, S. H. T., Mama, D., and Abou, Y.: Dynamic of eutrophication in a coastal shallow lagoon, the Lake Nokoué in Benin (West Africa), *J. Mater. Environ. Sci.*, 15, 1760–1775, 2024.
- Mama, D., Deluchat, V., Bowen, J., Chouti, W., Yao, B., Gnon, B., and Baudu, M.: Caractérisation d'un Système Lagunaire en Zone Tropicale: cas du lac Nokoué (Bénin), *European Journal of Scientific Research*, 56, 516–528, 2011.
- Montcho, S. A., Agadjihouèdé, H., Montchowui, E., and Lalèyè, A. P.: Population parameters of *Oreochromis niloticus* (Cichlidae) recently introduced in Lake Toho (Benin, West Africa), *International Journal of Fisheries and Aquatic Studies*, 2, 141–145, 2015.
- Ouma, S. O., Ngeranwa, J. N., Juma, K. K., and Mburu, D. N.: Seasonal variation of the physicochemical and bacteriological quality of water from five rural catchment areas of lake victoria basin in Kenya, *Journal of Environmental Analytical Chemistry*, 3, <https://pdfs.semanticscholar.org/3166/3e0db4da3746305cb32f32a9f07878ff35f3.pdf> (last access: 12 November 2025), 2016.
- Programme d'Appui au Développement Participatif de la Pêche Artisanale (PADPPA): Plan de gestion de plan d'eau (PGPE): Lac Toho, Version finale, 75 pp., 2008.
- Rodier, J., Legube, B., Merlet, N., and Brunet, R.: L'Analyse de l'eau, Dunod, Paris, 9th En., 1579 pp., ISBN 978-2-10-054179-9, 2009.
- Saturday, A., Lyimo, T. J., Machiwa, J., and Pamba, S.: Spatio-temporal variations in physicochemical water quality parameters of Lake Bunyonyi, Southwestern Uganda, *Applied Sciences*, 3, 684, <https://doi.org/10.1007/s42452-021-04672-8>, 2021.
- Topanou, N., Gbaguidi, J. G., Essegbemon, A., Josse, R. G., Mama, D., and Aminou, T.: Assessment of Some Heavy Metals in Fresh Fish (*Oreochromis aureus*): Case of Toho Lake in South Eastern Benin, West Africa, *Journal of Geoscience and Environment Protection*, 8, 159–172, <https://doi.org/10.4236/gep.2020.83012>, 2020.
- World Health Organization (WHO): Guidelines for Drinking-water Quality, 4th edition, incorporating the 1st addendum, Geneva, 631, ISBN: 978-92-4-154995-0, 2017.