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Dynamic of eutrophication in a coastal shallow lagoon, Lake Nokoué in Benin (West Africa)

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Abstract: Despite international recognition of the Lake Nokoué classified as a Ramsar site 1018 in 2000, this Lake is still not spared from environmental pressures, mainly of anthropogenic origin, including eutrophication. This study aims to assess the dynamics of its trophic state. A total of 180 water samples were taken at 10 stations during six campaigns from November 2022 to October 2023. Basic physicochemical parameters were measured *in situ*. The Suspended solids, Ammonium, Nitrite, Nitrate, Total nitrogen, Phosphate, Total phosphorus and Chlorophyll were measured using the spectrophotometer method. The Trophic State Index (TSI) results in all the studied stations showed strong fluctuation of physicochemical parameters as a function of hydrological regimes. With regard to trophic state and transparency, Lake Nokoué were found to be eutrophic with turbid water (TSI=62.88 and Secchi Depth (SD) =0.74 m). Almost all stations in this Lake were meso-eutrophic with clear water (TSI=58.67 and SD=1.01 m) during the low water, before becoming eutrophic with turbid water (TSI=66.61 and SD=0.61 m). Thus, eutrophication of this lake is essentially influenced by phosphorus enrichment. Phytoplankton blooms are regulated by high turbidity due to suspended fine particles. These results will help the managers of this lake to take appropriate measures for its layout and restoration, with a principal view to its sustainable management.

1. Introduction

Although Africa is the leading continent in terms of the area occupied by wetlands, estimated at 110 million hectares or 48% of the global surface area, it is also the continent with the most threatened coastal and marine wetlands (Xu *et al.*, 2019). Coastal lagoons are highly dynamic wetlands, heterogeneous and complex from a functional point of view, as they are influenced by both fresh and marine waters (Pérez-Ruzafa *et al.*, 2011 & 2012). As a result, they are considered both the most productive wetlands and the most vulnerable to pollution-induced eutrophication (Pérez-Ruzafa *et al.*, 2011 & 2012), (Chacón-Abarca *et al.*, 2021), (Lobo *et al.*, 2023). Indeed, water eutrophication is a phenomenon of excess enrichment of nitrogen, phosphorus and other inorganic nutrients in hydrosystems that leads to deterioration of water quality, loss of aquatic habitats, algal blooms and rapid growth of macrophytes (Zhang *et al.*, 2021), (Gogoi *et al.*, 2022). Bacroume *et al.* (2015) described eutrophication as a complex phenomenon induced by environmental factors that can lead to changes in the dynamics of physico-chemical parameters in aquatic ecosystems. For this reason, it is currently a subject of debate and a field of research par excellence on an international scale (Zhang *et al.*, 2021), (Bonsdorff, 2021), (Zhang *et al.*, 2022), (Neverova-Dziopak *et al.*, 2023). Monitoring and assessment of eutrophication plays a crucial role in preserving hydrosystems (Bonometto *et al.*, 2022).

The Lake Nokoué is a coastal lagoon system located in the heart of the Cotonou city in southern Benin. Several authors have demonstrated its importance both nationally and internationally (Leite, 2001), (Lalèyè *et al.*, 2003), (Yehouenou *et al.*, 2013), (Ramsar Convention Secretariat, 2019). It is both the most productive coastal lagoon system, with production estimated at 2 tons of fish per hectare (Lalèyè *et al.*, 2003), (Yehouenou *et al.*, 2013) and the largest in Benin, with a surface area of 150 km^2 during low water period (Colleuil, 1987), (Yehouenou *et al.*, 2013), (Sintondji *et al.*, 2022). It provides a panoply of ecosystem services that contribute to the well-being of the Beninese community, such as food and the supply of water and building materials, flood regulation, transportation, recreation, natural laboratory, place of worship and spiritual rites, and ecotourism (Ramsar Convention Secretariat, 2019). Despite its classification as Ramsar Site 1018, which dates back more than two decades, this lagoon complex is unfortunately still not spared from environmental stresses, notably eutrophication. Studies carried out by (Mama, 2010), (Djihouessi, 2018), (Capo-Chichi *et al.*, 2022) have shown that Lake Nokoué is generally in a eutrophic or hypereutrophic state as a result of various forms of pollution, notably waste and effluent discharges of various origins without prior treatment. To this end, regular monitoring is essential for the long-term preservation of the ecosystem services and biodiversity of this Ramsar 1018 site. This is the rationale behind this study, whose overall objective is to assess the spatial dynamic of the trophic state of the Lake Nokoué as a function of hydrological regimes.

2. Methodology

2.1 Study area

This study was carried out on the Lake Nokoué situated in southern Benin. It extends precisely between parallels 6°22' and 6°30' North and meridians 2°20' and 2°35' East, and covers an area of 150 km^2 during low water level (Lalèyè *et al.*, 2003), (Zandagba *et al.*, 2021), (Sintondji *et al.*, 2022). This Lake benefits from a subequatorial climate, typical of southern Benin (Colleuil, 1987). As such, it is observed in four seasons, notably two dry seasons (November to mid-March and August to mid-September) and two rainy seasons (mid-March to August and mid-September to October) (Colleuil, 1987), (Lalèyè *et al.*, 1995), (Gnohossou, 2006), (Mama, 2010), (Djihouessi *et al.*, 2019). The Lake is connected directly to the Atlantic Ocean from the Cotonou channel at a distance of 4.5 km and a width of 300 m (Sintondji *et al.*, 2022). The Lake Nokoué is linked to Porto-Novo lagoon by the Totchè channel to the east and connected to the Lagos lagoon at a distance of over 100 km to the west (Colleuil, 1987), (Adandedjan *et al.*, 2011). The Lake is therefore supplied with freshwater by local rainfall, runoff and rivers, notably the Ouémé, Sô and Djonou, and with saltwater by intrusion from the Atlantic Ocean (Djihouessi *et al.*, 2019). With regard to the hydrological cycle, there are three distinct regimes, namely the low water regime that runs from December to May, the slightly rising-water regime that runs from June to August, and the high-water regime that runs from September to November (Mama *et al.*, 2011), (Djihouessi and Aina, 2018), (Djihouessi *et al.*, 2019).

2.2 Sampling plan

In situ measurements and water sampling were carried out at ten stations on Lake Nokoué (see **Figure 1**). It should be noted that at each station, three measurement and sampling points separated by a distance of around 100 m were selected. The stations on Lake Nokoué were: Sô-Ava (RS), Calavi (N1), Zogbo (N2), Vèkky (N3), Lake center (N4), Cotonou Channel (N5), Dékamnè (N6), Agbato (N7), Aguégué (N8) and Tchonvi (N9). These different stations were selected on the basis of their accessibility during all seasons, the level of intensification of human activities and the influence of tributaries on the ecological functioning of this Lake.

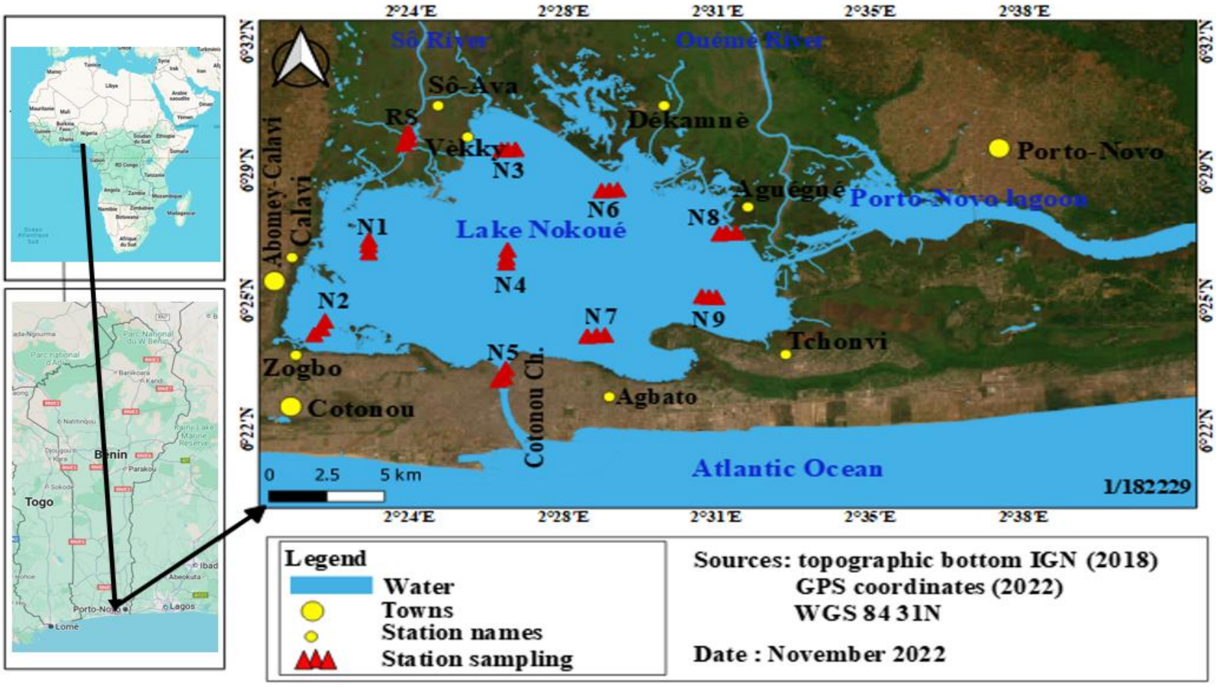

Figure 1. Location of the Lake Nokoué and sampling stations

For this study, six sampling campaigns were carried out from November 2022 to October 2023, with two campaigns per hydrological regime, namely the low water regime (campaigns in January and March 2023), the slightly rise water regime (campaigns in June and August 2023) and the high water regime (campaigns in November 2022 and October 2023). A total of 180 samples were taken (30 samples per campaign). Each campaign lasted three days, from 8 am to 1 pm.

2.3 Water physicochemical characterization

In the field, aboard a motorized boat, basic physicochemical parameters such as water depth, secchi depth, temperature, pH, dissolved oxygen, salinity and turbidity, were measured using Secchi disk, a multi-probe meter HANNA HI 9829, a Conductivity meter WTW Cond 3210 SET 1 (2CA201) and a Turbidity meter Eutech TN-100. After measurements had been taken, water samples were collected in 1.5 liter plastic bottles, which were rinsed before use. For chlorophyll a, samples were filtered directly in the field using Whatman GFA filter paper (porosity 0.7 µm) and a manual vacuum pump. Each sample taken was labelled with the name of the sampling point and the date before being stored in a cool box. It is worth mentioning that measurements and sampling were carried out in accordance with the protocol developed by Rodier *et al.* (2009) used by Odountan *et al.* (2019). After the fieldwork, the collected water samples were transported to the Laboratory of Ecology and Management of Aquatic

Ecosystems (LEMAE) at the University of Abomey-Calavi and stored in a refrigerator at 4°C. Analyses of suspended solids and nutrients such as chlorophyll a, ammonium, nitrite, nitrate, total Kjeldhal nitrogen, phosphate and total phosphorus were carried out no more than 48 hours after sampling, using a molecular absorption spectrophotometer HACH DR 6000 at an appropriate wavelength and the appropriate method for each parameter (**Table 1**). Chlorophyll *a* concentration was determined according to the following equation in **Eqn. 1** (Lorenzen, 1967), (Rodier *et al.*, 2009) :

$$Chl\text{-}a = 27x\ [(Ao665 - Ao750) - (Aa665 - Aa750)]\ x\ v / L\ x\ V \qquad \textbf{Eqn. 1}$$

with *Ao*: absorbance before acidification, *Aa:* after acidification; v: volume of acetone used; L: optical path and V: volume of filtered water.

Table 1. Analytical methods used to measure suspended solids and nutrients

Designations	Analysis methods
Suspended solids (mg/L)	Direct spectrophotometer measurement
Chlorophyll a (µg/L)	In situ filtration of water samples and measurement of absorbance at 665 nm and 750 nm before and after acidification with a spectrophotometer
Ammonium (mg/L)	Nessler reagent spectrophotometer assay method
Nitrate (mg/L)	Nitraver 5 reagent spectrophotometer assay method
Nitrite (mg/L)	Nitriver 3 reagent spectrophotometer assay method
Phosphate (mg/L)	PhosVer 3 reagent spectrophotometer assay method
Total nitrogen Kjeldhal (mg/L)	Peroxodisulfate mineralization method
Total phosphorus (mg/L)	Persulphate digestion + ascorbic acid method

2.4 Data analysis

Trophic status was assessed using the Comprehensive or Integral Trophic State Index (Yang *et al.*, 2012), (Cuevas-Madrid *et al.*, 2020) calculated from equations for calculating trophic state based on total phosphorus (µg/L), chlorophyll a (µg/L) and Secchi depth (m) developed in **Eqn. 2**, **Eqn. 3** & **Eqn. 4** and interpreted (**Table 2**) by Carlson (Carlson, 1977, Carlson and Simpson, 1996). The equations of Carlson and Integral Trophic State Index are calculated as follows in **Eqn. 5**:

$$TSI\ (SDD) = 60.0 - 14.41 \ln (SDD) \qquad \textbf{Eqn. 2}$$
$$TSI\ (TP) = 4.15 + 14.42 \ln (TP) \qquad \textbf{Eqn. 3}$$
$$TSI\ (Chl\text{-}a) = 30.6 + 9.81 \ln (Chl\text{-}a) \qquad \textbf{Eqn. 4}$$
$$Int\text{-}TSI = 0.297 * TSI\ (SDD) + 0.16 * TSI\ (TP) + 0.540 * TSI\ (Chl\text{-}a) \qquad \textbf{Eqn. 5}$$

where SDD: Secchi Depth, TP: Total Phosphorus, Chl-a: Chlorophyll a, TSI: Trophic State Index and Int-TSI: Integral Trophic State Index.

The integral trophic state index was used because it limits the influence of TSI (TP) values, which are responsible for overestimating Carlson trophic state index values (Yang *et al.*, 2012), (Cuevas-Madrid *et al.*, 2020). Moreover, the values of Secchi depth are interpreted in **Table 3**. With regard to deviations in trophic state index values, two-dimensional analysis was established to explain the interaction between Carlson's trophic index equations among others TSI (Chl-a)-TSI (SDD) and TSI (Chl-a)-TSI (TP) (Carlson and Havens, 2005), (Lin *et al.*, 2022). Data analysis involved firstly calculating the mean and standard deviation of the various physicochemical parameters selected as a function of hydrological regimes. The data obtained were then subjected to the Shapiro-Wilk normality test and Bartlett's variance homogeneity test, in order to decide which mean comparison test to use. Afterwards, the calculated means were compared using robust ANOVA at the 5% significance level (Mangiafico, 2015). In addition, Spearman's correlation test was used to verify the relationship between the physicochemical parameters of the water and the values of the trophic state index. All statistical analyses of the data were carried out using R software version 4.2.3.

Table 2. Interpretation of Carlson trophic state index values (Carlson and Simpson, 1996).

TSIC	Trophic degree	Attributes
< 30	Oligotrophic	Clear water, oxygen throughout the year in the hypolimnion
30-40	Oligo-mesotrophic	Hypolimnia of shallower lakes may become anoxic
40-50	Mesotrophic	Water moderately clear; increasing probability of hypolimnetic anoxia during summer
50-60	Meso-eutrophic	Anoxic hypolimnia, macrophyte problems possible
60-70	Eutrophic	Blue-green algae dominate, algal scums and macrophyte problems
70-80	Hypereutrophic	Dense algae and macrophytes. Light limited productivity
> 80	Hyper-hypereutrophic	Algal scums, few macrophytes

Table 3. Interpretation of water turbidity from Secchi depth values (Mnyango *et al.*, 2022)

Parameter	Highly Turbid	Turbid	Clear
Secchi disk depth (m)	<0.2	0.2-0.8	>0.8

3. Results and Discussion

3.1 Water physicochemical characterization in the Lake Nokoué

The results presented in **Table 4** show the variations in physicochemical parameters of the water in Lake Nokoué as a function of hydrological regime. Significant variations were observed in all parameters. Apart from the depth of Lake Nokoué, the other physicochemical parameters showed highly significant differences in terms of hydrological regimes (p-value<0.05).

The maximum mean values for Water depth (2.95±2.07 m), Chlorophyll *a* (27.41±15.52 µg.L^{-1}) and Total phosphorus (0.16±0.07 mg/L) were obtained during the high water, and minimum mean values were observed during the low water (2.20±1.87 m, 12.58±9.90 µg.L^{-1} and 0.08±0.03 mg/L respectively). Conversely, maximum mean values for Secchi depth (1.01±0.32 m), Temperature (30.62±0.92 °C), pH (2.20±1.87), Dissolved oxygen (5.56±1.48 mg/L), Salinity (20.14±6.44 PSU), Ammonium (1.50±0.91 mg/L) and Total nitrogen Kjeldhal (16.17±3.53 mg/L) were recorded during the low water, and minimum mean values were observed during the high water (6.52±1.10, 2.56±1.08 mg/L, 0.23±0.24 PSU, 0.17±0.07 mg/L and 9.98±6.39 mg/L respectively) with the exception of Secchi depth (0.60±0.34 m) and Temperature (28.02±1.19 °C), which were observed during the slight rise water. Finally, the maximum mean values for Suspended solids (28.12±32.28 mg/L), Turbidity (38.76±48.52 NTU), Nitrite (0.08±0.05 mg/L), Nitrate (12.94±7.59 mg/L) and Phosphate (0.25±0.19 mg/L) were observed during the slight rise water, and minimum mean values were obtained during the low water (8.35±7.94 mg/L, 5.92±5.66 NTU and 0.17±0.07 mg/L) with the exception of Nitrite (0.05±0.01 mg/L) and Nitrate (7.36±2.41 mg/L), which were observed during the high water.

From an ecological functioning, Lake Nokoué is a coastal lagoon located in the heart of urban areas in the heart of the urban agglomeration. It is influenced by both natural factors and anthropogenic actions that affect its ecological functioning in one way or another, in particular water quality and biodiversity. The observed fluctuation in depth is explained on the one hand by the drought of the long dry season, which increases evaporation and reduces the flow of its main freshwater tributaries, notably the Ouémé and Sô rivers, during the low water period, and on the other hand by the local rainfall of the short rainy season at the end of August, during the slight rise in water levels and the freshwater inflow from its tributaries, as well as bottom abrasion during the high-water regime. According to Colleuil (1987), the depth of Lake Nokoué varies from 0.5 to 1.5 m during low water and does not exceed 3 m in its basin. However, even greater depths, in excess of 10 m, can be observed in the Cotonou channel. Furthermore, the results obtained by Niyonkuru and Lalèyè (2010) on the depth of Lake Nokoué show that it fluctuates between 0.4 and 3.4 m, with an average annual variation of 1.20 m. Sintondji *et al.* (2022) pointed out in their study that local rainfall is not the cause of the flooding observed on Lake Nokoué, as it begins after the main rainy season, precisely in June, but rather the waters of its tributaries, mainly the Ouémé and Sô rivers, during the period from August to November.

Table 4. Variation of water physicochemical parameters in Lake Nokoué as a function of the hydrological regime. PSU: Practical Salinity Units, Sign: Significance test, ***: p-value significance, ns: p-value no significance. The same letter on the mean values shows that there is no significant difference between the values

Parameters		**Hydrological regimes**			**F-val**	**Sign**
		Low water	**Slight rise water**	**High water**		
Depth (m)	Min-Max	0.84-8.05	0.97-8.15	1.31-9.28	2.36	ns
	Mean±Sd	2.20[a]±1.87	2.40[a]±1.89	2.95[a]±2.07		
Secchi Depth (m)	Min-Max	0.40-1.80	0.15-1.30	0.30-1.38	36.62	***
	Mean±Sd	1.01[a]±0.32	0.60 [b]±0.34	0.61[b]±0.24		
Suspended solids (mg/L)	Min-Max	2.00-42.00	2.00-124.00	1.00-41.00	18.18	***
	Mean±Sd	8.35[a]±7.94	28.12[b]±32.28	10.72[a]±7.00		
Turbidity (NTU)	Min-Max	1.31-29.90	2.44-184.00	3.71-54.40	18.98	***
	Mean±Sd	5.92[a]±5.66	38.76[b]±48.52	25.24[c]±14.06		
Temperature (°C)	Min-Max	29.27-33.65	26.49-30.70	28.40-33.70	85.63	***
	Mean±Sd	30.62[a]±0.95	28.02[b]±1.49	30.48[a]±1.19		
pH	Min-Max	6.07-7.98	5.90-7.31	5.13-8.91	19.94	***
	Mean±Sd	7.32[a]±0.35	6.79[b]±0.39	6.52[b]±1.10		
Dissolved oxygen (mg/L)	Min-Max	2.88-7.79	0.54-8.24	0.64-4.51	71.64	***
	Mean±Sd	5.56[a]±1.48	4.51[b]±1.57	2.56[c]±1.08		
Salinity (PSU)	Min-Max	5.30-32.70	0.05 -22.2	0.05-1.16	198.70	***
	Mean±Sd	20.14[a]±6.99	6.01[b]±6.79	0.23[c]±0.24		
Chlorophyll *a* (µg/L)	Min-Max	3.41-51.70	0.85-59.38	8.10-60.06	28.85	***
	Mean±Sd	12.58[a]±9.90	14.59[a]±12.23	27.41[b]±15.52		
Ammonium (mg/L)	Min-Max	0.08-3.96	0.05-1.85	0.03-0.38	82.03	***
	Mean±Sd	1.50[a]±0.91	0.67[b]±0.4	0.17[c]±0.07		
Nitrite (mg/L)	Min-Max	0.05-0.13	0.03 -0.27	0.03-0.09	21.31	***
	Mean±Sd	0.06[a]±0.01	0.08[b]±0.05	0.05[c]±0.01		
Nitrate (mg/L)	Min-Max	4.40-12.60	5.1-45.1	3.1-13.1	26.31	***
	Mean±Sd	9.83[a]±1.49	12.94[b]±7.59	7.36[c]±2.41		
Total nitrogen (mg/L)	Min-Max	11.36-24.94	9.17-23.19	1.51-22.44	31.89	***
	Mean±Sd	16.17[a]±3.53	15.90[a]±3.98	9.98[b]±6.39		
Phosphate (mg/L)	Min-Max	0.06-0.36	0.04-0.67	0.01-0.51	7.60	***
	Mean±Sd	0.17[a]±0.07	0.25[b]±0.19	0.25[b]±0.11		
Total phosphorus (mg/L)	Min-Max	0.04-0.15	0.05-0.28	0.06-0.36	29.97	***
	Mean±Sd	0.08[a]±0.03	0.11[b]±0.06	0.16[c]±0.07		

The minimum and maximum average depth values obtained in this study closely resemble those reported by Chaigneau *et al.* (2023), while being higher than those provided by Odountan *et al.* (2019). This disparity can be attributed to the fact that Odountan *et al.* (2019) did not take into account the depth of the Cotonou channel when calculating their averages. From an ecological functioning, Lake Nokoué is a coastal lagoon located in the heart of urban areas in the heart of the urban agglomeration. It is influenced by both natural factors and anthropogenic actions that affect its ecological functioning in one way or another, in particular water quality and biodiversity.

The observed fluctuation in depth is explained on the one hand by the drought of the long dry season, which increases evaporation and reduces the flow of its main freshwater tributaries, notably the Ouémé and Sô rivers, during the low water period, and on the other hand by the local rainfall of the short rainy season at the end of August, during the slight rise in water levels and the freshwater inflow from its tributaries, as well as bottom abrasion during the high-water regime. According to Colleuil (1987), the depth of Lake Nokoué varies from 0.5 to 1.5 m during low water and does not exceed 3 m in its basin. However, even greater depths, in excess of 10 m, can be observed in the Cotonou channel. Furthermore, the results obtained by Niyonkuru and Lalèyè (2010) on the depth of Lake Nokoué show that it fluctuates between 0.4 and 3.4 m, with an average annual variation of 1.20 m. Sintondji *et al.* (2022) pointed out in their study that local rainfall is not the cause of the flooding observed on Lake Nokoué, as it begins after the main rainy season, precisely in June, but rather the waters of its tributaries, mainly the Ouémé and Sô rivers, during the period from August to November. The minimum and maximum average depth values obtained in this study closely resemble those reported by Chaigneau *et al.* (2023), while being higher than those provided by Odountan *et al.* (2019). This disparity can be attributed to the fact that Odountan *et al.* (2019) did not take into account the depth of the Cotonou channel when calculating their averages.

Variations in Secchi depth, suspended solids and turbidity could be explained by the settling of suspended particles, which improves light penetration in the water column during low-water periods, and by the significant input of organic and mineral matter from the watershed and its freshwater tributaries, as well as the re-suspension of particles due to bottom abrasion during low water and high water periods. Leite (2001) states that the color of the water in the Lake Nokoué varies from brown to black, with transparency nowhere exceeding 1.25 m. For him, "transparency is a good parameter for tracing the evolution of fluvial currents in this Lake". The maximum transparency is observed at low water levels, when the salinity of the water determines the floculation of the clays, and minimum transparency rarely exceeds 30 cm during the floods associated with the Sô-Ouémé river complex. According to Baglo (1980) cited by Leite (2001), the turbidity of the Lake Nokoué during floods is explained by the suspension of materials brought by the Ouémé River, 90% of which are fine clay materials (lutites or pelites). Regarding transparency, the results obtained indicate average values slightly lower than those found by Sintondji *et al.* (2022) and Capo-Chichi *et al.* (2022), but remain slightly higher than the data from Odountan *et al.* (2019). The variations in suspended matter according to the hydrological regime are consistent with the observations made by Ntangyong *et al.* (2024), although the measured values are lower than those reported by them. Concerning turbidity, the results obtained are lower than those noted by Odountan *et al.* (2019), Chaigneau *et al.* (2023), Ntangyong *et al.* (2024). That of temperature is linked to the ambient temperature during sampling. Leite (2001) observed that temperature variations are much greater than seasonal variations. There is an average amplitude of 5°C (25.6 to 30.6°C) in the morning and an amplitude of 2°C (30 to 32°C) in the afternoon on Lake Nokoué. He affirms that the minimum temperature (26.2 to 27.5°C) is reached between August and October, then remains fairly high (28 to 31°C) throughout the rest of the year. Temperature fluctuations, averaging around 30°C, show a notable similarity with the results from Odountan *et al.* (2019), Capo-Chichi *et al.* (2022), Sintondji *et al.* (2022), Chaigneau *et al.* (2023). However, the average values observed are slightly higher than those reported by these authors.

The variations observed on the pH and dissolved oxygen are the result, on the one hand, of the intensity of phytoplankton photosynthesis during the low water regime and, on the other, of the excessive input of allochthonous organic matter from the watershed. Leite (2001) notes that the waters of Lake Nokoué are weakly alkaline (8.1 to 6.5). According to Agbohessi *et al.* (2023), pH changes with the seasons are perfectly synchronous throughout the complex, with a remarkable drop at the beginning of May, probably linked to the first rains, and at the end of August, due to the loading of the complex. Dersseh *et al.* (2020) assert that the eutrophic state induced by pollution leads to a decrease in dissolved oxygen content and the growth of macrophytes. The average values concerning pH demonstrate a similarity with those provided by Odountan *et al.* (2019), Sintondji *et al.* (2022). These results also overlap with those obtained by Odountan *et al.* (2019), Sintondji *et al.* (2022), Chaigneau *et al.* (2023). Salinity variation observed are due to the intrusion of salt water from the Atlantic Ocean during the low-water regime, and to freshwater inflows from local precipitation and watercourses, notably the Ouémé, Sô and Djonou rivers, during the slightly rising and high-water regimes respectively. Leite (2001) points out that the salinity of the lagoon complex fluctuates according to season and location, with areas close to the lagoon outlet showing very high values that decrease the further away from the outlet you are. He points out that desalination of the Porto-Novo lagoon is faster due to the low sodium chloride content of its water (0-17%) compared with Lake Nokoué. According to Mama *et al.* (2011) and Djihouessi *et al.* (2019), salinity increases from December to May during the low-water regime, decreases from June to August during the slight rise in water levels and desalination from September to November during the high-water regime on Lake Nokoué. The study of Okpeitcha *et al.* (2022) revealed that seawater intrusion into Lake Nokoué begins in December, at the bottom and south-west of the lake before spreading north-eastwards and mixing vertically to become homogeneous; then, it is only from May onwards that desalination of the lake begins from the north-east to gradually reach the south-west, which remains ever more so; finally, complete desalination of the lake is often observed from August until November. In addition, their elaborate model revealed that around 30% of the salty water from the Atlantic Ocean enters Lake Nokoué during high tides and remains trapped, increasing the lake's salinity. However, complete desalination occurs when river discharge exceeds around 50-60 m^3/s. Sintondji *et al.* (2022) assert that the observed Salinity variation in Lake Nokoué are potentially the cause of the wide fluctuation in its physicochemical parameters. This also applies to the results obtained on both Lake Nokoué.

The variations in nutrients obtained could be explained by the denitrification of organic matter during the low water regime, the runoff of urban wastewater into the complex during the low water regime, the input of inorganic nutrients mainly from agricultural activities in the Ouémé lower valley, and the resuspension of nutrients trapped in the sediment from bottom abrasion during the high-water regime. Mama *et al.* (2011) and Odountan *et al.* (2019) have shown that there is strong mineralization of organic matter with release of phosphorus from December to May during the low water regime, and a significant input of inorganic nutrients from September to November during the high water regime. Sintondji *et al.* (2022) speculated that the release of waste and nutrients and the decomposition of water hyacinth and materials used in the construction of acadjas lead to a decrease in dissolved oxygen, a change in pH and the filling of Lake Nokoué. Dersseh *et al.* (2020) noted that the tributaries of Lake Tana in Ethiopia had higher phosphorus and nitrogen concentrations during the rainy season than during the dry season. However, the opposite was observed for total phosphorus content in this lake, due to the high residence time and wind-induced resuspension and increased water temperature during the dry season. The spatial fluctuations of chlorophyll-a concentrations related to the hydrological regime can be attributed to the level of photosynthetic activity of phytoplankton within the lake. This observed increase during the flood period is explained by a rise in phosphorus concentration in the environment, a nutrient essential for phytoplankton proliferation. Regarding chlorophyll a, the average values are almost similar to those provided by (Chaigneau *et al*., 2023).

3.2 Spatial variation of trophic state in the Lake Nokoué as a function of hydrological regime

Eutrophication results show that Lake Nokoué is eutrophic. However, there are spatial variations in trophic state depending on the hydrological regime. With trophic state index values ranging from 54.04 to 66.20 during the low water, almost all stations were in the meso-eutrophic state, except for the Zogbo (N2), which reached the eutrophic state (**Figure 2**). After, trophic state index values ranging from 55.83 to 67.00 during slight rise water showed that the majority of stations had reached eutrophic status, with the exception of Lake center (N4), Cotonou Channel (N5) and Dékamnè (N6) (**Figure 3**).

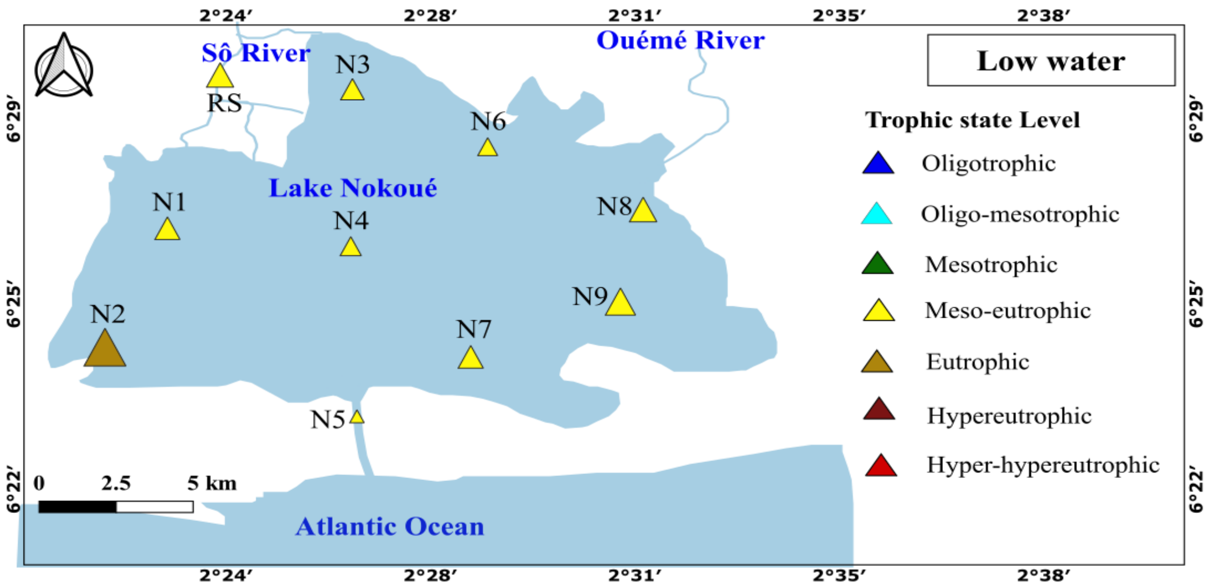

Figure 2. Spatial variation of trophic state in Lake Nokoué during Low water period. RS : Sô-Ava, N1 : Calavi, N2 : Zogbo, N3 : Vèkky, N4 : Lake Center, N5 : Cotonou Channel, N6 : Dékamnè, N7 : Agbato, N8 : Aguégué and N9 : Tchonvi

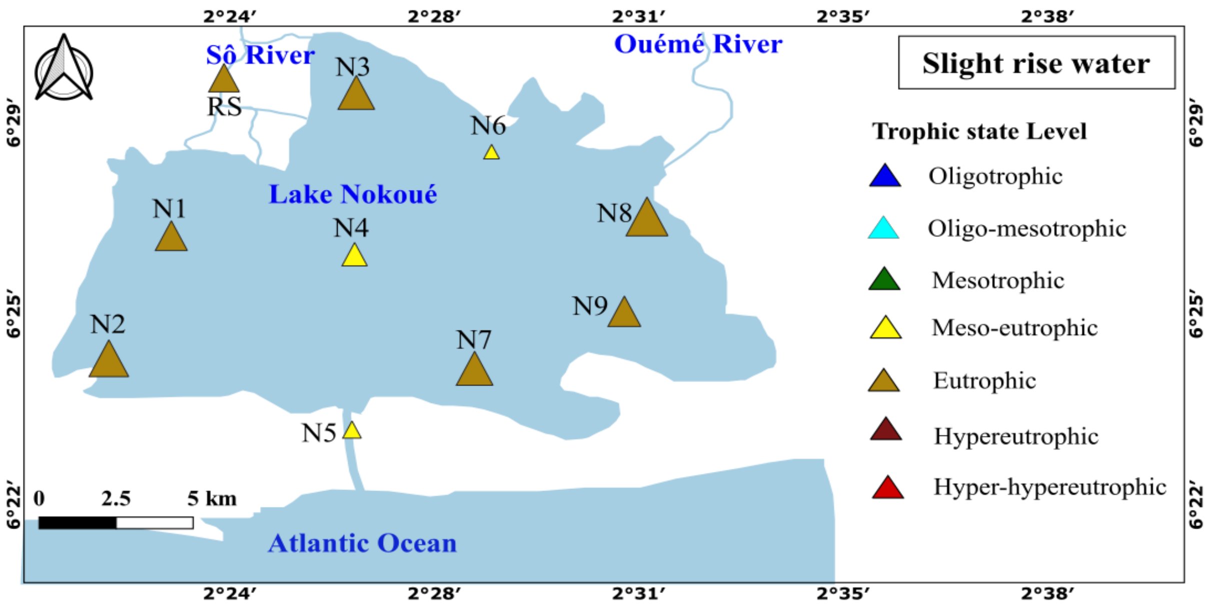

Figure 3. Spatial variation of trophic state in Lake Nokoué during Slight rise water period

Finally, trophic state index values fluctuating between 59.89 and 71.73 during the high water indicate that most stations were eutrophic, with the exception of the Center Lake, which maintained its meso-eutrophic state, while the Cotonou Channel and Agbangandan (N7) reached the hypereutrophic state (**Figure 4**). With regard to water transparency in this Lake (**Figure 5**), the water at most stations was clear, except for Zogbo (N2) and Aguégué (N8), which appeared turbid during the low water. However, during the slightly rising and high water, water became turbid at almost all stations, with the exception of Center Lake and Dékamnè, which were clear.

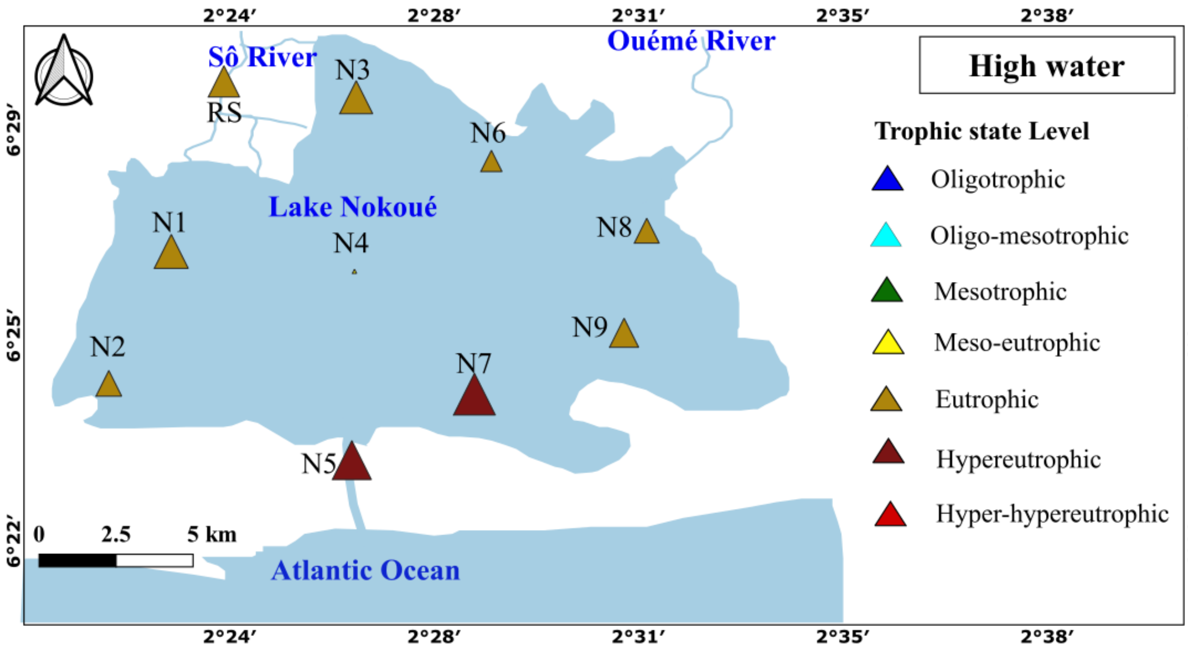

Figure 4. Spatial variation of trophic state in Lake Nokoué during High water regime

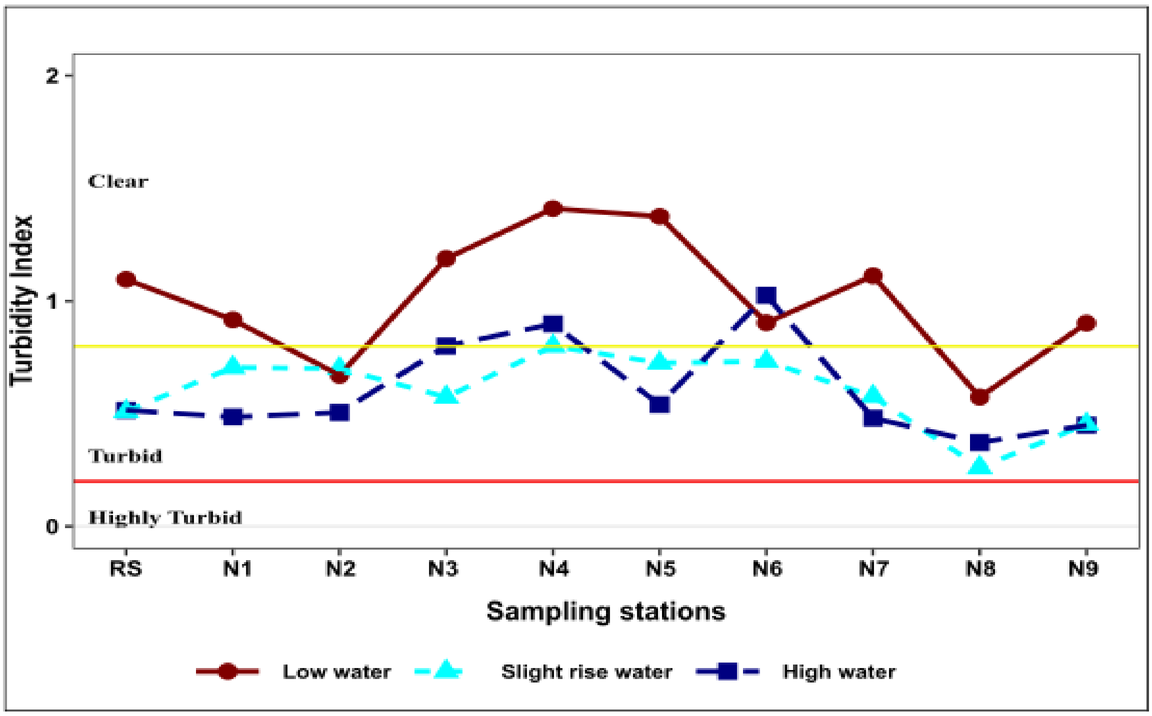

Figure 5. Water transparency spatial variation in the Lake Nokoué as a function of the hydrological regime

With regard to the deviation of the trophic state index, **Figure 6** shows that 85% of the eutrophication of Lake Nokoué is due to phosphorus, while suspended fine particles are responsible for the increase in water turbidity, hence influencing the eutrophication phenomenon.

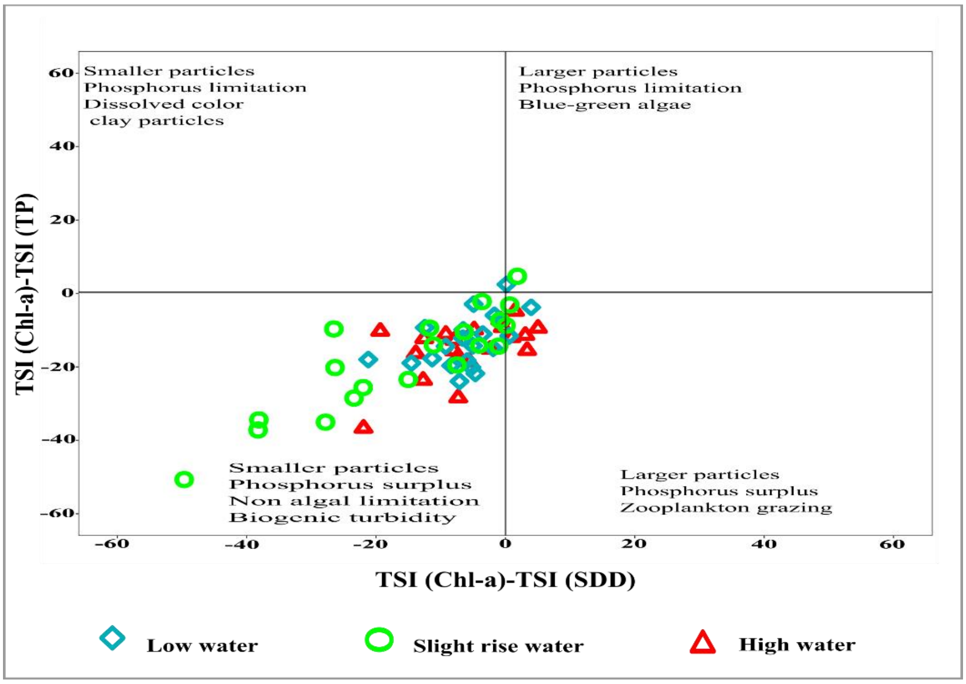

Figure 6. Scatterplot of Trophic state deviation for Secchi depth, Total phosphorus and Chlorophyll-a in the Lake Nokoué and Porto-Novo lagoon as a function of hydrological regime

Shallow water bodies with reduced surface area are more sensitive to environmental change linked to rising water levels, nutrient inputs and human management (Cuevas-Madrid *et al.*, 2020). For water quality management, several authors have used Carlson's trophic state index to assess their level of eutrophication (Dersseh *et al.*, 2020), (Jargal *et al.*, 2021), (Lin *et al.*, 2022), (Mnyango *et al.*, 2022).

The Lake Nokoué is faced with both point-source and nonpoint-source pollution linked to human activities, notably the establishment of lakeside villages and acadja fishing on Lake Nokoué, agriculture in the lower Ouémé valley, sand extraction and uncontrolled urbanization. This pollution, particularly organic pollution, is at the root of the eutrophication of the complex. Yehouenou *et al.* (2013) noted that pollution of the Lake Nokoué is essentially linked to the regular discharge of wastewater from gutters and residues from surrounding towns, making it a receptacle for pollutants due to its geographical position. The dispersion of pollutants in Lake Nokoué results from surface runoff of wastewater from anthropogenic activities (Deguenon *et al.*, 2021). For Vinh *et al.* (2022), urban lakes are mainly exposed to pollution, eutrophication and algal bloom as a result of waste dumping and wastewater runoff from urban environments. The observed dynamics of eutrophication in this complex are the result of variations in the physicochemical parameters of the water as a function of hydrological regime.

The trophic status levels obtained eutrophic on Lake Nokoué bear further witness to the influence of human actions on the ecological functioning of this Lake. This reveals that Lake Nokoué is subject to more anthropogenic pressures, including the establishment of lakeside villages on the lake, traditional acadja fishing, the inflow of pollutant-laden water from tributaries and the existence of the large markets of kpota in Abomey-Calavi and Dantokpa in Cotonou. Dersseh *et al.* (2020) also observed the spatial and seasonal dynamics of eutrophication in Lake Tana in Ethiopia, induced by internal and external nutrient inputs. For Peng *et al.* (2023), improvement in Lake Eutrophication can be considerably slowed even if external inputs are monitored, as a result of internal loading. Djihouessi *et al.* (2021) noted that point-source nutrients responsible for pollution are trapped during the low-water regime at the bottom of Lake Nokoué. The reduction in allochthonous input and the trapping of nutrients would explain the meso-eutrophic state observed at almost all sampling stations during low water. Our results obtained disagree with their assertion that the trophic state changes from eutrophic to mesotrophic during flooding due to the leaching of polluted water from Lake Nokoué into the Atlantic Ocean. The eutrophic state achieved by the Zogbo station on Lake Nokoué could be justified by the input of organic matter from houses built on stilts and materials used in the manufacture of acadjas at the Zogbo. The resuspension of phosphorus deposited at the bottom of Lake in the sediment during the rainy season, or the degradation of waste at the bottom of the lake, is the source of phosphorus during the dry season (Dersseh *et al.*, 2020). The change from meso-eutrophic to eutrophic state for the majority of Lake Nokoué stations during light rise and high-water regimes would be mainly linked to the significant input of organic and mineral matter from the watershed and its freshwater tributaries, and to the resuspension of nutrients due to bottom abrasion and the marked reduction in dissolved oxygen. Apart from these inputs, the transition from eutrophic to hypereutrophic conditions would result from the direct discharge of water laden with inorganic pollutants from the Dantokpa market and the city of Cotonou.

The results obtained on the eutrophic state of the majority of Lake Nokoué stations converge with those obtained by Mama *et al.* (2011) and Djihouessi (2018) but diverge from those obtained by (Capo-Chichi *et al.*, 2022) who obtained the hypereutrophic state during all their studied period. This discrepancy is justified by the OECD method used by Capo-Chichi *et al.* (2022) to assess eutrophication, which is not highly recommended for reservoirs and lakes. The trophic level index and trophic state index (TLI and TSI) methods are recognized for assessing eutrophication in lakes and reservoirs (Zhang *et al.*, 2021).

With regard to deviations in the trophic state index, the results obtained are similar to those obtained by Lin *et al.* (2022) on the various reservoirs in Taiwan and Madyouni *et al.* (2023) on the Joumine reservoir in Tunisia, whose turbidity is linked to fine suspended particles containing phosphorus, but different to those obtained by Jargal *et al.* (2021) on the Yongdam Reservoir in Korea, whose eutrophication is linked to the proliferation of blues and green algae with large particles and phosphorus limitation. According to Carlson and Havens (2005), there is a relationship between phosphorus and transparency when TSI (SDD) and TSI (TP) values are higher than those of TSI (chl *a*). Light penetration in the water column is attenuated by non-algal turbidity consisting of particles containing phosphorus of organic or inorganic origin, but not chlorophyll *a*. Lin *et al.* (2022) claim that the influence of large particles on algal growth is insignificant with regard to non-algal turbidity. To reduce eutrophication in Lake Nokoué, it is important to reduce the internal and external loads of organic and inorganic matter responsible for it.

Conclusion

This study showed the spatial variation of water physicochemical and trophic state in the Lake Nokoué as a function of the hydrological regimes observed. The increase from Suspended solids, Turbidity, Nitrite, Nitrate and Phosphate values results from the re-suspension of settled particles and nutrients trapped in the sediment, as well as from the runoff of organic and inorganic particle-laden wastewater from the watershed during slight rise water and high water. The increase from Water depth and Chlorophyll a is due to the inflow of freshwater from local precipitation and especially from its main tributaries, namely the Ouémé, Sô and Djonou rivers, followed by the invasion of water hyacinths, which increase photosynthetic activity and prevent air dissolution. With regard to the dynamic of the trophic state of the complex, the eutrophication was observed from Lake Nokoué linked to the degree of pollution in this ecosystem. The trophic state variation as a function of hydrological regimes results from the variations observed in physicochemical parameters during this study. The observed eutrophication results from an excessive enrichment of phosphorus in the Lake. It is characterized by non-algal turbidity, specifically due to the presence of fine suspended particles. It is therefore essential to determine the influence of the dynamics of this eutrophication on biodiversity, in particular benthic macroinvertebrates, in order to implement effective strategies to reduce pollution and ensure the sustainable use of the resources and services of this Lake.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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