



Spatio-temporal dynamics of nutrients at the water-sediment interface: case of the Nokoue lagoon in Southern Benin

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Abstract Lake Nokoué, a major component of the hydrographic system of the Ouémé delta, is the largest lagoon-estuarine ecosystem in Benin. Recent studies have shown that benthic processes would actively participate in the maintenance of the eutrophication and biogeochemical cycle of this ecosystem. In order to understand the implication of the bottom on the quality of the waters of the lake, a monthly follow-up of ten (10) parameters of quality of the waters of the bottom was undertaken from July 2020 to December 2021 on a network of nineteen (19) stations distributed on the whole lake. Univariate and multivariate

analysis techniques were used to assess the spatial and temporal dynamics of these waters. The Kruskal–Wallis test, PCA, correlation analysis and discriminant analysis all showed a very marked influence of the hydrological regime on the concentration of nutrients compared to the influence of anthropogenic activities around the lake and an influence of climatic conditions on internal processes. Indeed, water inflows from the Ouémé watershed are the main contributors of phosphorus in the lake while benthic processes are the most important contributors of nitrogen. Cluster analysis defined three significantly different areas in Lake Nokoué: the channel, the centre of the lake and the river mouth. A single station in each cluster could be used for a spatial assessment of water quality over the entire lake.

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Introduction

Eutrophication is now the second greatest global threat to aquatic environments, after climate change (Boutaud & Gondran, 2020; Couture et al., 2018; De Jonge et al., 2002; Paerl & Paul, 2012; Souchu et al., 2018). It is mainly linked to an uncontrolled increase in anthropogenic activities and is the cause of environmental crises of various kinds: anoxia, toxic algal blooms, uncontrolled proliferation of macrophytes, chemical and biological contamination (from pathogenic species, invasive species) (Chapelle et al., 1994; Malone et al., 1986; Peppas et al., 2020; Smith & Schindler, 2009). The environmental problems generated by eutrophication compromise the health of aquatic ecosystems with consequences for biodiversity and biogeochemical functioning. These problems also compromise the goods and services provided by these aquatic ecosystems to the local populations (Pinay et al. 2017; Nobre et al., 2005) with direct and indirect consequences on the social, cultural and economic activities of these populations. It, therefore, seems appropriate for decision-makers to take measures to prevent the eutrophication of water bodies. In the case where these ecosystems are already affected by eutrophication, the measures to be taken should allow for a gradual return to “natural” functioning. This idea led to the concept of preservation and trophic restoration of rivers and water bodies at the end of the 1990s (Jeppesen et al., 2005; Søndergaard et al., 2003).

The restoration of aquatic ecosystems affected by eutrophication requires the control of nutrient inputs, particularly nitrogen (N) and phosphorus (P), which have been identified as the main limiting elements for primary production (Carpenter, 2008; Conley et al., 2009; Duarte et al., 2009; Howarth & Marino, 2006; Malone et al., 1996; Schindler, 2012). Most European and North American countries have been very aware of this situation since the 1980s and have focused their efforts on wastewater collection and treatment to reduce N and P inputs to rivers and lakes (Crouzet, 1983; Hale et al., 2015; Van Drecht et al., 2009). Thus, in these countries, the multiplication of wastewater treatment plants, the improvement of wastewater treatment and the progressive banning of nutrient-rich products such as polyphosphates in laundry detergents have made it possible to reduce N and P flows in aquatic ecosystems and to progressively

improve their trophic status (Billen et al., 2007; Howden et al., 2010; Minaudo et al., 2019). However, the results of these measures in certain ecosystems, particularly coastal ecosystems, remain mixed and in some cases algal blooms occur quite regularly (Aissa Grouz Jerbi, 2015; Duarte et al., 2009; Jeppesen et al., 2007; Minaudo, 2015).

In developing countries, especially those on the tropical fringe, the situation is very different from that of the countries of the North. Measures to control and reduce nutrient pollution in these countries are still almost non-existent (Le et al., 2015). Indeed, the development of sanitation networks in the large cities of these countries does not sufficiently accompany the population increase (Trinh et al., 2012), with the direct consequence of untreated domestic wastewater being discharged into the receiving aquatic environment, resulting in high levels of organic and nutrient pollution. Moreover, in parallel with urban growth, the evolution of agricultural practices requires ever-increasing quantities of fertilizers and ever-larger areas of land. This leads to deforestation and the subsequent leaching and runoff of large amounts of nutrients into waterways. The situation is even more alarming in the coastal ecosystems of West Africa, which, in addition to the intense pressure of population growth and urbanisation, are under increasing pressure from climate change (Dada et al., 2021).

In West Africa, almost 80% of the countries' economies are based on the coastal strip, exposing ecosystems to serious pollution problems including eutrophication (Dada et al., 2021; Diaz & Rosenberg, 2008). Among these ecosystems, the situation of Benin's Nokoué coastal lagoon (commonly known as Lake Nokoué) is all the more interesting as it lies at the heart of a highly urbanised area, and is of major economic and tourist importance for the country. Indeed, Lake Nokoué contributes to the well-being of more than 500,000 inhabitants and hosts one of the most visited tourist sites (the stilt village of Ganvié). Its fisheries production is an important part of Benin's gross domestic product (GDP). Most ecological studies conducted on this water body have shown that it is threatened by eutrophication, resulting in a significant drop in dissolved oxygen levels and excessive proliferation of water (Djihouessi & Aina, 2018; Gnohosou, 2006; Lalèyè, 2000; Mama, 2010; Negusse & Bowen, 2010; Zandagba et al., 2016). At low water level, water hyacinth plants that do not support the

rise in salinity in the lake, die and settle to the bottom of the lake to constitute an additional source of nutrients. The establishment of the N and P balance of Lake Nokoué has shown that nutrient salt inputs are not sufficient to justify the high productivity of this ecosystem (Djihouessi et al., 2021). The water–sediment interface being an ultimate deposition zone for all particulate organic and inorganic material that sediments in the water column (Henrichs, 1992; Smith & Hollibaugh, 1993), it is strongly suggested that a large part of the nutrients available for eutrophication come from internal sources, notably degradation and resuspension of respectively organic and inorganic matter from the sediments (Djihouessi et al., 2021). Surface sediments, in addition to their primordial importance in the process of degradation of organic matter (Bernier, 1980; Jørgensen, 1996) play a significant role in enriching the water column with nutrients and therefore in maintaining eutrophication. Thus, the sediments of aquatic ecosystems are the compartment in which the highest environmental concentrations of pollutants can be found (50 to 500 times higher than that of the water column according Henderson-Sellers et al., 1993; Yi et al., 2011). The verification of such a hypothesis would require a good knowledge of nutrients dynamics at the water-sediment

interface of Lake Nokoué. On this subject, the literature reveals a significant information deficit that extends to the majority of West African coastal ecosystems. Thus, the present study responds to a need to fill the gaps and improve knowledge on water quality at the water–sediment interface of Lake Nokoué in order to better understand the mechanisms that promote eutrophication in this system and in West African coastal lagoons. More specifically, the study aimed to describe the spatio-temporal variation in the nutrient content of the bottom waters of Lake Nokoué, in order to assess the potential contribution of sedimentary layers on the nutrient enrichment of the water column. This constitutes the starting point for the formulation of effective restoration measures for this water body.

Materials and methods

Study area

Lake Nokoué (6°20' and 6°30' North and 2°20' and 2°35' East) is located in the South-East of the Republic of Benin (Fig. 1) in the sub-equatorial climate zone. In this climate zone, the temperatures

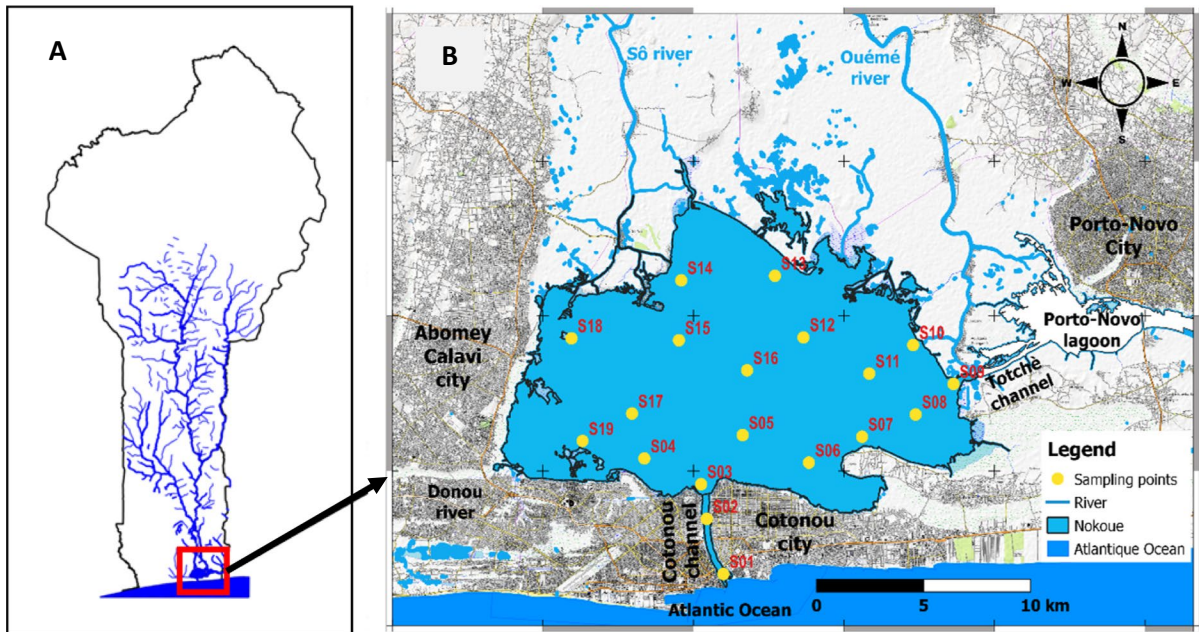


Fig. 1 Presentation of the Ouémé (A) and Lake Nokoué (B) watersheds with sampling stations in yellow

between 26 and 34°C and average annual rainfall of about 1200 mm. With an area of about 150 km² at low water, it is the largest coastal lake in West Africa (Petrequin & Johnson, 1984) and is located in the centre of a highly urbanised area with a population of over 2,500,000 (INSAE-Benin, 2016). Lake Nokoué has the particularity of being home to several lakeside villages built on stilts (nearly 100,000 inhabitants), and of being more than 60% covered by Acadjas (parks of branches imported from the land and artificially planted in the muddy bottom of the lake to attract fish and shellfish) (Negusse & Bowen, 2010).

The hydrological regime of Lake Nokoué is quite particular. Water levels in the lake are very slightly influenced by the local season (or precipitation). Rather, they are more influenced by precipitation falling on the Ouémé basin (about 45,000 km²), of which the lake is the outlet. Consequently, three main periods characterised the hydrological regime of Lake Nokoué. A period of low water from December to mid-May; followed by a slight rise in water caused by heavy local rainfall around the lake from June to August; and finally, a period of high water from September to November governed by the descent of rainwater from the Ouémé watershed which covers an area of over 45,000 km² (Djihouessi et al., 2021; Le Barbe et al., 1993; Texier et al., 1979). The bottom of Lake Nokoué is largely muddy, especially in the western and northern parts where the seasonal decimation of the water hyacinth and the strong practice of Acadjas have increased deposits of detritus (Kaki et al., 2011).

Data collection

Data on the water quality of the bottom of Lake Nokoué were collected monthly at 19 stations (Fig. 1) over the period from July 2020 to December 2021. This period covers a full hydrological cycle, and a full period of high water, which is the period of greatest sediment deposition from the watershed (Djihouessi et al., 2021). The selection of the collection locations is based on a combination of criteria including spatial representativeness of all areas of the lake through analysis of the results of previous studies (Djihouessi & Aina, 2018; Djihouessi et al., 2021; Mama et al., 2011) and accessibility of the identified points.

In situ water quality measurements and water sampling were carried out at the bottom of the lake at 20 cm above the sediments. In situ water quality measurements and water sampling were carried out at 20 cm above the bottom lake sediments using a sampler fitted with a hose and pump. This is mainly to be able to capture the water quality near the sedimentary layer without provoking disturbance or physical sediment resuspension (Grenz et al., 2019; Ratmaya et al., 2022). The parameters measured in situ were pH, temperature, salinity and dissolved oxygen, using a WTW-Multi 3630 multi-parameter connected to a MPP 930 profiler module and a Valeport CTD. At each station, 500 ml of water was collected, 250 ml of which is filtered immediately in the field using 0.7-µm pore size membranes, and 250-ml unfiltered. After filtration, the membrane was placed in the

Table 1 Statistical analysis of water quality parameters at the bottom of Lake Nokoué

Parameters	Descriptive statistics							SW-T	SW-T LogT	SW-T IT
	<i>n</i>	Mean	Sd	Med	Min	Max	SE	<i>p</i> value	<i>p</i> value	<i>p</i> value
Temp (°C)	323	28.8	1.7	29.3	24.2	32.2	0.1	3.82E-07	1.1E-07	2.35E-08
pH	269	7.54	0.46	7.67	6.02	8.24	0.03	2.21E-10	1.8E-11	1.44E-12
Sal	323	11.05	11.98	3.95	0.00	35.30	0.68	2.20E-16	2.20E-16	
Turb (FTU)	323	39.91	58.41	15.36	0.08	362.07	3.26	2.20E-16	3.73E-05	2.20E-16
N_NO2 (µg/L)	323	6	12	3	0	116	1	2.20E-16	1.27E-11	
N_NH4 (µg/L)	323	94	77	64	9	470	4	2.20E-16	0.002219	2.20E-16
NT (mg/L)	323	12.3	5	10.9	0.1	33.1	0.4	2.20E-16	2.20E-16	2.20E-16
PT (µg/L)	323	139	81	115	9	521	5	7.43E-16	0.000662	2.20E-16
P_PO4 (µg/L)	323	49	31	43	1	167	2	6.14E-16	9.21E-09	2.20E-16
Chla (µg/L)	152	16	11	12	1	66	1	2.31E-14	0.01332	2.20E-16

SW-T Shapiro–Wilks test; SW-T LogT Shapiro–Wilks test after logarithmic transformation; SW-T IT Shapiro–Wilks test after inverse transformation, *n* number of observations

filter holders, and the filtrate was collected in polystyrene plastics. The filter holder assembly containing the membranes and the filtered and unfiltered samples were stored at 4°C and then transported to the laboratory for measurement of chlorophyll-a, nitrite, ammonium, orthophosphate, total nitrogen and total phosphorus following standard methods presented in (Baird et al., 2017).

In the end, the database consisted of 10 water quality parameters and 323 observations. Chlorophyll was measured seasonally and included 152 observations and pH included 269 observations (see Table 1).

Data processing and analysis

The exploratory analysis of the database was carried out for each variable by calculating the position and dispersion parameters. The creation of boxplots according to the location of the sampling stations and the dates of sampling allowed an overall assessment of the spatial and temporal distribution of each variable. The boxplots were also used to detect extreme values and the Grubbs test was carried out to check whether these values could be considered as outliers. Thus, outliers were detected for orthophosphate, nitrite, total nitrogen and chlorophyll-a; they were replaced by the mean value of the month and the boxplots reconstructed. The Shapiro–Wilks test is performed to test the normality of the different water quality parameters. The implementation of this test revealed that the observations do not follow a normal distribution even after a logarithmic transformation and an inverse transformation (Table 1). Thus, the analyses carried out thereafter take into account the non-parametric tests when necessary.

To better understand the relationship between the 10 water quality parameters studied and the key processes governing their dynamics, Pearson correlation analysis, principal component analysis (PCA), and cluster analysis (CA) (Gradilla-Hernández et al., 2020; Singh et al., 2004) were performed. PCA was used to extract significant principal components to reduce the dimensionality of the data with minimal loss of information. CA was applied to cluster similar sampling stations and determine their biogeochemical characteristics (major processes taking place) using Ward's method, and Euclidean distances as a

measure of similarity. The clustering tendency was evaluated by the Hopkins statistic in order to verify whether the data contain an inherent clustering structure. The value obtained ($0.6 > 0.5$) indicates that the data are prone to clustering. The optimal number of clusters was determined using the linkage distance $(D_{link}/D_{max}) * 100$, which represents the quotient between the linkage distances for a particular case divided by the maximum distance. Furthermore, it should be noted that PCA and CA were applied to the standardised data in order to eliminate the influence of different units of measurement and make them dimensionless.

The spatial and temporal variation of the studied parameters were examined separately by the non-parametric Kruskal–Wallis test of variance and the discriminant analysis (DA) with respectively the location of the stations and the date of sampling as grouping factors. When a significant effect was observed for a parameter with the Kruskal–Wallis test (i.e. $p < 0.05$), a pairwise comparison was performed by Dunn's post hoc test. The DA was applied to the raw data using standard mode, stepwise forward and stepwise backward modes to construct discriminant functions. The standard mode takes into account all available information and ensures that the variables are statistically relevant after processing. For the stepwise mode, variables are added starting with the most significant (stepwise forward mode) or removed starting with the least significant (stepwise backward mode) until no significant change is obtained. At each step, a test of significance (Lambda Wilks test) was used to validate the operation (Gradilla-Hernández et al., 2020). At the end of the process, only the parameters that were important to the construction of the model, i.e. those that contributed most to discriminating between the groups, were retained. Of the 323 observations, three quarters were randomly selected and used for modelling and the remaining quarter for prediction. The sampling stations (spatial) and the periods of the hydrological regime (temporal) were the grouping (dependent) variables, while all measured parameters were the independent variables.

All statistical analyses were performed in R version 4.1.3 (R Core Team, 2022).

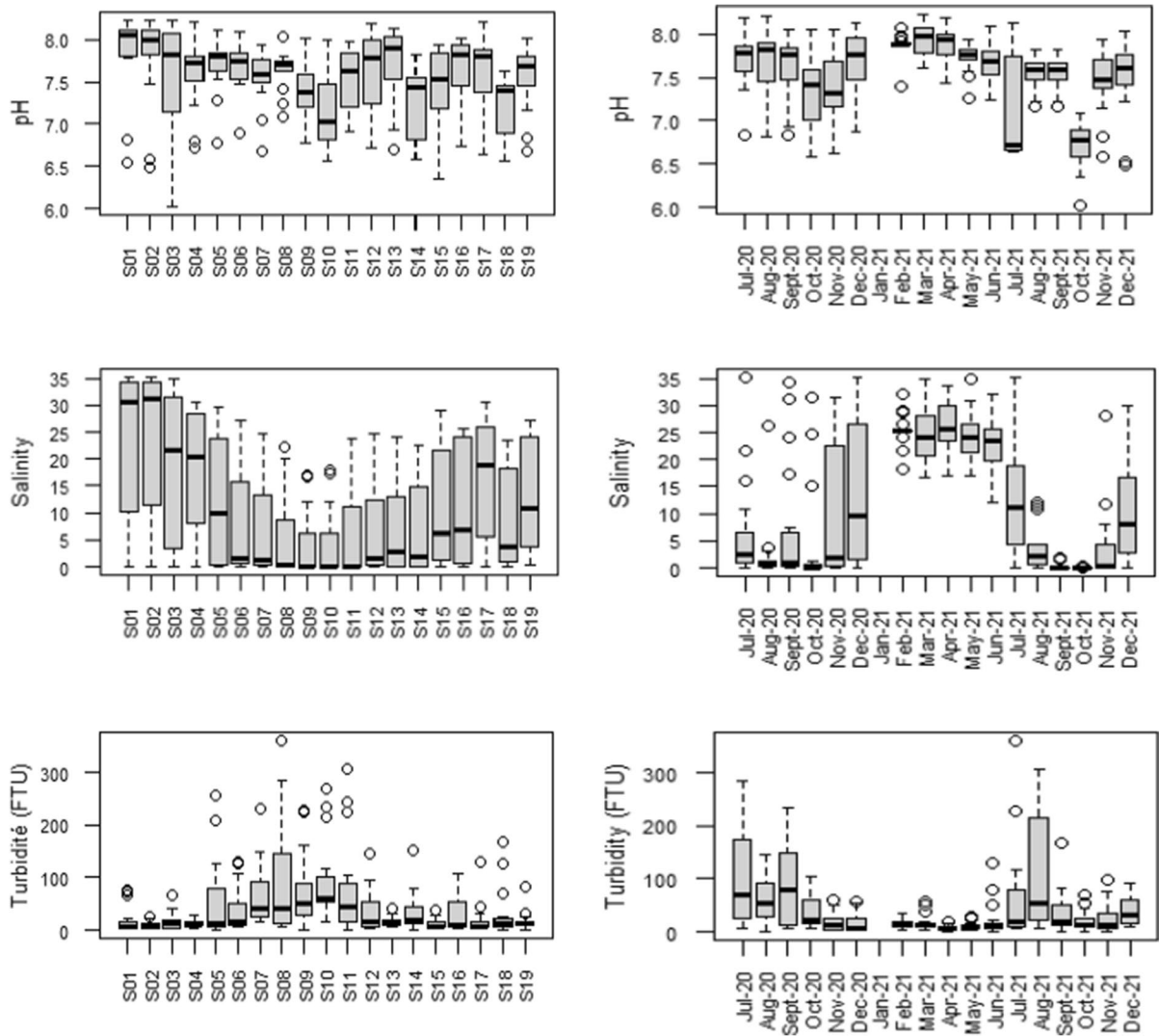


Fig. 2 Spatio-temporal distribution of physico parameters in the bottom waters of Lake Nokoué

Results and discussion

Physicochemical parameters distribution

The overall characteristics of the bottom waters of Lake Nokoué over the period from July 2020 to December 2021 are presented in the form of summary tables and boxplots (Table 1, Figs. 2 and 3). Over the 2020–2021 seasons, the bottom waters of Lake Nokoué showed temperatures between 24.2 and 32.2°C with an average of 28.8°C (Table 1). These temperatures were very close to the atmospheric temperatures recorded at the surface of the lake, indicating the

influence of climatic conditions on the entire water column of Lake Nokoué down to the sedimentary layer. This could be explained by the shallow depth of the system (less than 2 m). The pH values recorded ranged from 6.02 to 8.24 with an average pH of 7.54 (Table 1), indicating that the bottom waters of Lake Nokoué are slightly alkaline. The highest pH values were recorded in the South of the lake and a decreasing longitudinal gradient is observed in both the South-East and South-West axes (Fig. 2). This suggests that the inflow of water from the tributary rivers would lead to a decrease in the pH of the bottom waters of Lake Nokoué.

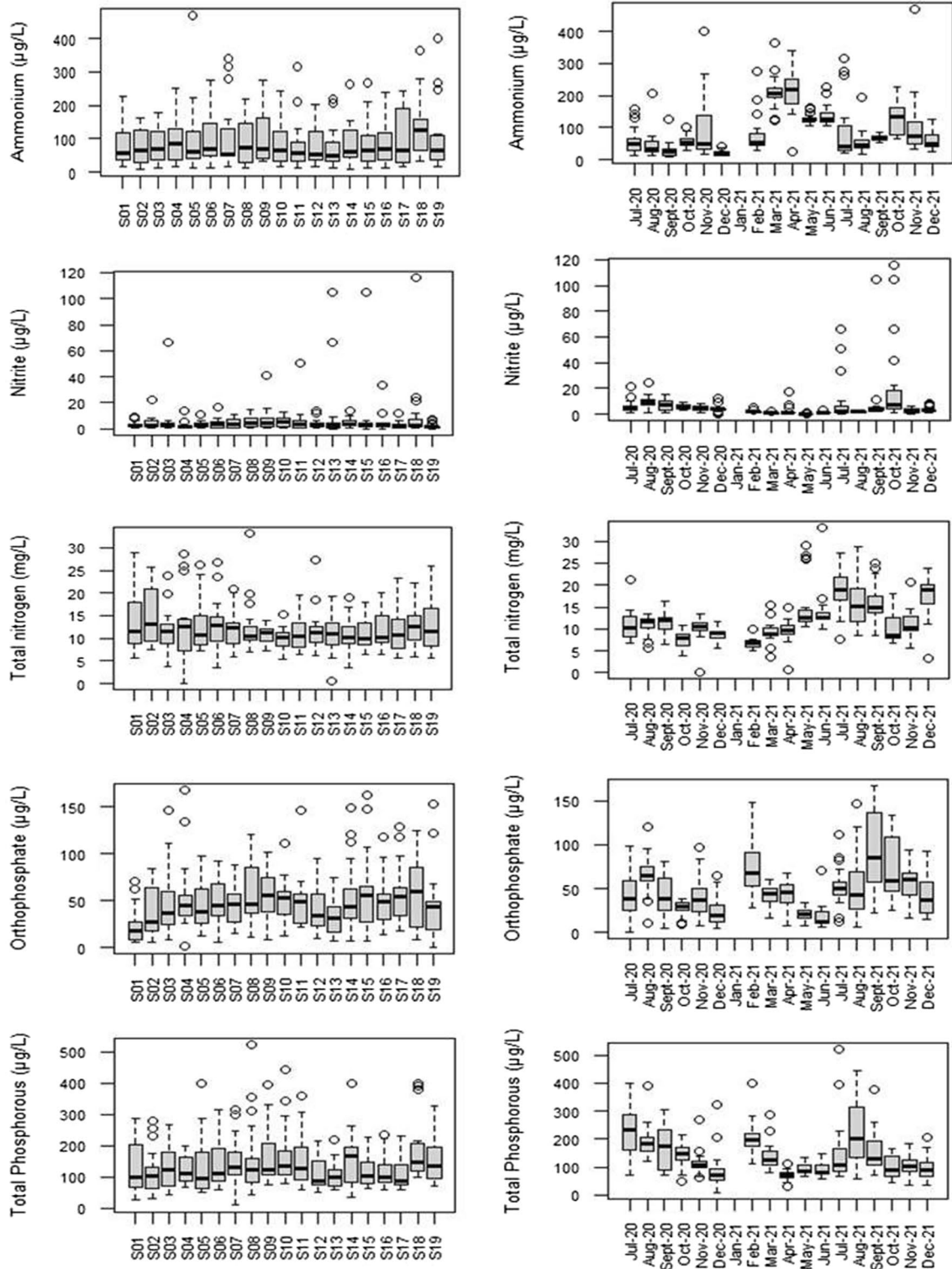


Fig. 3 Spatio-temporal distribution of nutrients in the bottom waters of Lake Nokoué

The standard deviations obtained for temperature and pH are clearly low compared to the mean values, suggesting low variability of these parameters. The other water quality parameters including salinity, turbidity, nitrite, ammonium, orthophosphate, and chlorophyll-a showed high standard deviations which is an indication of high spatial and temporal variation of these parameters.

Distribution of salinity and turbidity

Salinity is one of the determining factors of ecological processes in coastal ecosystems. For Lake Nokoué, saline intrusion is governed by saltwater inflow from the Atlantic Ocean through the Cotonou Channel and is counterbalanced by freshwater inflow from the Ouémé and Sô rivers (Fig. 1). In this study, the salinity of the water at the bottom of Lake Nokoué varied between 0.00 and 35.30 with desalination of the entire water column of the lake during high water periods and very high salinisation (close to that of the Atlantic Ocean) of the entire bottom of the lake during low water periods. Salinity is thus an effective indicator that allows for a fairly precise delimitation of the different phases of the hydrological regime of Lake Nokoué. By convention, the beginning of each hydrological cycle could be considered as the date of complete desalination of the lake. It should be noted that over the entire 2020–2021 cycle, the salinity of the Eastern part of the lake (S07 to S14) was significantly lower than that of the western part (Fig. 2). Assuming that the effect of the wind on the mixing of the water column is homogeneous over the whole lake, this East-West difference in salinity could indicate that the freshwater inflow from the Ouémé River (East) is more important than that from the Sô River (West).

The variation of the turbidity of the lake bottom water showed an opposite trend to that of the salinity (Fig. 2). Thus, the high turbidity values were recorded during high water periods and are on average 300 to 500 times higher than the turbidity values recorded during low water periods (Fig. 2). Also, the Eastern zone (S07 to S14) of the lake showed significantly higher turbidity values than the other zones of the lake, thus supporting the hypothesis of more significant water inflows from the Ouémé River than from the Sô River. This high turbidity in the East would undoubtedly come from rainwater runoff

over thousands of square kilometres of agricultural land in the Ouémé basin (more than 45,000 km²). The Ouémé basin is heavily farmed, with practices that tend to increase the amount of particulate matter discharged. This runoff causes high turbidity in the river during high flow periods, which in turn affects turbidity in the lake. The strong relationship between Ouémé River flow and lake water levels highlighted by Djihouessi et al. (2018) confirms this result, as do the low transparency values measured at high water in the two aquatic ecosystems (Djihouessi et al., 2018).

Spatial and temporal distribution of nutrients

In general, the bottom waters of Lake Nokoué are rich in total nitrogen with the majority of measured concentrations ranging between 5 and 25 mg/L (Fig. 3). The 2021 cycle had higher values than the 2020 cycle, and the eastern zone (S07 to S15) had lower total nitrogen concentrations than the other zones of the lake. The lowest total nitrogen concentrations were measured during the low water period (February–April). These concentrations then gradually increased until they reached their peak in July 2021. Although not all forms of inorganic nitrogen were measured (nitrate was not measured) in this study, the comparison of the orders of magnitude of total nitrogen and ammonium suggests that organic nitrogen is predominantly dominant in the bottom waters of Lake Nokoué.

The concentrations of N-NH₄⁺ measured at the bottom of Lake Nokoué, ranging from 9 to 470 µg/L, progressively increased at the end of the high water period (low salinity period) to reach their peak in the middle of the low water period (high salinity period) in March and April (Fig. 3), suggesting a strong mineralisation of nitrogen during this period. The other peaks in N-NH₄⁺ were measured during the high water period (October–November) suggesting a diffusion of ammonium attached to sediment particles in the bottom waters, and/or, an input from tributary rivers.

The concentrations measured in N-NO₂⁻ were mostly low. They fluctuated around 1 µg/L in low water periods and average peaks of around 16 µg/L were measured in high water periods (Fig. 3). The low concentrations of N-NO₂⁻ measured suggest an absence of nitrite accumulation in the surface sediment layers and therefore complete nitrification in the bottom waters of Lake Nokoué.

The concentrations of TP (9 and 521 $\mu\text{g/L}$) and P-PO_4^{3-} (1 and 162 $\mu\text{g/L}$) measured in the bottom waters of Lake Nokoué showed an almost similar spatio-temporal dynamic over the entire study period. The TP content was on average more than three times higher than the P-PO_4^{3-} content, suggesting that the organic phosphoric fraction is more important than the mineral one. Spatially, TP concentrations did not differ significantly, although the highest values were measured in the East (near the Ouémé River) and in the north-East (near the pile-dwelling villages). The lowest P-PO_4^{3-} concentrations were measured in the South (S01, S02, S03; Cotonou channel) and north of Lake Nokoué (S12, S13, S14). From a temporal point of view, the highest concentrations of TP and P-PO_4^{3-} were recorded during the high water period with a progressive decrease in concentrations throughout the period. However, it should be noted that the peak concentrations were recorded between February and April when the mineral fraction represented more than half of the total phosphorus. This period coincided with a peak in NH_4^+ concentration, thus suggesting a strong mineralisation of organic matter during this period. The high temperatures measured and low river inputs during this period support this result.

Identification of major water quality processes

Correlation analysis

The correlation data of the water quality parameters of the bottom waters of Lake Nokoué are presented in Fig. 4. A strong positive correlation was observed between pH and salinity suggesting that the intrusion of saline water into the bottom waters of Lake Nokoué would increase the pH. In contrast, a strong negative correlation was observed between salinity and turbidity since salinity, governed by clear sea water inflow, decreases with freshwater inflow from rivers with higher turbidity. The negative correlation observed between temperature and turbidity indicates that periods of low temperature (high water period) coincide with high turbidity concentrations.

Salinity was positively associated with ammonium and negatively associated with orthophosphate indicating a greater input of ammonium in low water and a greater input of phosphorus in high water; while pH was negatively associated with nitrite reflecting the nitrification process. During this process, the released

H^+ ions are the cause of the pH decrease. A strong positive correlation was observed between turbidity and total phosphorus indicating that the two parameters are strongly associated and would share a common source. Total nitrogen showed no significant correlation with the water quality parameters measured in this study. Most of the parameters measured except total nitrogen are linked to salinity and/or turbidity which are indicators of the different phases of the hydrological regime of Lake Nokoué. This suggests that much of the organic nitrogen, which is the most important form of nitrogen in the lake, comes from human activities in and around the lake.

Principal component analysis

As a prelude to PCA, the Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity tests were applied to ensure that the data had the required characteristics for factor analysis (Varol et al., 2012). The KMO gave a value of 0.62, and the significance level of Bartlett's sphericity test ($p < 2.2\text{e-}16$) was less than 0.05 suggesting that there is substantial correlation in the data, so that all variables can be used in the principal component analysis.

The PCA results for each sampling station are presented in Table SM1 (See in supplementary Material). For the choice of the number of significant principal components (PC), a minimum threshold of cumulative variance above 70% was set as proposed by Henson and Roberts (Hensen and Roberts, 2006; Liu et al., 2003). Thus, three significant principal components were found for most of the sampling stations, except for stations S13 and S18 for which four significant components were required.

The first principal component (PC1) explained between 30 and 50% of the variability in background water quality parameters at all sampling stations (Table SM1). This component was strongly correlated with salinity at all stations, then with temperature, turbidity, salinity and phosphorus compounds at most stations except S04, S13, S16, S17, and 19 (the South-west and Northeast zones of the lake). For the stations between S05 and S16 (Eastern zone), PC1 additionally showed a strong correlation with the mineral forms of nitrogen. PC1 is linked to climatic conditions and phosphorus for the majority of the stations and the negative contribution of salinity compared to that of phosphorus indicates that the enrichment of the lake

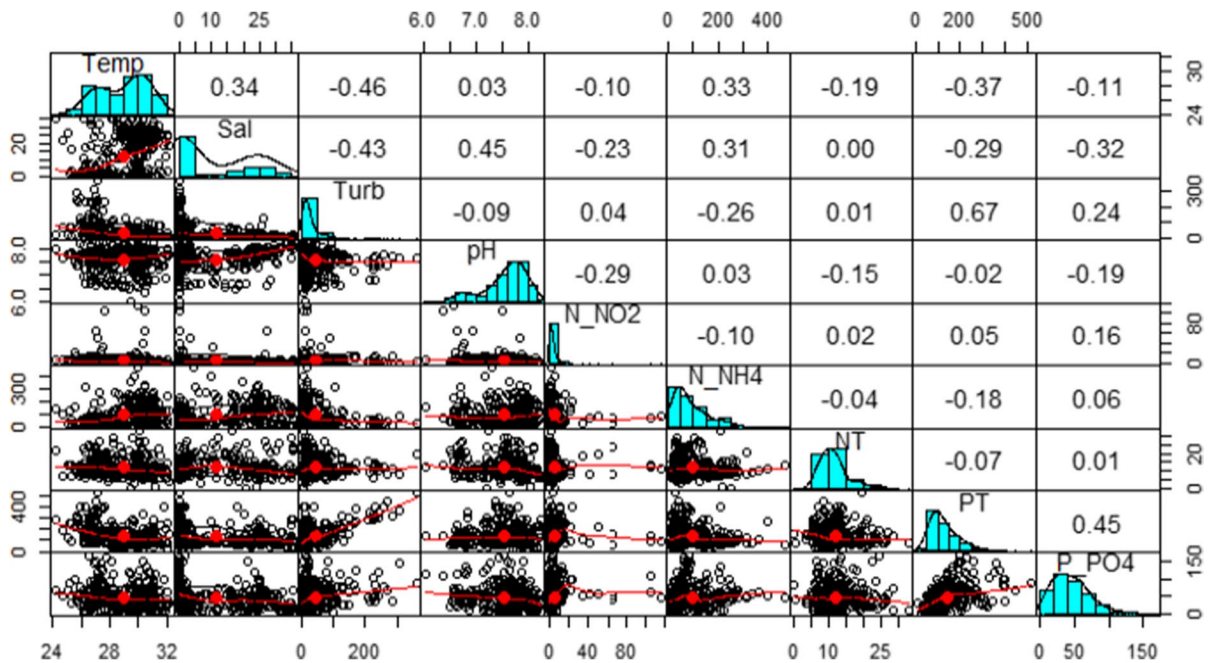


Fig. 4 Pearson correlation matrix of water quality parameters

water in phosphorus takes place during periods of low salinity, therefore during high water. The fact that turbidity and total phosphorus have the same sign in their contribution to PC1 indicates that they have the same source. Djihouessi and Aina (2018) also showed for surface waters of the same lake that the first component is influenced by climatic conditions and phosphorus with turbidity as a vector of the increase in phosphorus concentrations. The present study in addition to the findings of Djihouessi and Aina (2018) shows that in parallel to this process the climatic condition also influences the formation of mineral nitrogen in the bottom waters of Lake Nokoué. The increase in temperature and salinity in the lake bottom waters favoured the increase of ammonium (ammonification), while the decrease of ammonium seems to be marked by the increase of nitrite (nitrification). The fact that ammonium and salinity have contributions of the same sign suggests that ammonium is produced largely in low water periods.

The second principal component (PC2) explained between 16 and 25% of the variability of the background water quality parameters at all sampling stations (Table SM1). This component is specifically correlated with pH and mineral forms of nitrogen (nitrite, ammonium). It seems to highlight the

processes of nitrification and ammonification. At all monitoring stations, the contributions of pH and nitrite are of opposite sign, indicating a decrease in pH as nitrification progresses and vice versa. The same observations have been made by several authors in aquatic environments and in wastewater treatment plants (Collins et al., 1975; Malchair, 2002; Strauss et al., 2002). The studies of Strauss et al. (2002) showed that nitrification is controlled by several variables, the most important of which are pH availability and ammonium. The high ammonium levels during low water periods are due to the degradation of organic matter (ammonification), especially of dead water hyacinth residues (correlation test). It thus appears that this component highlights the ammonification and nitrification process.

The third principal component (PC3) explained between 12 and 19% of the variability of the quality parameters measured at all sampling stations. This component showed a strong correlation with total nitrogen and to some extent with ammonium, nitrite and orthophosphate and total phosphorus. It seems to indicate that some of the nutrients in the bottom waters of Lake Nokoué come from the same source. In view of the anthropogenic pressures that Lake Nokoué is undergoing, this source of nutrients could

be water hyacinth detritus, wastewater discharges from the cities of Cotonou, Abomey-Calavi and the lakeside town of Ganvié, and/or riverine inputs of agricultural runoff. According to Djihouéssi (2018), a good part of the fluvial inputs are immediately evacuated into the ocean, so the source of nutrients at the origin of the eutrophication of Lake Nokoué is undoubtedly the water hyacinth detritus, the residues of Acadja, and the wastewater discharges from the cities of Cotonou, Abomey-Calavi, and the lakeside town of Ganvié.

The fourth principal component (PC4) explained 12% of the variability of the parameters measured at stations S13 to S18, both of which are characterised by the presence of lakesides villages on stilt (Ganvié and Houedo-Gbadji). This component is significantly correlated with total phosphorus.

Ultimately the principal components (PC1, PC2 and PC3) are related to both natural and anthropogenic processes. Principal components 1 and 2 alone explained more than 55% of the variability in the data for each monitoring station. PC1 highlights the influence of the hydrological regime (through saline intrusion) on the dynamics of nutrients in the bottom waters of Lake Nokoué. Also, PC1 shows the influence of climatic conditions on the processes of appearance of mineral forms of nutrients. PC2 and PC3 show that the nutrient inputs have mainly the same source, namely the organic residues of water hyacinth deposited at the water-sediment interface and the wastewater discharges of the cities of Cotonou, Abomey-Calavi and the lake city of Ganvié.

Analyses of the spatio-temporal variation of water quality and classification

Kruskal–Wallis test

At first glance, the Kruskal–Wallis test was used to evaluate the spatial and seasonal variation of the water quality parameters. This test shows that all the quality parameters studied except chlorophyll-a show a significant median variation over all months ($p < 0.01$). The pairwise comparison with Dunn's test shows two significantly different periods; period 1 includes the months July to October and period 2 the months December to May. Depending on the salinity regime, these periods correspond to high and low water respectively. Within each period, the median

values for temperature, salinity, turbidity, ammonium, orthophosphate, total phosphorus and total nitrogen did not vary significantly. The months of November, December and June serve as a transition between these high water and low water. For pH, apart from the months of October and November, no significant variation is observed. For nitrite, apart from the months of July, September and October, no significant variation is observed. For spatialization, the Kruskal–Wallis test shows that salinity, turbidity, pH and chlorophyll-a show significant spatial variation ($p < 0.01$). The peer comparison shows 4 significantly different groups: Eastern Lake stations (S06, S07, S08 and S11), channel stations (S01 to S03), central stations (S04, S05, S06, S12, S13, S15, S16, S17, S19), river entrance stations (S09, S10, S14, S18). Within each group, the median values for salinity, turbidity and chlorophyll-a did not vary significantly. For pH, apart from the channel stations (S01, S02) and the river entrance station (S09, S10, S14, S18), the median values of the other stations did not vary significantly

The results of the analysis of the spatio-temporal variation of nutrient concentrations (N-NH₄⁺, N-NO₂⁻, NT, P-PO₄³⁻, PT) in the bottom waters of Lake Nokoué by the Kruskal–Wallis test suggested that the temporal variations of these parameters are much more pronounced than the spatial ones (Fig. 3). This would indicate a much stronger influence of the hydrological regime on nutrient concentrations than the influence of the distribution of activities around the lake.

Cluster analysis

Physical and biogeochemical similarities across seasons and between several sampling stations were observed in the exploratory analysis, PCA and Kruskal–Wallis test of water quality parameters measured at the bottom of Lake Nokoué. In order to clearly identify similar stations and possible groupings, a spatial cluster analysis was carried out and the resulting dendrogram is presented in Fig. 4. Considering groups such that $(D_{\text{link}}/D_{\text{max}}) * 100 < 30$, five clusters emerge with one cluster consisting of station S18 only, located near the lake village of Ganvié, a highly anthropogenic area under the influence of the Sô River. If we consider $(D_{\text{link}}/D_{\text{max}}$

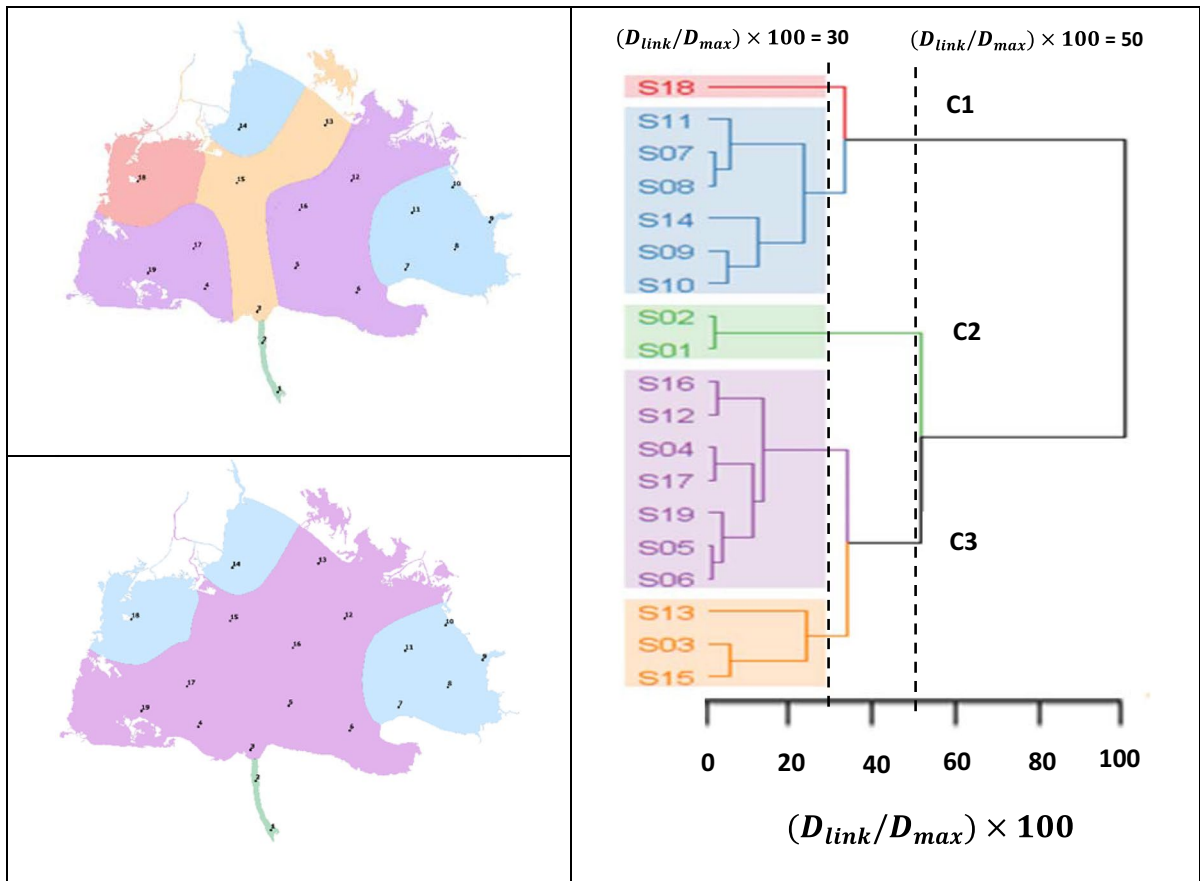


Fig. 5 Clusters from the hierarchical bottom-up classification of stations and positioning

) $\times 100 < 50$, then we obtain three clusters, and this result would seem to be more coherent with the configuration of the lake, since sites S03, S04, S05, S06, S12, S13, S15, S16, S17, and S19 composing cluster 3 (C3) are in the centre of the lake, while sites S07, S08, S09, S10, S14, and S18 composing cluster 1 (C1) are at the mouths of the Ouémé River in the extreme East and of the Sô River in the extreme north-west, and sites S01 and S02 composing cluster 2 (C2) are in the South on the channel (Fig. 5).

These cluster analysis results, consistent with the configuration of Lake Nokoué, suggest that for a rapid assessment of water quality, only one station in each cluster could be used for a spatial assessment of water quality over the whole lake. The CA technique is useful for providing a reliable classification of surface waters and allows for optimal and less costly design of future strategic sampling areas. There are

other reports (Simeonov et al., 2003; Wunderlin et al., 2001) where this approach has been successfully applied in water quality monitoring programmes.

Discriminant analysis

Discriminant analysis is both an exploratory and predictive method used to obtain a statistical classification of several samples when there is prior knowledge of their membership of a specific group (Campbell, 1978; Huberty & Olejnik, 2006). It has been used to analyse spatial and temporal variations in water quality using three different approaches: standard mode, ascending stepwise mode and descending stepwise mode.

Spatial DA was applied on the raw database using the three clusters formed by cluster analysis as grouping variables (dependent variables) and the measured water quality parameters as independent variables. The classification matrices (CM) and classification

Table 2 Classification matrix for spatial and temporal discriminant analysis (HW= high water lever, LW = low water lever, IP = interim period, T = total, Riv_M = river mouth)

Classification matrix for spatial DA									
Standard mode					Stepwise mode				
	% CA	Centre	Channel	Riv_M	T	% CA	Centre	Channel	Riv_M
Centre	87.23	41	1	5	47	91.49	43	1	3
Channel	46.15	6	6	1	13	30.77	9	4	0
Riv_M	51.35	18	0	19	37	48.65	19	0	18
T	61.58	65	7	25	97	56.97	71	5	21

Classification matrix for temporal DA															
Standard mode					Stepwise forward					Stepwise backward					
	%CA	LW	HW	IP	T	%CA	LW	HW	IP	T	%CA	LW	HW	IP	T
LW	97,14	34	0	1	35	97,14	34	0	1	35	97,14	34	0	1	35
HW	86,49	2	32	3	37	86,49	2	32	3	37	86,49	2	32	3	37
IP	44	4	10	11	25	36	4	12	9	25	44	4	10	11	25
T	75,88	40	42	15	97	73,21	40	44	13	97	75,88	40	42	15	97

Table 3 Classification functions for spatial and temporal discriminant analysis (LW = low water level, HW = high water and IP = intermediate period, RW_M = river mouth)

Spatial variation						
	Standard mode			Stepwise mode		
	Centre	Chenal	RW_M	Centre	Chenal	RW_M
Intercept	-463.82	-447.79	-471.57	-210.28	-193.42	-223.70
Temp	16.30	15.67	16.73	14.56	13.84	14.97
Sal	-1.34	-1.21	-1.37	-0.48	-0.34	-0.52
Turb	0.16	0.15	0.18	0.22	0.21	0.24
pH	56.98	56.65	56.18			
N_NO2	0.34	0.35	0.36			
N_NH4	0.01	0.01	0.02	-0.02	-0.03	-0.02
NT	1.94	2.02	1.93			
PT	0.04	0.04	0.04			
P_PO4	0.07	0.05	0.06			

Temporal variation									
	Standard mode			Stepwise forward mode			Stepwise backward mode		
	LW	HW	IP	LW	HW	IP	LW	HW	IP
Intercept	-740.54	-622.32	-664.70	-693.19	-581.28	-622.36	-708.79	-592.78	-634.13
Temp	28.23	25.26	26.69	26.86	24.07	25.45	27.63	24.69	26.11
Sal	1.62	1.03	1.29	1.51	0.92	1.18	1.54	0.95	1.21
Turb	0.22	0.20	0.21	0.28	0.24	0.26	0.20	0.18	0.19
pH	68.23	65.96	65.55	63.47	61.21	60.79	62.96	60.87	60.38
N_NO2	0.50	0.48	0.49						
N_NH4	0.13	0.10	0.10	0.09	0.07	0.07	0.11	0.08	0.09
NT	1.22	1.15	1.22	1.13	1.07	1.15	1.23	1.16	1.24
PT	0.10	0.09	0.09				0.10	0.09	0.09
P_PO4	-0.13	-0.10	-0.11				-0.10	-0.07	-0.08

functions (CF) obtained from the standard and stepwise DA mode are shown in Tables 2 and 3. The CFs from the standard approach used 9 water quality parameters (temperature, pH, salinity, turbidity, nitrite, ammonium, orthophosphate, total nitrogen and total phosphorus) to give CMs with 61.58% of cases correctly assigned. The CFs of the stepwise DA mode gave CMs with 56.97% correct attribution using 04 quality parameters (temperature, salinity, turbidity, ammonium). The spatial AD Wilks lambda statistic is 0.615 for the standard approach, 0.653 for the step-by-step approaches. The value of lambda Wilks being high (close to 1), the clouds of the clusters will not be clearly distinct, so the linear discriminant function did not identify enough variables to discriminate the different groups (cluster). The standardized coefficients of the two discriminant functions (DF) are reported in Table 3. The first DF (LD1) of the stepwise mode alone accounts for 89.2% of the total variance.

The parameters selected in order of significance are: temperature, salinity, turbidity and ammonium. Of all these parameters, only ammonium has a low coefficient, therefore not significant. The other three are significant with respective coefficients of 0.84, -0.79 , and 0.80, of which only salinity establishes a negative correlation. Thus, observations with low salinity will have high scores for the first discriminant function and vice versa and observations with low temperature or turbidity values will have low scores for the same function. Of the 4 selected parameters, the second DF (LD2) with an explained variance of 10.8% shows that salinity and turbidity are the most significant with coefficients of -0.85 and -0.98 respectively, indicating that observations with high salinity or turbidity values will have low scores for the second discriminant function and vice versa.

The results of the two FDs of the spatial AD suggest that temperature, salinity and turbidity are the main parameters that discriminate the three zones of the lake defined by the AC. On the other hand, it appears from the Kruskal–Walis test and the spatial AD that only salinity and turbidity undergo a strong spatial variation. This means that the hydrological regime is at the origin of the spatial variability observed on the lake and not the anthropogenic pollution. The low spatial variability for most of the parameters studied would be associated with the continuous mixing of the lake waters due to the processes of advection and diffusion driven mainly by

the winds which are permanent in the shallow lakes and lagoons. The same observations were made by Gradilla-Hernández et al., (2020) on Lake Cajititlán in Mexico.

The temporal discriminant analysis was then evaluated with the same raw data set using a grouping according to three hydrological periods: high water (HW), low water (LW) and intermediate period (PI) of Lake Nokoué. The measured water quality parameters constitute the independent variables. The classification functions (CF) and classification matrices (CM) obtained from the standard mode, forward and backward DA mode are shown in Table 3 and Table 2 respectively. The standard mode with nine parameters (temperature, pH, salinity, turbidity, nitrite, ammonium, orthophosphate, total nitrogen and total phosphorus) and the stepwise backward mode with eight parameters (temperature, pH, salinity, turbidity, ammonium, orthophosphate, total nitrogen and total phosphorus) each gave a corresponding MC correctly assigning 75.88% of the cases. However, the stepwise forward mode provided a correctly assigned MC of 73.21% using six parameters (temperature, pH, salinity, turbidity, ammonium and total nitrogen). In all three cases, the correctly assigned MCs for the high water and low water period are very significant. In the spatial DA, the Wilks lambda statistic is 0.188 for the standard mode, 0.198 for the stepwise forward mode and 0.19 for the stepwise backward mode. These low Wilks lambda values imply that the groups are well separated and the LDA correctly classifies the different groups. Figure 6 presenting the scores of the two discriminant functions shows that the temporal DA correctly discriminates the three hydrological

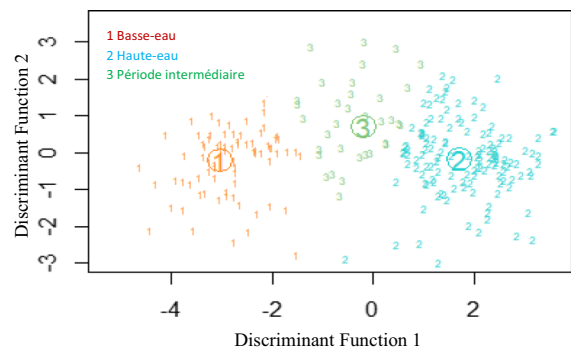


Fig. 6 Scatterplot of the scores of the two linear discriminant functions

Table 4 Standardized coefficients of the linear discriminant function of spatial and temporal variation (Eig.Val = Eigenvalue, Cum.Eig = Cumulative Eigenvalue.)

Spatial variation						
	Standard mode		Stepwise mode			
	LD1	LD2	LD1	LD2		
Temp	0.79	0.04	0.84	0.16		
Sal	-0.68	-0.70	-0.79	-0.85		
Turb	0.77	-0.57	0.80	-0.98		
pH	-0.16	0.38				
N_NO2	0.05	-0.23				
N_NH4	0.32	-0.19	0.34	-0.16		
NT	-0.16	-0.20				
PT	0.03	-0.58				
P_PO4	0.00	0.70				
Eig.Val	7.25	3.42	7.09	2.47		
Cum.Eig	0.82	1.00	0.89	1.00		
Temporal variation						
	Standard mode		Stepwise forward mode		Stepwise backward mode	
	LD1	LD2	LD1	LD2	LD1	LD2
Temp	-1.11	0.40	-1.06	0.47	-1.11	0.41
Sal	-1.37	0.13	-1.42	0.20	-1.38	0.14
Turb	-0.33	0.28	-0.42	0.02	-0.34	0.28
pH	-0.19	-0.45	-0.23	-0.47	-0.20	-0.43
N_NO2	0.05	-0.09				
N_NH4	-0.46	-0.53	-0.42	-0.60	-0.47	-0.52
NT	-0.16	0.665	-0.14	0.78	-0.17	0.67
PT	-0.23	-0.42			-0.23	-0.42
P_PO4	0.224	-0.12			0.23	-0.13
Eig.Val	20.21	3.95	19.76	3.63	20.19	3.94
Cum.Eig	0.96	1.0	0.97	1.00	0.96	1.00

regimes. The results of the temporal DA suggest that all the studied quality parameters except nitrite are significant in discriminating the three hydrological periods with a different level of significance, which means that these parameters explain most of the expected temporal variations in water quality.

The standardised coefficients of the linear discriminant functions for temporal variation are presented in Table 4. Two discriminant functions are estimated and the coefficients of the parameters of each function are very close for the two stepwise modes. When considering the first discriminant function of stepwise backward mode which explains 96.3% of the total variance, salinity and temperature have the most significant coefficients (-1.38 and -1.11). Thus, observations with low salinity or temperature will have high scores for this function

and vice versa. In decreasing order of significance, ammonium, turbidity, orthophosphate, TP and pH and NT are less significant than salinity and temperature and contribute negatively to this first function except for pH which has a positive contribution. For the second discriminant function of the stepwise backward mode which explains 3.7% of the total variance, ammonium and NT have comparable significant coefficients (-0.52, 0.67) with an inverse correlation. Observations with high ammonium values will have low scores for this second function and vice versa while observations with high total nitrogen values will have high scores for this second function and vice versa.

The results of the temporal DA show that all the water quality parameters at the bottom of Lake Nokoué, except nitrite, are significant in discriminating

the three hydrological periods. These results are in line with those of the Kruskal–Wallis test, with the difference that this test showed variability for nitrite. This confirms that the hydrological regime has an influence on nutrient dynamics.

Conclusion

This study aims to contribute to the data collection and literature needs for a better understanding of the biogeochemical functioning of the Nokoué system, to propose strategies for monitoring this ecosystem, and for restoration measures. As the bottom waters are an intermediate zone between the sediment layer and the water column, the study of their quality has made it possible to identify the internal and external sources and processes governing the eutrophication of the waters of Lake Nokoué.

The hydrological regime and the climatic conditions are the main factors determining the spatial and temporal dynamics of the water quality of Lake Nokoué, with a very pronounced influence compared to that of the anthropogenic activities around the lake. The analysis of nutrient dynamics shows a strong temporal variability of nutrients to the detriment of spatial variability, with a predominance of organic forms. This low spatial variability of nutrients is due to the continuous mixing of the entire water column down to the sediment layer of the lake, induced by the processes of advection and wind-driven diffusion, which are permanent in shallow lakes and lagoons. Furthermore, from a spatial point of view, apart from the Cotonou Channel and the river mouth, no significant differences were observed in other parts of the lake. Therefore, for a rapid assessment of the water quality of Lake Nokoué, a single station in each zone (river mouths, lake, and channel) could be used for a spatial assessment of the water quality of the lake. From a temporal point of view, the input of orthophosphate is greater during periods of high water, while the input of ammonium is greater during periods of low water. The processes of mineralization of organic matter and nitrification control the occurrence of mineral forms of nitrogen under the influence of climatic conditions. Although the river inputs of NT and PT are greater, their residence time is short due to the renewal of water in the system. It, therefore, appears that the nutrients responsible for primary production

and eutrophication come from organic residues deposited at the water-sediment interface (water hyacinth, Acadja, effluents from the cities of Cotonou, Abomey-Calavi, and the lakeside town of Ganvié).

Multivariate statistical techniques can be used as a tool to monitor and effectively manage the water quality of Lake Nokoué. To restore this ecosystem, this study proposes several measures. These include regular monitoring of water and sediment quality in Lake Nokoué, collection and treatment of domestic sewage from the lakeside villages and surrounding towns, continuous harvesting of water hyacinth before salinity increases, working with fishermen to reduce or limit the spread of Acadjas, and controlling the use of fertilizers.

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Author contribution Akilou Socohou Amadou: conceptualization, collected water samples, analyses of the samples, data processing and interpretation, drafted and finalized the manuscript ; Metogbe Belfrid Djihouessi: conceptualization, data processing, manuscript review and editing; Beatrix Amen Tigo: conducted laboratory, collected water samples, analyses of the samples; Vignon Mechtilde Viainon: collected water samples, analyses of the samples; Firmin Mahoutin Adandedji: conducted the field work, collected water samples; Julien Adoukpe: manuscript review and editing; Martin Pépin AINA: manuscript review and editing.

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Data availability As part of this study, the data collected that supports our conclusions is the property of the l'Institut Nationale de l'Eau (INE/UAC). They are available only on request from the corresponding author.

Declarations

All authors have read, understood and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the instructions for authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Conflicts of interest The authors declare no competing interests.

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