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Accepted manuscript

Bayesian inference of physicochemical quality elements of tropical lagoon Nokoué(Benin)

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Abstract

In view of the very strong degradation of aquatic ecosystems, it is urgent to set up monitoring systems that are best able to report on the effects of the stresses they undergo. This is particularly true in developing countries, where specific and relevant quality standards and funding for monitoring programs are lacking. The objective of this study was to make a relevant and objective choice of physico-chemical parameters informative of the main stressors occurring on African lakes and to identify their alteration thresholds. Based on statistical analyses of the relationship between several driving forces and the physico-chemical parameters of the Nokoué lagoon, relevant physico-chemical parameters were selected for its monitoring. An innovative method based on Bayesian statistical modeling was used. Eleven physico-chemical parameters were selected for their response to at least one stressor and their threshold quality standards also established: Total Phosphorus (<4.5mg/L) , Orthophosphates (<0.2mg/L), Nitrates (<0.5 mg/L), TKN (<1.85 mg/L), Dry Organic Matter (<5 mg/L) , Dissolved Oxygen (>4 mg/L), BOD (<11.6 mg/L) , Salinity (7.6 ‰) , Water Temperature (<28.7 °C) , pH (>6.2) , and

Transparency (>0.9 m) . According to the System for the Evaluation of Coastal Water Quality, these thresholds correspond to "good to medium" suitability classes, except for total phosphorus. One of the original features of this study is the use of the bounds of the credibility interval of the fixed-effect coefficients as local weathering standards for the characterization of the physico-chemical status of this anthropized African ecosystem.

Keywords: Driving forces, Alteration thresholds, Acadjas, Monitoring, Modeling, Human activities.

1 Introduction

Human activities around the world affect ecosystems and the biological communities they shelter, thus leading to their alteration(Barnosky et al., 2011; Bowler et al., 2020; Dornelas et al., 2019; Isbell et al., 2017). Among these ecosystems, aquatic ecosystems are the most threatened and degraded environments, whose biodiversity is in clear decline (IPBES, 2019) and for which the evolution forecasts are bleak (Sala et al., 2000). These observations are even more negative because aquatic ecosystems are part of many ecosystem services. This is particularly true of the great African lakes. Indeed, the African Great Lakes are an immense source of dietary protein and clean water as well as of avenues for transport, recreation, tourism, and fish export (Ogutu-Ohwayo, Hecky, Cohen, & Kaufman, 1997). Nearly 17% of inland fisheries and over 85% of water withdrawals for agriculture are from African lakes (africa.wetlands.org)[1](Mulonga, 2022).These lakes are threatened by global and local environmental challenges, including climate change, water pollution, and overfishing (Plisnier, Nshombo, Mgana, & Ntakimazi, 2018), in the face of a growing population whose natural resource needs exceed what the ecosystem can support (Juma, Wang, & Li, 2014). Given the crucial role of these lakes in Africa (UNEP & Belgium, 2006) and the fact that they are likely to face even greater threats in the coming decades (Jenny et al., 2020), it has become urgent to set up a monitoring program that is able to facilitate protection and/or restoration actions. In addition, water quality monitoring is expected to be an increasingly major concern for these developing countries, especially given the rapid population growth and urbanization rate they also encounter (Sim & Tai, 2018). Maintaining and restoring the quality of aquatic ecosystems are at the origin of various ambitious regulatory commitments. Most of them are based on increased monitoring of the biotic and/or abiotic components of ecosystems to diagnose their status and quality. Among these regulatory frameworks is the United States Clean Water Act of 1972 that has enabled the US government and industry to help reduce water pollution through extensive investment

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[1] https://africa.wetlands.org/en/our-approach/water-stores-from-mountains-to-sea/rivers-and-lakes/

programs (Shapiro & Keiser, 2018). Another example is the European Water Framework Directive (WFD, Directive 2000/60 / EC, October 23, 2000), which is a decisive signal in the monitoring and assessment strategy of water quality of European continental waters (Laronde & Petit, 2010). Although African lakes play a vital role for local populations, nothing similar is set up in Africa. Integrated water resources management (IWRM) is the main West African mechanism that has emerged as a panacea for the increasing socio-environmental degradation and insufficient funding for public actions related to water resources management (Molle, 2012). Unfortunately, according to the status report on the implementation of IWRM in Africa (UNEP-DHI, 2018) and that of the Water Research Commission (Jonker, 2007), a large number of African countries are still struggling with the implementation of this mechanism. The IWRM program, which should lead to the development of tools and monitoring mechanisms, has become a shadow of its former self and is only set up as a goodwill of the various states (Molle, 2012). Indeed, with rare exceptions (e.g., lakes Malawi, Tanganyika, Victoria), environmental monitoring of African lakes is often lacking (Plisnier et al., 2018). The only actions associated with the monitoring of water quality in West Africa are essentially those sporadically carried out within the framework of individual scientific research, the activities of some water agencies with private or foreign funding, and those sometimes noted within the framework of tourism and fisheries development projects, producers of wealth. Nokoué, the largest lake in southeastern Benin, is a eutrophic (Djihouessi, Mahougnon Bernauld Djihouessi, & Aina, 2019) subtropical coastal lagoon (Villanueva et al., 2006). It is part of the shallow, naturally warm, and most productive West African ecosystems (Djihouessi et al., 2019; Laleye, 1995; Villanueva et al., 2006; Welcomme, Azim, Verdegem, van Dam, & Beveridge, 2005). Historically, the fishery resources taken from this lake have been used for the survival of entire communities in the south of Benin. Nevertheless, from a commercial point of view, there has been a decrease in income associated with a reduction in the size of the catch and an increase in fishing populations. To compensate for these losses of income, the target of the riparian populations is now an increased exploitation of the sand quarries of the lake. Due to its multiple functions, this West African lake is exposed to various pressures. These include the intensification of fishing practices through the acadjas, urbanization around the lake, increasing nutrient loading through wastewater, almost permanent discharge of solid waste by the riparian populations (Djihouessi et al., 2019), the opening of the Cotonou canal (19th century) followed by the construction of a deep water port (20th century), and the development of sand dredging activities. Nokoué was the subject of a series of studies within the framework of several research works initiated at the University of Abomey-Calavi based on its own resources and through international financing collaborative programs. One of these includes the recording of numerous physicochemical parameters in various parts of the lagoon (Gadel & Texier, 1986; Gnohossou, 2006; Mama, 2010; Zandagba, Adandedji, Mama, Chabi, & Afouda, 2016). This information, however, is collected but not used from a management perspective. This is due to the difficulty of disentangling the variability of the values of physicochemical parameters linked to stressors from the variability that results from "natural" environmental factors. For all surface water scientific publications that use drinking water quality standards or other standards and indicators established in one context to assess water status in other contexts, defining reference values for each of these parameters is also an issue. The purpose of this study is to understand the relationships between driving forces and physicochemical parameters in order to select relevant physicochemical monitoring parameters and alteration thresholds that reflect the status of the Nokoué lagoon's water quality and that can provide information on the origin of the disturbances it is undergoing. Our approach also aims to consider the concerns of managers and local authorities through a simple and inexpensive implementation of monitoring programs.

2 Materials and methods

2.1 Study Area

Located between parallels 2 °24' and 2 °37' North and meridians 6 °23' and 6 °28' East, Nokoué (Fig. 1) is one of the vast lagoons and lake water bodies that border the Atlantic coast in the Gulf of Guinea (Gnohossou, 2006; Goussanou, 2012; Odountan, de Bisthoven, Koudenoukpo, & Abou, 2019). The surface area of the Nokoué is approximately 150 km2 in the dry season, with the largest dimensions of $20km \times 11km$ measured, respectively, from east to west and from north to south, (Le Barbé et al., 1993; Mama et al., 2011; Vennetier, 1991). It is fed by four main tributaries: the Ouémé and Sô rivers to the north and the Cotonou and Totchè canals to the south, which connect Nokoué to the Atlantic Ocean and to the Porto-Novo lagoon, respectively. Nokoué is subject to a sub-equatorial climate characterized by two alternating rainy and dry seasons of unequal duration: a long dry season (mid-November to mid-March), a long rainy season (mid-March to mid-July), a short rainy season (mid-September to mid-November), and a short dry season (mid-July to mid-September) (Gnohossou, 2006). Humidity is high and often above 72% Foscolo (1985). Due to the crystalline subsoil, the rainfall recorded in August in the north and center of Benin is almost entirely drained to the south. This is the origin of the floods observed in the Ouémé and Sô rivers, which, together with the Nokoué and its deltaic region, can reach more than three times the summer surface area of the lagoon (Pétrequin & Pétrequin, 1984). Hydrodynamic functioning with its sedimentary inputs, eutrophication (Maiga, Denyigba, & Allorent, 2001; Mama, 2010), and the exponential development of the acadjas (system of branch parks stored as fish traps) has led to the filling of the lagoon by approximately 0.03 m/year (Mama et al., 2011).

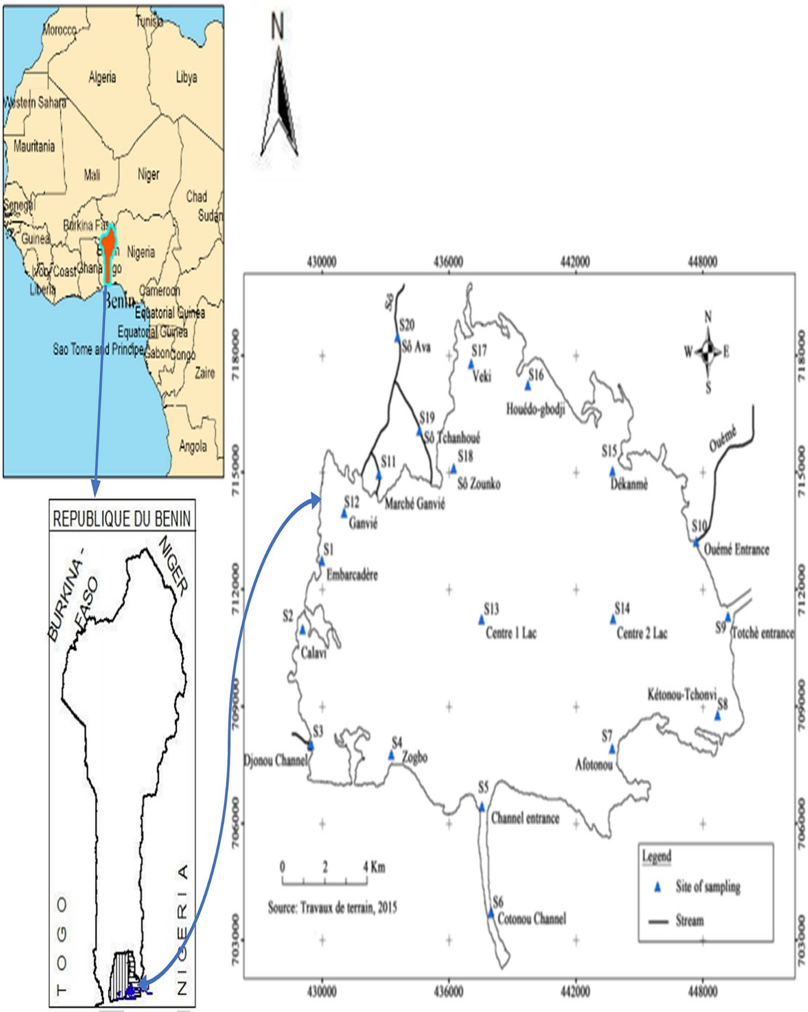

Figure 1 Location of the sampling sites (Source : Adapted and modified from Zandagba et al. (2016)))

2.2 Physicochemical parameters, stressors, and natural forcing variables

The data collection covered a 9-year period divided into three subperiods: 2002-2006 and 2014-2016 as model training data and a set of new observations over 2021, i.e., approximately 5% of the observations for cross-validation. All data were acquired from several comparable scientific studies using the same sampling protocols and laboratory analyses based on standardized methods (AFNOR (1997); SIAppendix,Table1)

2.2.1 Physicochemical parameters

A total of 17 physicochemical parameters were monitored on 20 sampling points (Fig. 1): water temperature (Temp), transparency (Trans), turbidity (Turb), conductivity (Cond), salinity (Sal), pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), Kjeldahl nitrogen (TKN), ammonium (NH_4^+), nitrates (NO_3^-), nitrites (NO_2^-), dry organic matter content (DM), orthophosphates ($PO_4^{(}3-)$), total phosphorus (TP), and suspended matter (SM). The geographical distribution of these sampling points was selected to cover the entire lagoon complex while considering the inflows and outflows at the level of the tributaries, the salinity gradient, the diversity of substrates, as well as the areas where various human activities take place around and on the lagoon. Physicochemical parameters were extracted from several publications (Gnohossou, 2006; Odountan et al., 2019; Zandagba et al., 2016) and completed by unpublished and additional physicochemical data collection. Parameters were measured according to the four seasons of the year in samples taken at 5 cm from the surface. The measurement methods and variation ranges of the parameters can be found in SIAppendix,Table1

2.2.2 Stressors

A circular buffer of 5 km around each physicochemical sampling point was defined as a station. We selected nine driving forces that described factors likely to induce pressures and to explain the physicochemical characteristics of the station (Bouchoucha, Battut, Laugier, & Derolez, 2010; Pirrone et al., 2005). The absence (0) or presence (1) of a lake village (LV) and of acadjas (Acd) was determined for each sampled year. Frequentation (Frq) of the station corresponds to the number of visits estimated from the counts made by Sossou-Agbo (2009), some data from the Department of Tourism and mostly from observations of people familiar with the place. Frq is the expression of the approximate cumulative number of tourists, lagoon sand dredgers, traders, and users of pirogues or motorboats. Frq was coded into three classes: low (class 1, frequency of 3,000 or fewer visits), medium (class 2, frequency of 3,000-10,000 visits), or high (class 3, frequency of more than 10,000 visits). Potential sources of discharges (Sdr: dumps, direct discharges of solid and household waste, domestic sewage, sewage outfall discharges, and stormwater collectors) were determined by the number of sources present in the area of each station. Sdr was encoded into four classes: "No release sources" (0); "One release source" (1); "Two release sources" (2); and "More than three release sources" (3). The number of fishermen and fish wholesalers (FW) operating in a station was coded into two classes: number of FW below 3,000 (1) and above 3,000 (2). These three qualitative variables were established based on extrapolations made from the monographs of the various communes and on personal knowledge of the lagoon and its environment. Tributaries were considered at the origin of considerable nutrient and sediment loading in the lagoon. Their impacts were taken into account by measuring the distance in kilometers separating each of the four main tributaries [Sô River (So), Ouémé River (MR), Totchè channel (TC), and Djonou River (DR)] from each of the stations with Arc GIS (10.4.1). Land cover data were obtained using land cover maps developed from Sentinel-1A imagery, satellite imagery, and existing land cover maps, corresponding to each of the years sampled. We thus defined for each year the proportion of each station area occupied by forest (OcF), agriculture (OcA), and urbanized (OcU) land. OcF includes mangrove patches, wet grasslands, swamps, herbaceous cover, tree and shrub cover, forest patches, and coconut groves; OcA includes food crops, crops under palms and palm groves, cultivated savannahs, market gardens, and cultivated land; and OcU gathers built-up areas, paved main and secondary roads, industrial areas, residential areas, bridges, and culverts.

2.2.3 Natural forcing environment

Temporal variation was assessed using years and seasons (SWS: short wet season or flood period; SDS: short dry season; LWS: long wet season; LDS: long dry season) as explanatory variables. In addition, the monthly average water level (MAWL) and average wind speed (AWS), known to influence the physicochemical parameters in the context of Nokoué (Mama, 2010), were also used as variables able to explain the physicochemical variability and therefore to improve the modeling of the physicochemical parameters. MAWLs were reduced averages calculated on the basis of water heights taken hour by hour on the SHOM site[2](SHOM, 2022) for the Port of Cotonou (Coordinates: 006 °21' 00.0" N, 002 °26' 00.0" E), excluding 20% of the extremum of the daily tidal heights observed over a month. AWS was an arithmetic average of values taken month by month from the history of wind speed recorded at Cadjehoun Airport (Cotonou) and available on the Weather Underground website[3](Underground, 2022). The data set had approximately 16% of missing data for all these physicochemical and stressor observations. Missing data imputation was performed using the "missForest" nonparametric analysis algorithm for mixed-type data (Stekhoven & Bühlmann, 2012).

2.3 Selection of physicochemical parameters for water quality monitoring

Selection of the physicochemical monitoring parameters comprised four steps (Fig. 2).

Step 1: Multicollinearity of the data is often a source of redundancy (Chang, Wu, Tsai, & Herricks, 2009; Kovács, Petres, & Tóth, 2006), instability, and regression interpretation problems (Adedayo & Ojo, 2018). The aim of this step was therefore to remove the redundant (multicollinear) predictors (stressors, temporal variables, and natural forcing environment variables)

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[2] https://maree.shom.fr/harbor/COTONOU/wl/0?date=2021-04-15&utc=1
[3] https://www.wunderground.com/history/daily/bj/cotonou/DBBB

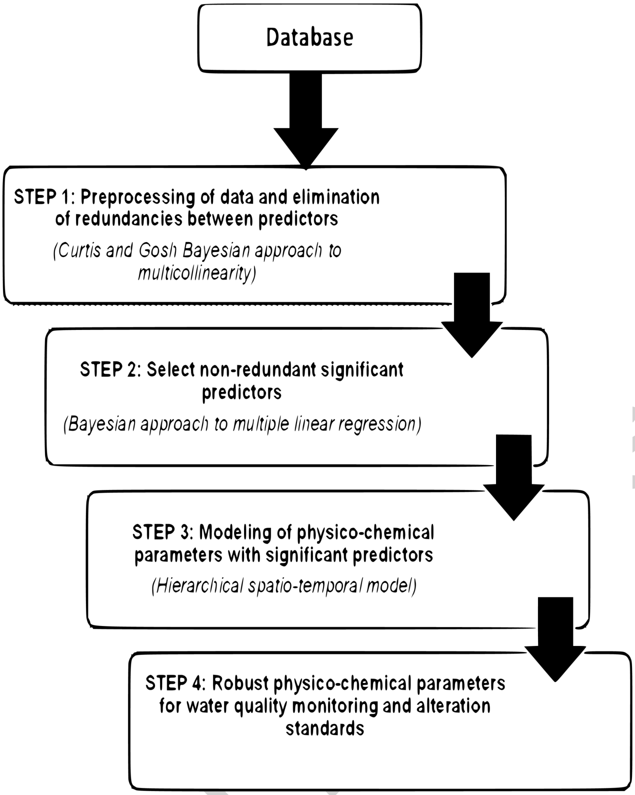

Figure 2 Schematic view of the selection steps

through a hierarchical Bayesian model developed by Curtis and Ghosh (2011), where some coefficients of the posterior medians are forced to be zero. For each of the physicochemical parameters, only predictors with non-zero coefficients of the posterior medians are non-redundant and thus retained. To this end, data preprocessing consisted in centering the response variables (physico-chemical parameters), then in centering and scaling the predictors so that the intercept term may be ignored.

Step 2: The most significant predictors explaining each physicochemical parameter taken individually were selected by a Bayesian multiple linear regression analysis. It aims at testing each of the physicochemical parameters one after the other among the non-redundant predictors associated with them (step 1). This step will lead to the design of an effect matrix (EM) summing up the relationships between the predictors and the physicochemical parameters (response variables).

Step 3: A spatiotemporal prediction of each of the physicochemical parameters was necessary to confirm their effective variability with respect to their different observations. This modeling will allow us to deduce, for each predicted physicochemical parameter, the limits of the credibility interval of the intercept term (beta0) as a local alteration standard. This consideration comes from the fact that beta0 is the estimated mean of the response variable in all groups when the within-subject predictors are assumed to be equal to 0 (Kruschke, 2015). Indeed, in most cases, water quality in watersheds is subject to both temporal and spatial changes. These changes are the results of various combinations of natural and/or anthropogenic factors (Bojarczuk, Jelonkiewicz, & Lenart-Boron, 2018). The model developed here integrates factors characterizing seasonal and interannual temporal variability (sub-model 1) and one or more spatial random effects (sub-model 2) and should therefore lead to the selection of physicochemical parameters with a good fit $R^2 \geq 50\%$ following their prediction. Stressors associated with each of the response variables (step 2) were used for the modeling. The implementation of this model was performed with R software version 4.0.4 (R Development Core Team, 2010) and Bayesian inference with jags packages that are rjags (Plummer, Stukalov, Denwood, & Plummer, 2016) and R2jags (Su, Yajima, Su, & SystemRequirements, 2015). MCMC simulation with a Gibbs sampler was used as a computational tool to generate samples of the posterior distribution Gilks (2005). Three chains per parameter were used with 30,000 iterations per chain and burning the first 5,000 iterations. Details of the model are shown in SIAppendix,Figure1

Step 4: The objective of this step is to determine among the physicochemical parameters selected at the end of step 3 (Fig. 2), those that were redundant and, when two of these parameters were redundant, to select only the one presenting more responses to the stressors and fewer temporal variations. The Bayesian equivalent of Spearman's correlation test (Rasmus, 2013) between the response variables was used to detect redundancies (rho≥0.75). This value of rho in our case seems to be more consistent with the approach used and is just as robust as the 0.8 proposed by Hering, Feld, Moog, and Ofenböck (2006).

2.4 Definition of quality thresholds and prediction validation criteria

We assume that the greater the impact of the stressors, the further a station's water quality will deviate from the intercept term (beta0). A better compromise for the threshold value will be the lower limit of the credibility interval ($C-interval$) of beta0 for all parameters except Trans, pH, and DO. For these three parameters, the compromise was the upper limit of the $C - interval$ of beta0. When this lower bound was negative, we opted for the median value of $C - interval$. These threshold values were considered as local alteration standards or those defined with the minimum disturbance conditions (Stoddard, Larsen, Hawkins, Johnson, & Norris, 2006). The cross-validation of the model was assessed by the following group of 03 indicators: R^2, nRMSE (Normalized Root Mean Square Error), and bias.

3 Results

3.1 Physicochemical elements selected and impacts of stressors

Among the 17 physicochemical parameters analyzed, 16 responded to at least one of the factors considered (Table 1); 11 parameters fluctuated with the seasons and/or the year. This makes these two temporal variables ”stable factors” that cause significant changes and impact the water quality of the lagoon. Several of the most significant seasonal changes occurred during SWS and to a lesser extent during LWS(Table 1). Interannual variability was observed for the following physicochemical parameters: $PO_4^{(}3-);NO_3^-;NO_2^-;NH_4^+$; TKN; Turb; DO (Table 1). Overall, $PO_4^{(}3-);NO_3^-$ and DO contents tended to decrease, while there was an increasing trend instead for NO_2^-, NH_4^+, TKN, and Turb. Stressors represented by the Ouémé River (MR) did not significantly affect any physicochemical parameter. Temperature was influenced by three driving forces. OcA and LV contributed to a reduction in water temperature while a positive effect of FW was noted. The number of discharge sources (Sdr) contributed to an increase in total phosphorus while a negative influence of forests on this chemical parameter was indicated. The increase in $PO_4^{(}3-)$ is the result of four driving forces: agriculture (through fertilizers) and repeated point source discharges by lagoon and non-lagoon populations and acadjas. The negative effect of winds that was highlighted reflects the small impact of this natural forcing factor on sediment resuspension in our case. OcF and OcA tend to acidify the lagoon while, conversely, Sdr, LV, and FW tend to make it alkaline. In addition, flooding (SWS) and wind (AWS) cause acidification of the lagoon. NH_4^+ is negatively influenced by the stressors OcA and Acd. TKN is sensitive to six of the 12 stressors and is therefore influenced by human activities. The stress factor Frq causes a decrease in nitrate content. The Nokoué is enriched in nitrates by effluents (Sdr) and through soil leaching by runoff during floods. While OcF, Acd, and MAWL cause the Nokoué to be depleted in nitrates, OcU, Sdr, and FW induce its enrichment in nitrites. In total, five out of seven stressors negatively influence nitrate (Table 1). The annual accumulation of NO_2^-, NH_4^+, and TKN in the lagoon further fuels its eutrophication. Djonou and Totchè supply the lagoon with organic matter. Although DM inputs might be expected to increase during floods and the main rainy season, they in fact tend to decrease. Acadja parks are systems with less organic matter. The very turbid character of the lagoon is maintained under the influence of OcA, LV, Acd, and floods as well as winds. Surprisingly, Djonou and Totchè do not contribute to the turbidity of the Nokoué, although they contribute to an increase in its organic matter. Sô and Totchè increased the oxygenation level of the lagoon while Sdr induced its hypoxia. Three stressors (LV, Frq, Sdr) are involved in the decrease of transparency. The negative impact of OcF and Acd on BOD is also noted. Winds influence DO negatively. In addition to continental and marine inputs of salt water, the dissolved salt content of the lagoon is positively related to four stressors: OcA, Totchè, Sô, and Sdr. These human activities therefore contribute significantly to its secondary salinity. OcF negatively affects salinity as well as the hydrodynamics induced by wind speed. The direct effects of land use are generally less perceptible. A better positioning of the sampling points, to consider what is happening directly in the watershed, would make the interpretations more readable.

Table 1 Effects matrix (EM) between physicochemical parameters and associated predictors

Physico-chemicals Parameters		**"Water Temperature"**	**"TotalPhosphorus"**	$PO_4^(3-)$	NO_3^-	NO_2^-	NH_4^+	**TKN**	**Turbidity**	**Dissolved oxygen**
"Driving Forces"	**Forest Occupation**		-		-			-		
	Agricultural Occupation	-		+			-	-	+	
	Urbanized occupation					+		-		
	Totchè								-	+
	Mouth river (MR)									
	River So									+
	Djonou							-	-	
	Lake village	-		+					+	
	Acadjas			+	-		-	-	+	
	"Discharge or Release Sources"		(4+)	+	(3)+	(2+)				(2-)
	Frequentations				(2)(3)-			(3)-		
	"Fishermen and Wholesalers"	+				+				
"Variables Temporal"	**Seasons**	LWS'SDS'SWS'-			SWS'+				SWS'+	
	Year			-	-	+	+	+	+	-
	Average Winds Speed			-					+	-
	Monthly Average Water Level				-					
Selected variables or not		S	S	S	S	X	X	S	D	S
Physico-chemicals Parameters		**Transparency**	**Dry Organic Matter**	**"Suspended Matters"**	**BOD**	**COD**	**pH**	**Salinity**	**Conductivity**	
"Driving Forces"	**Forest Occupation**	-			-		-	-		
	Agricultural Occupation		-				-	+		
	Urbanized occupation									
	Totchè		+					+		
	Mouth river (MR)									
	River So		-					+		
	Djonou		+							
	Lake village	-					+			
	Acadjas		-		-					
	"Discharge or Release Sources"	-					(3+)	(2)+		
	Frequentations	-				(3-)				
	"Fishermen and Wholesalers"	+					+			
"Variables Temporal"	**Seasons**		LWS/SWS'-	SWS'+			SWS'-			
	Year									
	Average Winds Speed	-			-	-	-	-		
	Monthly Average Water Level									
Selected variables or not		S	S	N	S	D	S	S	N	

Note:N = No significant response to predictors (dropped since step 2); X = Reject after step 3; D = Delete after step 4; S =Selected parameters; " + ": Positive effect; " − " Negative effect; (2)(3)(4) = Level of a categorical variable.

3.2 Modeling and redundancy deletion

Following step 2, the parameters Conductivity and SM were dropped because they did not respond to any stressors. In step 3 modeling, NO_2^- (R^2=3.89%), NH_4^+(R^2 =14.62%) were also excluded. Among the parameters responding to stressors (Step 4), COD and BOD were highly correlated (rho=0.879; C95%- interval [0.857, 0.897]) as were turbidity and DM (rho=-0.76; C95%-interval [-0.798, -0.725]). From this correlation analysis, BOD and DM were retained because they respond to more stressors and presented less natural variability than COD and turbidity. Finally, 11 of the 17 physicochemical parameters were selected for the monitoring of the water quality of Nokoué: TP,$PO_4^(3-)$,NO_3^-,TKN, DM, DO, BOD, Sal, pH, Trans, and Temp. The results of cross-validation reveal a model that generalizes well, and predictions are relevant for all physicochemical parameters ($R^2 \cong 0.99$). For all predictions, the model produced low bias and variance (Table 2).

The goodness-of-fit of the model to predict these physicochemical parameters showed that the stressors used for the prediction induced the actual changes in the observed physicochemical status. For verification, the graphical results of the predictions are presented in SIAppendix,Fig.2 In addition to

Table 2 Validation results of the prediction models

Predicted parameters	nRMSE (%)	Bias (%)	Predicted parameters	nRMSE (%)	Bias (%)
TP	0.7	-0.11	DM	0.7	-0.086
BOD	1.6	-0.31	TKN	1.5	-0.49
Temp	0	-0.048	Sal	0.1	0.012
DO	0.4	-0.13	NO_3^-	0	0.1
$PO_4^{(}3-)$	7.7	0.015	pH	0.1	0.15

the robust selection made (Step 4), the credibility intervals of the intercept term (beta0) for each of the modeled parameters (Step 3) allow us to define alteration norms for each of them. These different standards as well as the main stressors associated with the physicochemical parameters are presented in Table 3. These quality threshold values (Table 3) enable the evaluation of the degree of degradation.

Table 3 Alteration standards and stressors associated with physicochemical parameters

Physico-chemical monitoring parameters	Suggested physico-chemical alteration standards	Main Stressors Associated
BOD	GS$\leq$ 11.6$\leq$ BS (BOD,mg/L)	OcA;OcU;Totchè; Djonou;Acd
DM	GS$\leq$ 5$\leq$ BS (DM ,mg/L)	
Nitrates	GS$\leq$ 0.5$\leq$ BS (Nitrates,mg/L)	Frq;OcF;OcA; OcU;Sdr;Acd
TKN	GS$\leq$ 1.85 $\leq$ BS(TKN,mg/L)	
TP	GS$\leq$ 4.5 $\leq$ BS(TP,mg/L)	
Orthophosphates	GS$\leq$ 0.2$\leq$ BS (Orthophosphates,mg/L)	OcF;Sdr;Acd
pH	BS$\leq$ 6.2 $\leq$ GS (pH)	
Transparency	BS$\leq$ 0.9 $\leq$ GS(Trans,m)	FW;Totchè;So;Sdr
Salinity	Upstream $\leq$ 7.6 $\leq$ Downstream(Sal,‰)	
Dissolved Oxygen	BS$\leq$ 4 $\leq$ GS(DO,mg/L)	
Water Temperature	GS$\leq$ 28.7 $\leq$ BS(Temp,°C)	OcA;So

Note: (Upstream: Close to the So River and or the mouth of Ouémé River; Downstream : Close to the Totchè and Cotonou canals; GS: Good physicochemical status; BS: Bad physicochemical status)

4 Discussions

4.1 Physicochemical parameters selected and impacts of stressors

Our results show that among the 17 physicochemical parameters analyzed, 11 can be selected to monitor and highlight the anthropic impacts of different stressors identified in Nokoué. The temperature decrease observed is justified by the shade provided by the lake villages and the influence of the regularly flooded vegetation cover present in the Ouémé and Sô watersheds (Mama, 2010). Shading indeed has a well-known inhibiting effect on river warming (Kalny et al., 2017). The presence of trees and shrubs in cultivated areas near the lagoon and the shading caused by stilt houses would also help to explain the temperature decrease. However, the increase in temperature by fishing activities we observed is more likely a spurious correlation.

Domestic sewage as a source of discharge (Sdr) is mainly composed of detergents and is a source of phosphorus (Mama, 2010). Similarly, the composition of the acadjas (branch parks) can contribute to phosphorus enrichment (Menon & Holland, 2014). Mama (2010) estimate the annual phosphorus input by acadjas in Nokoué to be more than 1t. In view of the fact that orthophosphate is the bioavailable form of phosphorus in solution (C.S. Reynolds & Davies, 2001), we are able to determine that the acadjas also cause an increase in orthophosphate content. It should also be noted that wind-induced mixing can result in sediment resuspension releasing orthophosphate (Rollwagen-Bollens, Lee, Rose, & Bollens, 2018). The roles of the stressors Sdr, LV, and FW in increasing pH are comparable and confirm the roles of effluent and discharge in the work of Luklema (1969). The acidification of waters by forests is a well-described process (Dunford, Donoghue, & Burt, 2012; Nisbet, Evans, Great Britain, Forestry Commission, & New Zealand Forest Research Institute, 2014; B. Reynolds, 2004), while in agriculture, it is the use of nitrogen fertilizers that often causes acidification (Schindler, Turner, & Hesslein, 1985). Freshwater inputs leading to upwelling and driven by winds (Kuhlbrodt et al., 2007) could also lead to this acidification (Lachkar, 2014). Moreover, the nitrification processes highlighted by our results are also acid-releasing (Stroo, Klein, & Alexander, 1986).

The decrease in the water column nitrate content and in TKN could originate from sediment denitrification that releases N2 from nitrates whose particulate N remains buried in the sediment, especially in wave-dominated estuaries (Ryan, 2003). Multiple frequentations (Frq) observed during dredging activities, for example, could result in a significant difference in nitrate levels between dredged and undredged areas (Adekunbi, Elegbede, Akhiromen, Oluwagunke, & Oyatola, 2018). OcF and OcA are responsible for the hydrolysis of TKN to ammonia nitrogen. This seems to produce the observed decrease in TKN. TKN decreases when one of these components decreases. It should be borne in mind that ammonia nitrogen and/or organic nitrogen are the components of TKN (Haghighat & Kim, 2009). Organic nitrogen, a component of TKN that is released in OcU, will also hydrolyze to NH_4^+. Then, NH_4^+ also decreases because it is oxidized by nitrification to NO_3^- and/or NO_2^- (Bernhard, 2010) and this occurs mainly in estuaries (Garnier et al., 2006). Djonou inputs and acadjas areas appear to be acidic and have lower TKN. This seems to be the consequence of the nitrification process. In agreement with the work of Hagebro, Bang, and Somer (1983) on total nitrate inputs, it can be seen that inputs would come more from diffuse leaching than from discharge sources. Considering the number of stress factors negatively influencing nitrates, we could also affirm alongside Seitzinger et al. (2006) that estuaries such as the Nokoué are nitrate-loss zones.

Allochthonous inputs such as those related to organic matter and from near and distant sources in contiguous marine systems are already well known in estuaries (Lake & Brush, 2015). The decay in organic matter noted during periods of flooding and heavy rainfall is likely due to the rapid degradation of organic matter during flooding (Lin, Wood, Haskins, Ryffel, & Lin, 2004). Given that the acadjas are input-limiting systems (Guiral, ARFI, DA, & KONAN-BROU, 1993), they should a priori harbor less organic matter than Nokoué as a whole. Lastly, the decrease in dry organic matter due to OcA does not seem to be theoretically explicable. Floodplains during floods, such as those in the Totchè watershed and at the entrance to the Djonou River, are known to retain some of the suspended elements (Mulder & Syvitski, 1995), thus helping to lower turbidity. The extensive grass cover between the Djonou entrance and the lagoon could explain this decrease in turbidity. Riparian vegetation is generally considered a filter (Tanaka, Minggat, & Roseli, 2021).

The oxygenation provided by the Sô and Ouémé rivers is coherent since they are the main sources of freshwater in Nokoué (Mama, 2010) and carry a low COD load: mean COD Sô = 49.39 mg/L, mean COD Totchè = 42.36 mg/L, mean COD Djonou = 108.63mg/L. The negative impact of winds on DO is obviously surprising (Tamburrino & Martínez, 2017). However, it seems that winds are more responsible for hypoxic upwelling in our system than for mixing. This is even more true since the Nokoué is oligomictic and without stratification in its entirety, except in areas close to the sea (Millet, 1985). For most of the time, it is likely that hypoxia is maintained by point sources of discharge (Jenny et al., 2016) and indirectly by eutrophication (Selman, Sugg, Greenhalgh, & Diaz, 2008) as well as the factors favoring the accumulation of organic matter (Paerl, Pinckney, Fear, & Peierls, 1998) that are Djonou and Totchè.

The negative impact of forests on transparency highlighted here is hardly compatible with the findings from several publications that instead support a positive effect of forests on water transparency (Kasangaki, Chapman, & Balirwa, 2008; Roozen et al., 2003) or report that they reduce turbidity (Brauman, Daily, Duarte, & Mooney, 2007; Cunha, Sabogal-Paz, & Dodds, 2016), and is difficult to interpret. The lower transparency values observed in lake villages (LV) with high visitation rates and direct discharge of domestic effluent are more consistent with the expected mechanical effects of these stressors (Galib et al., 2018). Mangroves not only reduce the total nutrient load (Wang, Cheng, Chen, & Kuo, 2021), but they also have the potential to absorb pollutants (Nguyen, Truong, & Pham, 2020) and should therefore lead to a decrease in BOD. Grasslands are also no exception, as they show a negative relationship with organic pollution (Xu, Jin, Mo, Tang, & Li, 2020). Acadjas are branched parks, where several functional food groups live and feed on the degradation products of detritus feeders (Le Lay & Piégay, 2007) including organic pollution. Wind speed appears to negatively influence BOD and COD in Nokoué, as it does in other eutrophic lakes (Wu, Xia, Li, & Mou, 2014). Considering the transfer and transformation of nitrogen at the water-sediment interface

(Yongchuan & Li, 2005) to which waves could contribute, on the one hand, and the negative correlation that exists between COD in water and sediment nitrogen content (Shan et al., 2020), on the other hand, the negative effect of Frq on COD could probably be justified.

Finally, regarding secondary salinization (Cañedo-Argüelles et al., 2013), the present study seems to be the only one to reveal this type of alteration. The stressors causing such alteration are those generally implicated in the works of Létolle and Chesterikoff (1999) and Dikio (2010). The best justification for the inability of the model to capture the random fluctuations and variations in the training data set for the parameters (NO_2^-, NH_4^+) (Step3-Table1) would be that the significant stressors selected to explain these 02 parameters are not the only ones involved, or that the relationship between these parameters and the stressors that induce them is not linear.

Among the 11 physicochemical elements selected, the least common in monitoring programs is DM. The other physicochemical elements are often selected both for their ability to account for or to predict dynamically the environmental conditions at the origin of the state of the biological compartments. Compared to the 62 parameters monitored in India (Evans, Hanjra, Jiang, Qadir, & Drechsel, 2012), the 32 monitored in Pakistan (Magtanong, 2015), and the large number of physicochemical elements in use in European states (Claussen, Müller, & Arle, 2012), this selection of 11 parameters is the least exhaustive but is able to highlight the alterations related to all the driving forces occurring in Nokoué Lake and probably in other comparable ecosystems since these stressors are frequent in such tropical lakes.

4.2 Suggested thresholds of physicochemical alterations

The definition of physicochemical thresholds is often required for the management of ecosystems (Roubeix et al., 2017).Given the specificity of aquatic ecosystems (e.g. environmental context, ecological and typological zonation.), it is hardly possible to continue using standards and indicators established in one context to assess the status of waters in other contexts. In West Africa, as in Nigeria, water quality standards are developed based on a review of standards from developed and developing countries and international organizations (FEPA, 1991). Although the alteration thresholds proposed in this paper are not designed in coherence with the responses of biological communities to environmental gradients as indicated by the European Water Framework Directive (WFD, 2000/60/EC) (Roubeix et al., 2017), they are nevertheless comparable to those proposed by the System for the Evaluation of Coastal Water Quality (SEQ-Eau). The suggested thresholds that we proposed correspond to suitability classes that vary from very good to average, except for total phosphorus. The European standard for TP is 0.05 mg/L in lakes and 2 mg/L in Mediterranean transitional waters according to the decree of July 27, 2018 (Légifrance) (Bouchoucha et al., 2019), while we propose a limit of 4.5 mg/L. A sedimentary geological substrate very rich in phosphorus (Cózar et al., 2007) would explain this difference. Thus, there is an internal stock of total phosphorus in the lagoon that is not of anthropogenic origin.

However, at the African level, the Nigerian Industrial Standard (NIS; (Ayandiran, Fawole, & Dahunsi, 2018; Government, 2011) and the WHO Standards (Ayandiran et al., 2018) are the ones generally used as reference. In terms of defining coastal marine ecosystem quality standards for nutrients, the South African Department of Environmental Affairs recommends a range of values, derived from statistical/mathematical modeling or based on the 80th percentile or on expert basis (PAGE, 2018). Compared to the first two standard schemes(NIS; WHO), our threshold value for BOD is higher, while our suggested thresholds for pH, nitrate, and dissolved oxygen are lower. It would be good to know how these standards have been developed in order to discuss the difference observed. These differences are probably since these standards consider in their constitution health targets and the possibility of making surface water sources drinkable. This is not our case. A comparison with other international standards without consideration of typology (Table 4), reassures us of the validity of the proposed thresholds.

Table 4 Comparison of selected international standards for water quality parameters with the present impairment thresholds.

	Our Thresholds	US EPA *	DoE	DPHE
Total Phosphorus(mg/L)	<4.5	0.03-0.1	-	-
BOD(mg/L)	<11.6	<6	50	<6
Water Temperature(°C)	<28.7	20-30	20-30	20-30
Dissolved Oxygen(mg/L)	>4	3-5	4-6	6
Orthophosphates(mg/L)	<0.2	0.025-0.18	-	-
DM(mg/L)	<5	-	-	-
TKN(mg/L)	<1.85	1-1.7	-	-
Salinity (‰)	7.6	-	-	-
Nitrates(mg/L)	<0.5	0.25-45	-	-
pH	>6.2	6.0-8.5	6.5-8.5	6.5-8.5
Transparency (m)	>0.9	0.3-2.5	-	-

Note : Department of Environment (DoE- Bangladesh) (1997), Department of Public Health Engineering (DPHE- Bangladesh) (2019), and USEPA - United States Environmental Protection Agency; US EPA* The value ranges are taken for all types and all available states together. *Source*:Extracted values for DoE and DPHE from (Rahman, Jahanara, & Jolly, 2021))

4.3 Data and methodological considerations

Data-scarce regions of the world will continue to have uncertain assessments of their water resources (Stewart, 2015). This can be an a priori hindrance to the development of ecosystem management programs. The lack of continuous data and observations can lead to biases in the various estimates (Groenwold & Dekkers, 2020). The Bayesian approach is best suited to deal with these problems (Ma & Chen, 2018). Nevertheless, to avoid mis-specifying the shape of the missing data model, which can negatively affect the performance of

Bayesian methods (Mason, 2009), imputation of missing data with the non-parametric ”missForest” algorithm was a prerequisite. The use of Bayesian inference for the rest of the steps of this work was of great value. Indeed, it allowed us to bypass the obstacle of imprecise observations (Yao, 2020), to overcome more easily the problems of redundancy, to erase the strong natural variabilities, to establish the limits of a credibility interval of interest for the definition of pseudo-norms of alteration, and finally to infer a selection of robust physicochemical parameters for follow-up.

5 Conclusion

Using Bayesian inferences, we determined the 11 most relevant physicochemical parameters that make it possible to evaluate the impacts of the main stressors that may alter the ecological status of the Nokoué. Pseudo-quality standards were also proposed to quantify the level of alteration and the impacts of stressors on physicochemistry. The impacts of stressors on physicochemistry revealed a heterogeneous situation in terms of alteration, such as eutrophication mainly but also hypoxia, acidification, secondary salinization, and nitrite pollution.Overall, the understanding of the relationships between physico-chemical parameters and driving forces has made it possible to account for the specificity of the ecosystem studied, and to lift the veil on the most relevant and adapted parameters for certain evaluations of its state of physico-chemical alteration. It thus appears, following the example of Nokoué (Benin), that each ecosystem has parameters and alteration thresholds specific to its monitoring. Although most of the thresholds proposed for this ecosystem seem comparable to international standards, they are nevertheless very specific to it. This is the case for the alteration thresholds for total phosphorus, BOD, TKN.... These specificities as well as the understanding of the impacts of certain driving forces (Acadjas, Lake Villages, direct discharges, frequentation...) built from these analyses should allow to avoid uncertain evaluations of its physicochemical quality and to support its monitoring process. This set of physicochemical parameters and their alteration standards will provide the organizations in charge of water and ecosystem management with relevant information to carry out restoration actions limiting monitoring expenses. The results of this paper also constitute a basis for the monitoring of this ecosystem, which provides many services in the long term, and for enhanced knowledge of the system through the establishment of a database. In addition, while most West African aquatic ecosystems are poorly monitored, the methodology adopted here, applicable to all surface waters, could contribute to strengthen the monitoring of lakes in the region so as to prevent additional degradation and to alert in cases of degradation that may impact the ecosystem services. From this perspective, we plan to extend these physicochemical quality monitoring tools to other ecosystems in the region that consider the responses of biological communities and to design composite and metric indicators that could be even more informative.

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Declarations

- Availability of data and materials
  The authors declare that the data as well as the R scripts used in this manuscript can be downloaded from the links provided in Supplementary materials. Other supplementary information are presented too in Supplementary materials (SI.Appendix)
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