



Nitrogen and phosphorus spatio-temporal distribution and fluxes intensifying eutrophication in three tropical rivers of Côte d'Ivoire (West Africa)

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ABSTRACT

Nutrient contamination assessments in the three West African tropical Comoé, Bandama, and Bia Rivers (Côte d'Ivoire) were performed from March 2016 to March 2018. Five stations per river were sampled. Nutrients spatio-temporal distributions were mapped and showed nitrogen concentrations (nitrite 0.001 to 0.025 mg/L NO₂⁻-N, and nitrate 0.26 to 3.60 mg/L NO₃⁻-N) increased significantly with rainfall contrary to phosphorus (0.01 to 0.12 mg/L P). The Chl-*a* and TSI_{sr} data revealed the hypereutrophic status of rivers. Moreover, N:P mass ratio suggests nitrogen as the main limiting factor of primary production during the low (March) and high flow periods (October–November), while phosphorus is the limiting factor in June, at the high flow beginning. The land uses around watersheds were the main sources of phosphorus and nitrogen enhancing the rivers' eutrophication. Phosphorus and nitrogen fluxes were related to leaching river catchments and were significant sources of nutrients to the Atlantic Ocean.

1. Introduction

Eutrophication of continental waters such as rivers is one of the most prevalent environmental problems in the world in terms of water quality (Wang and Yu, 2014). The main consequences of this process are hypoxia/anoxia, increased primary production followed by high turbidity, and a decrease in phytoplankton diversity (Aguilar et al., 2011; Chen et al., 2016; Yasin et al., 2010). Land use along river watersheds is well known to impact their nutrient (N&P) enrichments (Castilla et al., 2015; Ding et al., 2015; Lopes et al., 2019). Rivers carry nutrients to downstream habitats and some of the effects of nutrients in large rivers or small streams reach coastal waters. In general, chlorophyll-*a* is the main indicator in monitoring eutrophication. However, there is no consensus on the mechanisms regulating nutrients - chlorophyll-*a* relationships in water masses located in different climatic regions (Huszar et al., 2006). Nitrogen limitation may be more common in tropical systems (Lewis, 2002). However, some authors have reported that nitrogen did not

explain a significant part of the variation in chlorophyll-*a* in tropical/subtropical waterbodies (Cunha et al., 2013a; Mazumder and Havens, 1998). In reality, nutrient cycles are not isolated from each other. A joint reduction of the inputs of N and P is therefore essential to slow down eutrophication along the land-sea continuum (Paerl et al., 2016). Globally, the nutrient concentration in rivers has been shown to increase by at least 50 % (Dodds, 2006). Yasin et al. (2010) estimated that between 1970 and 2000, total nutrient exports from African rivers to coastal waters increased dramatically by 10–80 % and that the total dissolved N and P forms will increase over the 2000–2050 time periods. This increase results from population growth associated with intensive agriculture, urbanization, and the increasing number of people connected to sewage systems (Cruz et al., 2019). In the coming decades, river nutrient exports may continue to increase, but not in all forms and not in all African basins (Yasin et al., 2010). It is therefore necessary to monitor the evolution of eutrophication for the preservation of the quality of freshwater.

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Rivers eutrophication is currently evaluated using indicators comprising three distinct characteristics, namely: the causes (nutrients contents such as inorganic nitrogen and phosphorus), the direct effects (primary productivity, chlorophyll-*a*, clarity), and the indirect effects (oxygen levels) (Ibsch et al., 2017; Le Moal et al., 2019). Many indices such as trophic indexes (TRIX, TLI, and TSI) are frequently used successfully both to monitor the surface water quality and to classify trophic levels of rivers and lakes using chlorophyll-*a*, nutrient concentrations as well as certain physico-chemical parameters (Cunha et al., 2013a; Huo et al., 2013; Moscuza et al., 2007; Ota et al., 2015; Pettine et al., 2007; Singh and Singh, 2015; Wu et al., 2018).

Although many multiyear water quality databases exist for the large number of worldwide rivers, more relevant studies are needed in West African regions. For example, in Côte d'Ivoire, all the rivers are facing great pressure from urbanization, intensive agriculture, and aquaculture besides the implementation of the main industrial poles in many areas of the country (Soro et al., 2020). Eutrophication studies have up to now focused on lagoons and lakes in Côte d'Ivoire (Adon et al., 2019; Koffi et al., 2019; Koné et al., 2006; Ouffoué et al., 2014; Scheren et al., 2004). However, these studies do not take much account of upstream nutrients drainage from the main rivers to the Atlantic Ocean and Ebrié, Aby, and Grand Lahou Lagoons which receive respectively the waters of the Comoé, Bia, and Bandama Rivers. Fishing activities (fish, shrimp ...) in these watersheds represent an important source of financial income for local populations. Considering the importance of the area, very few publications have provided new information in recent years, even though, over the past two decades, drastic changes related to anthropogenic pressures have occurred in the ecosystem of these rivers (Gueade et al., 2009; Soro et al., 2020). Therefore, this work attempts to fill these gaps by studying the eutrophication phenomenon of the Comoé, Bandama, and Bia Rivers.

The objective of this study was to determine the eutrophication

status of the continental waters of Côte d'Ivoire and their nutrient supply to the Atlantic Ocean.

To achieve this objective, the seasonal and spatial dynamics of nutrients were studied in relation to the hydrological regimes and anthropogenic pressures. A database providing information on the concentrations of dissolved oxygen, nutrients, and Chl-*a* in the Comoé, Bandama, and Bia Rivers was established, factors influencing nutrients loads and sources of nutrients inputs were examined through multivariate statistical analyses, the rivers water quality was assessed through water quality indices, N and P fluxes to the Lagoons/Atlantic Ocean were estimated, and the limiting factors of eutrophication were discussed. These could be of paramount importance to decision-makers with regard to river management.

2. Materials and methods

2.1. Study area

The study area concerned three main rivers which irrigate south-eastern Côte d'Ivoire, a West African country: the Comoé, Bandama, and Bia Rivers (Fig. 1). This area covers three districts: Abidjan autonomous, Comoé, and Lagunes. It has experienced a rapid population growth of about 9.9 million inhabitants according to the National Institute of Statistics (INS) population count in 2021 and has been subjected to intensive agriculture, and wild gold mining in the last 20 years, which affect the rivers water quality. This zone is dominated by cash crops such as rubber, oil palm, cashew nut, coffee, cocoa, pineapple, and sweet banana, and subsistence crops such as plantain, cassava, yam, rice, and the market gardener.

With a drainage basin of 82,408 km² and an annual average flow of about 106 m³/s, the Comoé River flows southward 1160 km in Côte d'Ivoire before discharging into Ebrié Lagoon and the Atlantic Ocean.

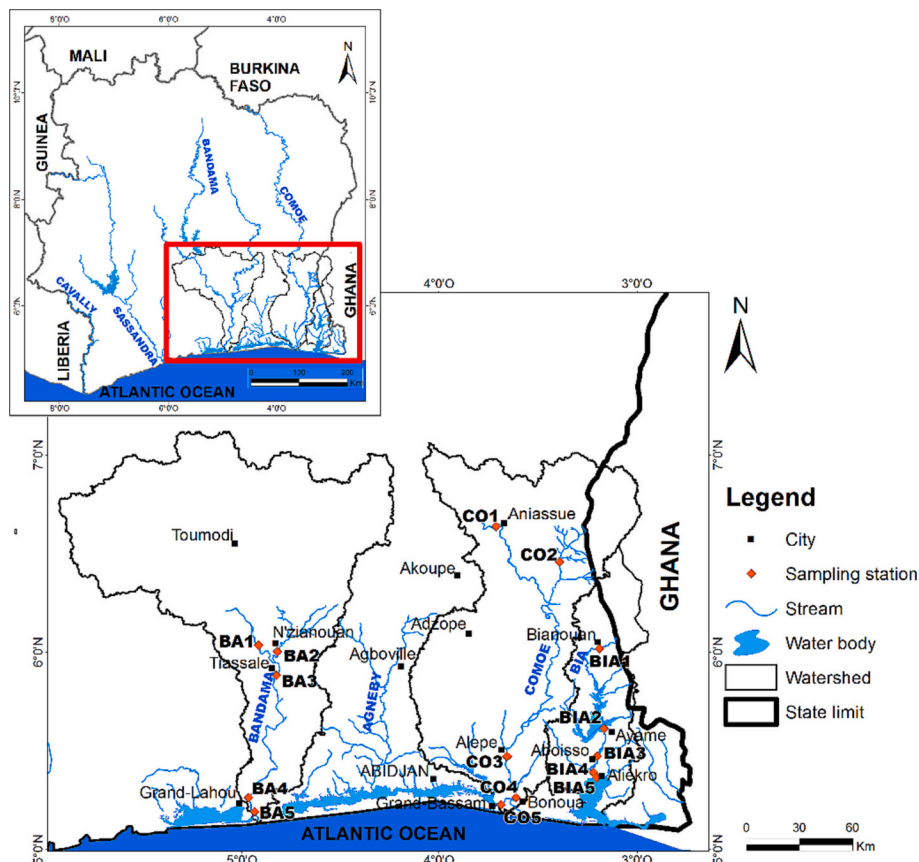


Fig. 1. Sampling stations along the Comoé, Bandama, and Bia Rivers.

Apart from a steep slope at the source, the average slope is quite low 250 m of difference in level for 1050 km, around 0.25 m per km. The Bandama River catchment area covers 97,500 km² and takes its source in the northern Côte d'Ivoire, between Korhogo and Boundiali at an altitude of 480 m and flows southward 1050 km before discharging into Grand-Lahou Lagoon and the Gulf of Guinea. The annual average discharge of this river is about 263 m³/s. The tropical transitional regime of the Comoé and Bandama Rivers is characterized by a single great flood (August–October), and a long period of low water (January–May) (Fig. S1).

The Bia River is a small river of 120 km in length with an annual flow of 104 m³/s, located in the southeast corner of Côte d'Ivoire and flows southward to discharge into Aby Lagoon. Along its watershed, the equatorial transition regime is characterized by two annual floods. The first one (usually the strongest) occurs in the June–July period and the second one spreads from October to November. A low water period is observed in August–September and another, much more marked, extends from December to March (Durand et al., 1994; Girard et al., 1970). The three river watersheds are subject to four climatic seasons, among which we have a long dry season (December–March), a long rainy season (April–July), a short dry season (August–middle September), and a short rainy season (Middle September–November).

2.2. Monitoring and sampling strategy

Six sampling campaigns in the Comoé, Bandama, and Bia Rivers were carried out in March, June, and October 2016, in June and November 2017, and in March 2018, during the dry, rainy, and flood seasons. Table 1 shows monitoring stations, geographic coordinates, and land use around the river basins. The stations distribution on the rivers follows a strategy aimed at a better understanding of the eutrophication phenomenon in the different streams. Two stations (CO1–CO2) upstream on the Comoé River characterized the water state upstream, one station CO3 in the city center of Alépé aimed at highlighting the impact of the city, and the last stations (CO4–CO5) were placed downstream to assess the impact of this river on estuarine waters (Ébrié lagoon).

Table 1
Sampling stations, geographic coordinates, and land use.

River	Stations	Localities (cities)	Coordinates	Land use
Comoé	CO1	Aniassué	6.63866 N –3.71177 W	Farming/cacao-rubber
	CO2	Manzan	6.45864 N –3.39423 W	Cacao-rubber/food crops
	CO3	Alepe	5.30091 N –3.39309 W	Urban
	CO4	Bonoua	5.26211 N –3.61379 W	Urban, lumber-mill
	CO5	Bassam	5.22661 N –3.68545 W	Urban, forest, and wetlands
Bandama	BA1	Bafécao	6.03575 N –4.91685 W	Farming/pasture, cacao-rubber
	BA2	N'zi	6.00297 N –4.82209 W	Urban, agro-pastoral farm
	BA3	Tiassalé	5.88340 N –4.82597 W	Urban, agro-pastoral farm
	BA4	Lahou	5.26339 N –4.96799 W	Forest, palm grove-rubber
	BA5	Braffedon	5.14446 N –4.97166 W	Forest/reserve
Bia	BIA1	Bianoua	6.01923 N –3.19150 W	Cacao-rubber, mining
	BIA2	Ayamé	5.61279 N –3.16751 W	Urban/dam reservoir
	BIA3	Aboisso	5.47413 N –3.20290 W	Urban
	BIA4	Krindjabo	5.38970 N –3.22159 W	Forest, palm grove-rubber
	BIA5	Thomandié	5.36250 N –3.20525 W	Urban, farming

The Watershed land use impact upstream of the Bandama River was assessed with two stations. One located on the western branch of the river, adjoining a large agro-pastoral farm was BA1 and the other one BA2 at the eastern was located on the main tributary of the N'zi River. Station BA3 was located in the center of the city Tiassalé to determine the combined impact of the city and the mixing waters from the confluence between the two branches (Bandama River–N'zi) in the north. The last stations (BA4–BA5) were located in the Bandama River estuary to assess the impact of the exchanging river water masses with the Grand-Lahou Lagoon.

The Ayamé 1 dam and its reservoir have a strong impact on the Bia River hydrology and can play a great role in regulating flows. Thus, the upstream station of Ayamé dam BIA1, the dam reservoir BIA2, and the downstream station of the dam BA3 were chosen to study these combined effects. Finally, the stations (BIA4–BIA5) made it possible to understand the urban impact of Aboisso city, and the river exchanges with the Aby Lagoon at the estuary. A GPS was used to mark the longitude and latitude values of each station with negative values westward and positive northward (Table 1).

The water sampling was carried out according to the reference methods for sampling in continental environments (Rodier et al., 2009). For each sample, surface water (0–30 cm below the surface) was taken by using a 2.5 L Niskin bottle in the middle of the river from a canoe. Immediate measurements of physico-chemical parameters were realized using a multi-parameter (HANNA HI 9828), e.g., temperature, pH, electrical conductivity, salinity, dissolved oxygen concentration, and total dissolved solids. Water samples for nutrient and chlorophyll-*a* analysis were collected in three bottles (two polyethylene and one amber type), stored in ice at 4 °C, and transported to the laboratory for analyses (<72 h).

2.3. Procedure, reagents, and quality assurance

Nutrients and chlorophyll-*a* were analyzed in the Laboratory of Centre Suisse de Recherches Scientifiques (CSRS) of Adiopodoumé (Abidjan), as per the methodologies recommended by the standard

methods for freshwater and wastewater examination (Rodier et al., 2009; Rice et al., 2012). Samples were filtered through a Whatman GF/F filter (porosity 0.45 μm) for analysis of dissolved nutrients and chlorophyll-*a*. A portable spectrophotometer (HACH model DR/2400) was used for analysis (Tarafder and Rathore, 1988 Griess reaction for nitrite ions; Koroleff, 1970 for ammonium ions measurements; Grasshoff et al., 1999 for nitrate ions; and Murphy and Riley, 1962 for reactive phosphorus). Chlorophyll-*a* was extracted with acetone (90 %) in the dark followed by a spectrophotometry measurement at 665 and 750 nm absorbance (Lorenzen, 1967).

Unfiltered water samples were used to measure Total P and Total N. For Total P determination, 40 mL of the water sample is first digested with concentrated sulfuric and nitric acids. Reactive phosphorus (PO_4^{3-}) measurement in the digested sample is done according to the Murphy and Riley colorimetric method (1962). For Total Kjeldahl N determination (Kjeldahl, 1883), 100 mL of the water sample is first digested with 10 mL of concentrated sulfuric acid and 1 g of selenium catalyst. The solution is then distilled with 50 mL of sodium hydroxide (35 %) in an automatic Kjeldahl distillation unit (UDK 149 VELP® SCIENTIFICA). The distillate is finally titrated with a hydrochloric acid solution (0.02 N). Samples digestion (e.g. Total P and Total Kjeldahl N) was performed with an automatic Kjeldahl digestion unit (DKL Series VELP® SCIENTIFICA).

Total N was obtained by summation of the Total Kjeldahl N and the oxidized N forms. Blanks were analyzed in each batch of water samples throughout the entire analytical procedure. The accuracy and precision of the results were checked by triplicate measurements. The detection limits were 0.004 mg/L for PO_4^{3-} , 0.002 mg/L for NH_4^+ , 0.005 mg/L for NO_3^- and 0.1 $\mu\text{g/L}$ for Chl-*a*. The errors in analyses in terms of standard deviations of triplicate samples were found to be 0.001, 0.005, 0.02 mg/L, and 0.38 $\mu\text{g/L}$ for PO_4^{3-} , NH_4^+ , NO_3^- , and Chl-*a*, respectively.

2.4. Eutrophication assessment

The trophic status of the Comoé, Bandama, and Bia Rivers was assessed using two tools: the classification scheme for Chl-*a* biomass of the European Environmental Agency eutrophication report (EEA, 2001; Huo et al., 2013) and the trophic state index for tropical/subtropical reservoirs TSI_{TSR} (Cunha et al., 2013a). Table 2 classifies the water quality according to the level of eutrophication. The classification ranges go from water of excellent quality (i.e. oligotrophic) to poor and degraded water (i.e. hypereutrophic), affecting for the latter the aquatic ecosystem and can cause a public health problem.

2.4.1. Chl-*a* biomass classification scheme

The classification scheme for Chl-*a* biomass established according to the internationally accepted eutrophication scale is based on Chl-*a* concentration (EEA, 2001; Huo et al., 2013; Jin and Tu, 1990). The Chl-*a* concentrations are classified into six grades: 0–1.6 $\mu\text{g/L}$ representing oligotrophic, 1.6–10 $\mu\text{g/L}$ mesotrophic, 10–26 $\mu\text{g/L}$ light-eutrophic, 26–64 $\mu\text{g/L}$ mid-eutrophic, 64–160 $\mu\text{g/L}$ high-eutrophic, and >160 $\mu\text{g/L}$ hypereutrophic (Table 2).

2.4.2. The trophic state index TSI_{TSR}

The annual trophic status of all sites was also assessed based on the expressions of TSI_{TSR} , established by Cunha et al. (2013a):

$$\text{TSI}_{\text{TSR}} = [\text{TSI}(\text{Chl}a)_{\text{TSR}} + \text{TSI}(\text{TP})_{\text{TSR}}] / 2 \quad (1)$$

where

$$\text{TSI}(\text{Chl}a)_{\text{TSR}} = 10 [6 - ((-0.2512 \ln \text{Chl}a + 0.842257) / \ln 2)] \quad (2)$$

$$\text{TSI}(\text{TP})_{\text{TSR}} = 10 [6 - ((-0.27637 \ln \text{TP} + 1.329766) / \ln 2)] \quad (3)$$

with annual geometric mean (Gmean) concentrations of TP and Chl a ($\mu\text{g/L}$).

Table 2 shows the different tools used for the eutrophication assessment, the classes of eutrophication status, and the eutrophication range.

2.5. Water quality assessment in rivers

2.5.1. The CONAMA classification for the freshwater quality

Water quality depends on its uses such as drinking water production, watering, aquaculture, irrigation, recreation, navigation, and landscape. Good quality water does not affect the aquatic ecosystem or human use, or animal consumption (Cruz et al., 2019). To assess the environmental quality of the rivers water in the present study, the maximum allowable concentration limits (MACLs) established for different classes of use by the Brazilian National Environmental Council (CONAMA) Resolution 357/2005 (Cunha et al., 2013b; Cruz et al., 2019) for freshwater bodies were adopted. River waters can be grouped into four classes (1 to 4). The first three classes of water are considered appropriate for human consumption but require varying degrees of treatment from almost none to advanced treatment. Waters of class 4 are considered suitable only for navigation and landscape uses. It should be emphasized that the Côte d'Ivoire Rivers does not yet have a water use directive. Thus, it was decided to evaluate each river according to the MACLs' values for freshwater classes (Class 1, Class 2, and Class 3) established by the CONAMA Resolution 357/2005 (Table S1).

2.5.2. The water quality indices (WQI)

The use of water quality indices (WQI) is a simple practice that overcomes many problems and allows the public and decision-makers to receive water quality information. The WQI also assesses changes in the quality of surface water (Moscuza et al., 2007).

The WQI calculations used here were proposed by Pesce and Wunderlin (2000).

$$\text{WQI} = \sum_{i=1}^n C_i P_i / \sum_{i=1}^n P_i \quad (4)$$

where n is the total number of parameters included in the study, C_i is the normalized value of parameter i , and P_i is the weight of parameter i (Table S2).

The WQI ranges from 0 to 100, with high values representing good

Table 2
Methodological tools and ranges used for the eutrophication assessment of the rivers.

Chl- <i>a</i> ^{a,*}	TSI_{TSR} ^b	State of water quality	Level of eutrophication	Trophic state
0–1.6	≤53.1	High	Low	Oligotrophic
1.6–10	53.2–55.7	Good	Medium	Mesotrophic
10–26	55.8–58.1	Moderate	High	Light-eutrophic
26–64				Mid-eutrophic
64–160	58.2–59.0	Poor and degraded	Elevated	High-eutrophic
>160	≥59.1			Hypereutrophic

* Arithmetic mean ($\mu\text{g/L}$).

^a EEA (2001); Huo et al. (2013); Jin and Tu (1990).

^b Cunha et al. (2013a).

water quality conditions. The water quality was classified into five grades based on the WQI scores: excellent (91–100), good (71–90), moderate (51–70), low (26–50), and bad (0–25) (Wu et al., 2018).

The WQI value of each sampling station was calculated on a seasonal basis.

2.6. Analyses and treatment of data

Analysis of variance (ANOVA) was performed to ascertain seasonal and spatial differences. The Kruskal-Wallis One Way Analysis of Variance on Ranks was performed when the equal variance test failed. The acceptable level of statistical significance was 5 %.

The spatial and temporal distributions of the reactive phosphorus and nitrates were examined through maps computed using the ArcGIS/ArcMap environment based on the Inverse Distance Weighting and Kriging methods of spatial interpolation. Bar and line graphs were generated using Sigmaplot® software version 14.0 with dry, rainy, and flood seasons results per monitoring point and the standard error of the mean for nitrites, ammonium, chlorophyll-*a*, and the Trophic State Index TSI_{TSR} .

Pearson's correlation of the water quality data and climatic variables was performed in Sigmaplot® software version 14.0, with a significance of 5 %.

The principal components analysis (PCA) and clusters were also used to analyze the factors influencing nutrient loads and the sources of nutrient inputs. Statistica® version 7.0 was used to generate weights and scores.

3. Results

3.1. Physico-chemical parameters

The water temperature range was (26.5–31.0 °C) with an average value of 28.9 ± 1.2 °C in the Comoé River, (28.3–33.4 °C) with an average value of 30.2 ± 1.6 °C in the Bandama River, and (24.9–30.9 °C) with an average value of 28.0 ± 1.7 °C in the Bia River (Fig. 2a). During the dry season, the water temperature showed significantly higher values than the rainy and flood seasons ($p < 0.05$, Table 3). The highest value observed was 33.4 °C in the Bandama River during the 2016 dry season (Fig. 2a). Moreover, water temperature varied significantly between stations CO1 and CO2 in the Comoé River, and stations BIA1 and BIA2 in the Bia River ($p < 0.05$, Table S3). The water pH values varied between 6.5 and 7.9 with an average value of 7.2 ± 0.4 in the Comoé River, between 6.7 and 8.0 with an average value of 7.4 ± 0.4 in the Bandama River; and between 6.5 and 8.4 with an average value of 7.5 ± 0.4 in the Bia River (Fig. 2b). The river pH showed low fluctuations over the three seasons in the Bandama and Bia Rivers. In contrast, the water pH increased significantly during the rainy seasons in the Comoé River ($p < 0.05$, Table 3 and Fig. 2b). Water pH was also significantly low at the upstream station of the Bia River (BIA1) than at the other stations ($p < 0.05$, Table S3). As for the Bandama River, the water pH was significantly higher on average at the urban station (BA3), compared to the upstream BA2 and the mouth BA5 stations ($p < 0.05$, Table S3).

Electrical conductivity (EC) values varied between 15.0 and 126.0 $\mu\text{S}/\text{cm}$, with an average value of 55.6 ± 29.7 $\mu\text{S}/\text{cm}$ in the Comoé River, between 30.0 and 1265 $\mu\text{S}/\text{cm}$, with an average value of 148.4 ± 244.3 $\mu\text{S}/\text{cm}$ in the Bandama River, and between 15.0 and 82.0 $\mu\text{S}/\text{cm}$, with an average value of 44.6 ± 18.5 $\mu\text{S}/\text{cm}$ in the Bia River (Fig. 2c). During the dry seasons, EC showed significantly higher values than the rainy and flood seasons in the Comoé and the Bia Rivers ($p < 0.05$, Table 3). In contrast, EC showed low fluctuations over the three seasons in the Bandama River. Moreover, EC varied significantly between the upstream station (BA1) and the mouth one (BA5) of the Bandama River. The highest values observed were 229.2–1265.4 $\mu\text{S}/\text{cm}$ at the mouth of the Bandama River during the rainy seasons – Fig. 2c ($p < 0.05$, Table S3).

The water dissolved oxygen (DO) concentration ranges were (2.6–8.4 mg/L) with an average value of 4.8 ± 1.6 mg/L in the Comoé River, (2.7–6.7 mg/L) with an average value of 5.0 ± 1.0 mg/L in the Bandama River, and (3.2–7.6 mg/L) with an average value of 5.5 ± 0.9 mg/L in the Bia River (Fig. 2d). DO showed low fluctuations over the three seasons in the Bandama and Bia Rivers. In contrast, DO evidenced a significant drop during the dry seasons in the Comoé River ($p < 0.05$, Table 3 and Fig. 2d). Moreover, DO was also significantly higher on average at the upstream station BA1, the agropastoral station in the Bandama River than at the other stations ($p < 0.05$, Table S3).

TDS concentrations showed significant seasonal variations in the Comoé and Bia Rivers ($p < 0.05$, Table 3 and Fig. 2e), and reached their highest values during the dry season at upstream stations CO2 (63.0 mg/L) in the Comoé River and BIA1 (41.0 mg/L) in the Bia River. However, the mean TDS value at the Bandama River mouth (117 ± 45.1 mg/L, station BA5) during the rainy season was higher than at the other stations. For salinity, values were almost zero in all rivers although seasonal fluctuations were observed in the Bandama River (a peak value of 0.9 psu was observed in the Bandama River during the 2017 rainy season) (Fig. 2f).

3.2. Nutrients and chlorophyll-*a*

3.2.1. Dissolved nutrients

Reactive phosphorus (PO_4^{3-}) concentrations ranges were (0.020–0.100 mg/L P) with an average value of 0.069 ± 0.027 mg/L P in the Comoé River, (0.010–0.120 mg/L P) with an average value of 0.062 ± 0.038 mg/L P in the Bandama River, and (0.030–0.110 mg/L P), with an average value of 0.084 ± 0.026 mg/L P in the Bia River (Fig. 3).

PO_4^{3-} showed significantly higher values during the dry and flood seasons than the rainy season in the Comoé and Bia Rivers ($p < 0.05$, Table 3). The highest value observed was 0.100 mg/L P at station CO3 located in Alepe city in the Comoé River during the dry season (Fig. 3), and 0.110 mg/L P at station BIA4 close to the village-Krindjabo in the Bia River during the dry season (Fig. 3). As for the Bandama River, PO_4^{3-} concentrations fluctuated slightly with no evident seasonality.

NO_3^- concentrations (Fig. 4) presented much fluctuation in the three rivers (from 0.26 to 1.90 mg/L NO_3^- -N in the Comoé River, from 0.33 to 3.60 mg/L NO_3^- -N in the Bandama River, and from 0.27 to 1.40 mg/L NO_3^- -N in the Bia River) with no evident seasonality ($p > 0.05$, Table 3 and Fig. 4). Average NO_3^- concentrations were higher during the dry season in the Comoé and Bia Rivers (1.06 ± 0.44 mg/L NO_3^- -N in the Comoé River, and 0.82 ± 0.40 mg/L NO_3^- -N in the Bia River, Table 3), and during the rainy season in the Bandama River (1.46 ± 1.32 mg/L NO_3^- -N, Table 3).

Average NO_2^- concentrations were significantly higher during the rainy season than the flood season in the three rivers (0.015 ± 0.004 mg/L NO_2^- -N in the Comoé River, 0.013 ± 0.007 mg/L NO_2^- -N in the Bandama River and 0.014 ± 0.009 mg/L NO_2^- -N in the Bia River during the rainy seasons; $p < 0.05$, Table 3). Moreover, NO_2^- concentrations presented low fluctuations in the three rivers during the dry and rainy seasons (Fig. 5a).

NH_4^+ concentrations ranged from 0.02 to 0.62 mg/L NH_3 -N in the Comoé River, from 0.01 to 0.52 mg/L NH_3 -N in the Bandama River, and from 0.01 to 0.14 mg/L NH_3 -N in the Bia River (Fig. 5b). Average NH_4^+ concentrations presented significant rise during the rainy season in the Comoé River (0.19 ± 0.24 mg/L NH_3 -N; $p < 0.05$, Table 3), and during the dry season in the Bia River (0.09 ± 0.04 mg/L NH_3 -N; $p < 0.05$, Table 3). In contrast, NH_4^+ did not present specific seasonal variations in the Bandama River ($p > 0.05$, Table 3).

3.2.2. Chlorophyll-*a* and total nutrients

Chlorophyll-*a* (Chl-*a*) concentrations ranged from 6.2 to 164.2 $\mu\text{g}/\text{L}$, with an average value of 61.2 ± 49.7 $\mu\text{g}/\text{L}$ in the Comoé River, from 9.5 to 96.4 $\mu\text{g}/\text{L}$, with an average value of 50.3 ± 34.8 $\mu\text{g}/\text{L}$ in the Bandama River, and from 9.2 to 92.6 $\mu\text{g}/\text{L}$, with an average value of 33.5 ± 21.8

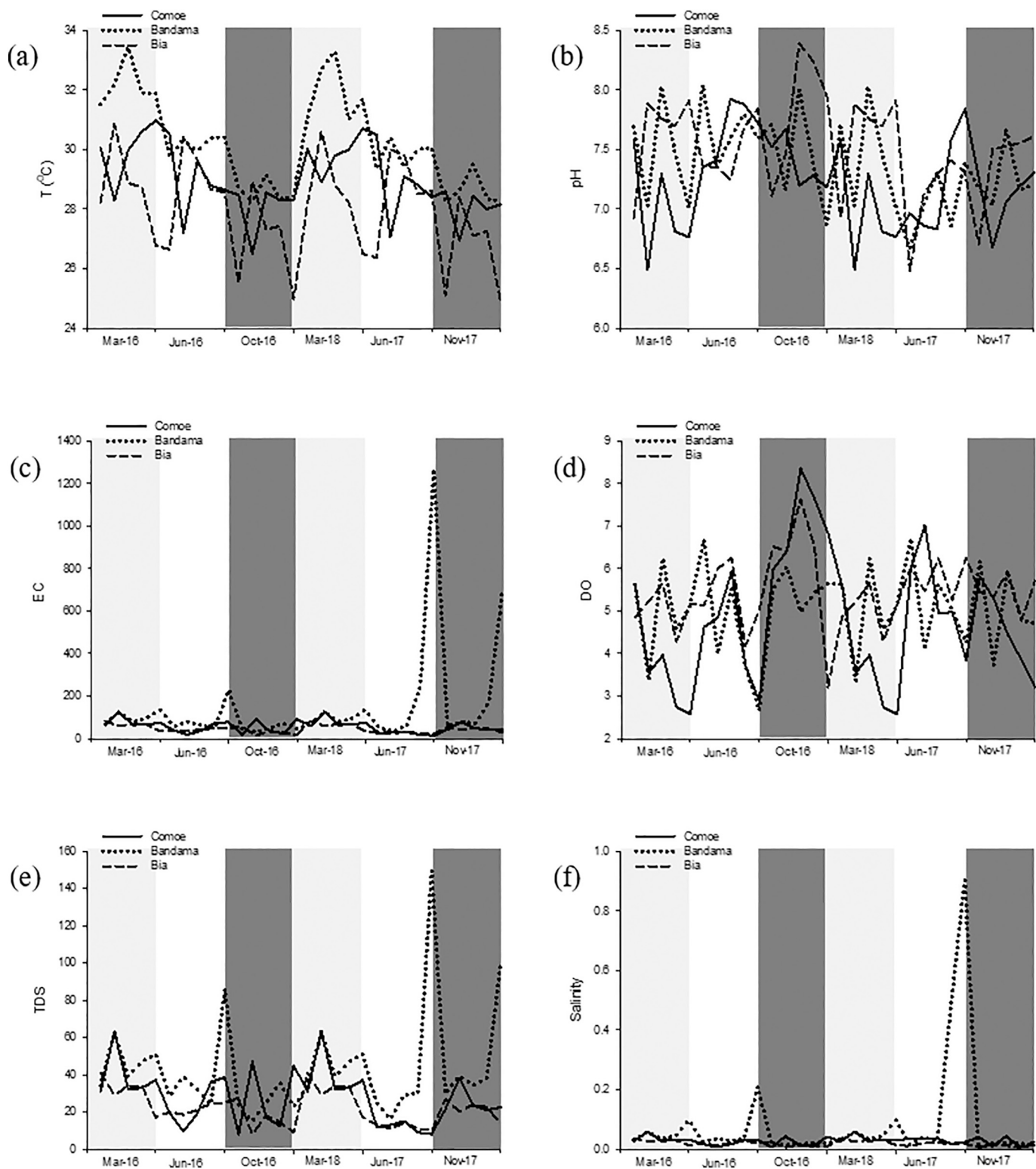


Fig. 2. Seasonal variations of (a) temperature ($^{\circ}\text{C}$), (b) pH, (c) electrical conductivity ($\mu\text{S}/\text{cm}$), (d) dissolved oxygen (mg/L), (e) total dissolved solids (mg/L) and (f) salinity (psu) in the Comoé, Bandama and Bia Rivers, during March 2016 to March 2018 periods. Gray color presents the dry seasons, white color presents the rainy seasons and black color presents the flood seasons.

$\mu\text{g}/\text{L}$ in the Bia River (Fig. 5c). Chl-*a* concentrations did not present specific seasonal variations at any of the three rivers ($p > 0.05$, Table 3).

Average total P concentrations were dramatically high in the three rivers ($> 0.10 \text{ mg}/\text{L P}$) (Table 3), and were within the range of the hypereutrophic rivers, according to Nürnberg (1996) and OECD (1982) trophic classification systems. Total P concentrations did not present

specific seasonal variations in the Comoé and Bia Rivers ($p > 0.05$, Table 3). For the Bandama River, total P was significantly higher during the dry season than the flood one ($p < 0.05$, Table 3).

Average total N concentrations were dramatically high in the Comoé River, and only during the dry and rainy seasons in the Bandama and Bia Rivers ($> 1.2 \text{ mg}/\text{L N}$) (Table 3) within the range of the hypereutrophic

Table 3
One-way analysis of the significance of seasonality factors with the physico-chemical and total nutrients variables.

	Comoé			Bandama			Bia		
	Dry	Rainy	Flood	Dry	Rainy	Flood	Dry	Rainy	Flood
	Temp. (°C)	29.9 ± 0.8a ^b	28.9 ± 1.2b	28.0 ± 0.7b	32.1 ± 0.8a	30.0 ± 0.4b	28.6 ± 0.4c	28.6 ± 1.4a	28.7 ± 1.4a
pH	7.0 ± 0.4a	7.4 ± 0.4b	7.2 ± 0.3ab	7.4 ± 0.4a	7.4 ± 0.4a	7.3 ± 0.4a	7.6 ± 0.4a	7.3 ± 0.4a	7.6 ± 0.5a
EC (µS/cm)	78.4 ± 25.5a	36.8 ± 22.1b	51.6 ± 26.7ab	100.3 ± 27.8a	212.9 ± 377.7a	131.9 ± 203.5a	62.1 ± 16.6a	34.8 ± 10.5b	37.0 ± 14.2b
DO (mg/L)	3.68 ± 1.14a	4.88 ± 1.22ab	5.78 ± 1.63bc	4.99 ± 1.03a	4.83 ± 1.32a	5.29 ± 0.75a	5.04 ± 0.48a	5.58 ± 0.69a	5.75 ± 1.19a
Sal. (psu)	0.035 ± 0.012a	0.024 ± 0.010a	0.023 ± 0.016a	0.052 ± 0.026a	0.180 ± 0.294a	0.018 ± 0.008b	0.027 ± 0.008a	0.019 ± 0.004b	0.013 ± 0.007b
TDS (mg/L)	39.2 ± 12.7a	18.0 ± 10.9b	25.6 ± 13.3ab	46.8 ± 10.6a	45.9 ± 41.2	36.3 ± 23.8a	31.0 ± 8.4a	16.8 ± 5.7bc	18.4 ± 6.9c
PO ₄ ³⁻ (mg/L P)	0.071 ± 0.029a	0.045 ± 0.022ab	0.089 ± 0.009ac	0.053 ± 0.036a	0.042 ± 0.045a	0.092 ± 0.005a	0.101 ± 0.009ac	0.059 ± 0.030b	0.093 ± 0.009bc
TP (mg/L P)	0.20 ± 0.14a	0.11 ± 0.02a	0.28 ± 0.17a	0.95 ± 0.53ab	0.43 ± 0.09b	0.25 ± 0.12bc	0.38 ± 0.24a	0.60 ± 0.33a	0.38 ± 0.26a
NO ₂ (mg/L NO ₃ -N)	1.06 ± 0.44a	0.79 ± 0.66a	0.59 ± 0.11a	0.90 ± 0.44a	1.46 ± 1.32a	0.48 ± 0.07a	0.82 ± 0.40a	0.53 ± 0.19a	0.60 ± 0.08a
NO ₃ (mg/L NO ₂ -N)	0.009 ± 0.004a	0.015 ± 0.004ab	0.002 ± 0.001ac	0.013 ± 0.001a	0.013 ± 0.007ab	0.003 ± 0.001c	0.009 ± 0.003a	0.014 ± 0.009ab	0.002 ± 0.001ac
NH ₄ ⁺ (mg/L NH ₃ -N)	0.05 ± 0.02a	0.19 ± 0.24ab	0.03 ± 0.01ac	0.07 ± 0.04a	0.16 ± 0.20a	0.03 ± 0.01a	0.09 ± 0.04a	0.03 ± 0.02b	0.03 ± 0.01bc
TKN (mg/L N)	0.91 ± 0.12a	1.18 ± 0.64a	0.87 ± 0.34a	0.73 ± 0.12a	0.87 ± 0.18a	0.56 ± 0.25a	0.97 ± 0.08a	1.06 ± 0.06a	0.50 ± 0.36a
TN (mg/L N)	1.98 ± 0.42a	1.99 ± 1.23a	1.46 ± 0.40a	1.64 ± 0.42a	2.33 ± 1.18ab	1.04 ± 0.28ac	1.81 ± 0.37a	1.60 ± 0.16ab	1.10 ± 0.42bc
Chl- <i>a</i> (µg/L)	43.1 ± 37.4a	59.5 ± 49.8a	33.7 ± 58.0a	43.3 ± 30.0a	60.5 ± 43.8a	26.1 ± 36.0a	32.0 ± 20.5a	31.2 ± 31.5a	14.1 ± 14.7a

Temp. water temperature, EC electrical conductivity, DO dissolved oxygen, Sal. Salinity, TDS total dissolved solids, PO₄³⁻ reactive phosphorus, NO₃⁻ nitrate ion, NO₂⁻ nitrite ion, NH₄⁺ ammonium ion, TKN total Kjeldahl nitrogen, TN total nitrogen, Chl-*a* chlorophyll-*a*.

^a Different letters are significantly different ($p < 0.05$).

rivers, according to the [Nürnberg \(1996\)](#) trophic classification. Nevertheless, total N concentrations during the flood season remained high (0.65–1.2 mg/L N) and confirmed a eutrophic status of the Bandama and Bia Rivers according to the [Nürnberg \(1996\)](#) trophic classification.

4. Discussion

4.1. Hydrographic characteristics

The water temperature was higher during the dry season followed by the rainy season and the flood season in the three rivers ([Fig. 2a](#)). This may be due to sunstroke ([Ota et al., 2015](#)). However, this variation could also be due to the sampling times. Significant water temperature changes result in important changes in the geographic distribution of aquatic species and the biogeochemistry of river ecosystems ([Álvarez-Cabria et al., 2016](#)).

In the Comoé River, the water pH value was higher in the rainy season due to the leaching of land heavily loaded with phosphate and nitrogen from agriculture and forest ecosystems ([Osaka et al., 2016](#)). The lower pH value (6.49 units) observed at station CO2-Manzan in the dry season is probably a consequence of high organic matter in the stream, causing a decrease in pH during the remineralization process ([Aguiar et al., 2011](#)). Moreover, water pH showed low fluctuations over the three seasons in the Bandama and Bia Rivers. Organic matter inputs were probably greater along the Bandama River watershed (especially at the urban station BA3-Tiassalé), leading to a gradual decline in water pH at the mouth BA5-Braffedon. On the other hand, in the Bia River, high flows have led to higher nutrient inputs from agricultural and urban origins (the highest value of 8.4 pH units observed at Aboisso station during the Oct-16 rainy season – [Fig. 2b](#)) favoring a gradual increase in water pH up to 7.9 units at station BIA5-Thomandié. An increase in algal activity (photosynthesis) fueled by higher inputs of nutrients from agricultural and anthropogenic sources appears to be the cause of the gradual increase in pH during the high flow period. For example, in the Bia River, significant Pearson correlations obtained between pH and chlorophyll-*a* ($r = 0.38$, Table S4), and pH with rainfall ($r = -0.34$, Table S4), supported an intense algal activity during the rainy season. When algae take up carbon dioxide during photosynthesis, they increase the pH by increasing the level of hydroxide ions. The reverse reaction occurs during respiration when carbon dioxide is produced, lowering the hydroxide ions; thus, lowering the pH. Therefore, a high-water pH (>8.0) may be an indicator of photosynthesis by large amounts of algae ([Raven et al., 2020](#)).

Similar distributions of EC and TDS in the Comoé and Bandama Rivers indicated that rainy inputs slightly altered the ionic strength along the stream ([Morrison et al., 2001](#)). On the other hand, the Bia River was strongly mineralized during the dry season (i.e. EC and TDS were significantly high during the dry season $p < 0.05$) due to the low water rate renewal compared to the rainy and flood seasons. Another important factor is that EC, TDS, and salinity are affected by the geology of the area through water flows, precipitation, and the evaporation-precipitation process. These streams pass through areas of clay soils (ferrallitic) which tend to increase EC and TDS due to the presence of materials that ionize when washed in water ([Bhateria and Jain, 2016](#)). Low levels of salinity (<500 psu) and TDS (<500 mg/L) would also promote an increase in algal productivity in the Comoé, Bandama, and Bia Rivers ([Sorensen et al., 1977](#)).

The three rivers were well-oxygenated during the flood season (Table S5). In contrast, low levels of dissolved oxygen near hypoxia were observed in most of the Comoé River stations during the dry season over the two-year sampling period. This would be the result of increased nutrient loading and organic matter decomposition (leaves, debris, and animal wastes), which typically occurs during periods of very low flow or in rivers with limited flushing rates ([Aguiar et al., 2011](#); [Conley et al., 2007](#)). Moreover, low oxygen levels during the dry season in the Comoé River can lead to the excessive release of nutrients from the sediment,

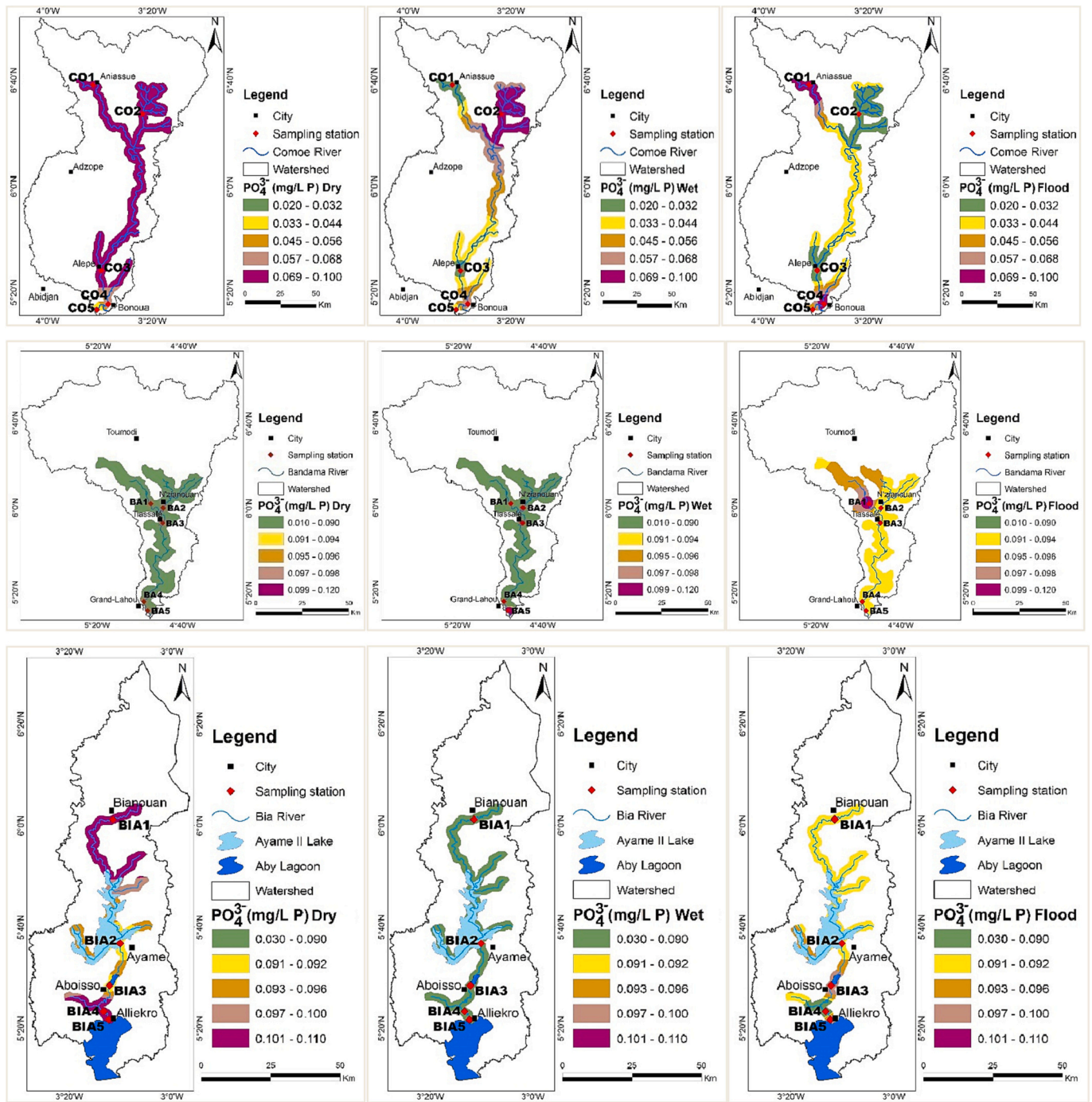


Fig. 3. Reactive phosphorus dynamic in the Comoé, Bandama, and Bia Rivers from March 2016 to March 2018 during the dry, rainy, and flood seasons.

which promotes algal blooms (Cao et al., 2017). In contrast, the Bandama and Bia Rivers' oxygenation was much better in the dry season, favored probably by a better movement of the water masses. Generally, the rivers were well oxygenated during the rainy season except at station BA2-N'zi (Bandama River tributary), and at the Comoé and Bandama Rivers estuaries (stations CO5-Bassam and BA5-Braffedon). The permanent movement of water masses towards these confluents seemed to favor the periodic deposition of large quantities of organic matter, and heterotrophic bacteria decomposition which causes a rapid drop in the oxygen level (Mallin et al., 2006; Sarma et al., 2009). DO concentrations of the Comoé, Bandama, and Bia Rivers coincided with the results reported by Gupta et al. (2017) (2.4–7.8 mg/L) in the Narmada River

(India) and by Arimoro et al. (2007) (3.2–10.1 mg/L) in the Orogodo River (Nigeria). In these tropical areas, low DO concentrations resulted from the release of wastes rich in organic matter and nutrients near the river site and then from the increased microbial activity occurring during the degradation of organic matter.

Some authors such as Gray et al. (2002), Vaquer-Sunyer and Duarte (2008) established in their work a conventional value of DO (1.4 mg/L) to designate hypoxic waters, which can impact fishes and crustaceans' life. This threshold was not reached in our study (minimum value > 2 mg/L). There was no apparent risk of mortality for aquatic species in the Comoé, Bandama, and Bia Rivers. However, the great diversity of physiological responses to hypoxia poses serious obstacles to any

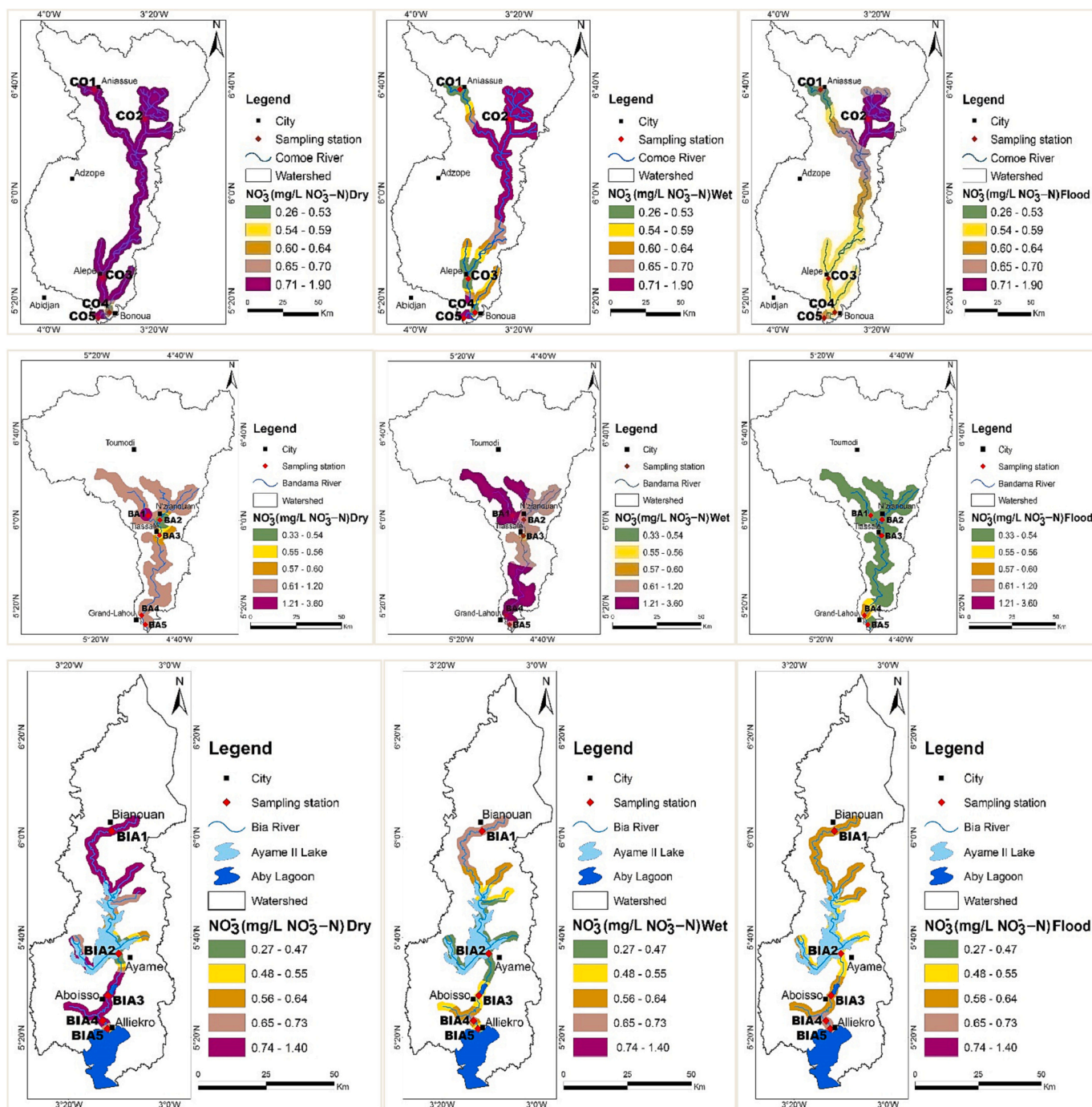


Fig. 4. Nitrate ions dynamic in the Comoé, Bandama, and Bia Rivers from March 2016 to March 2018 during the dry, rainy, and flood seasons.

attempt to predict community and ecosystem responses to low ambient oxygen conditions based on responses of individual species (Hernández-Miranda et al., 2012).

4.2. Spatio-temporal distribution of nutrients and Chl-a

4.2.1. Reactive phosphorus dynamic

The reactive phosphorus (PO_4^{3-}) dynamic in the Comoé, Bandama, and Bia Rivers during the three hydrological seasons are presented on maps of Fig. 3. PO_4^{3-} concentrations in the Comoé River (at all stations) were in the highest range (0.069–0.100 mg/L P) in the dry season, possibly due to sediment inputs, runoffs from cultivated land, urban discharges and untreated wastewater (Bhatia and Jain, 2016). Low

oxygen levels close to hypoxia were observed in most stations of the Comoé River (Table S5) during the dry season, which could lead to the excessive release of phosphorus from the sediments, and promotes algae proliferation (Cao et al., 2017). During the rainy and flood seasons, the washout effect resulted in high PO_4^{3-} concentrations upstream, which then gradually decreased in the direction of the currents and finally increased sharply in the estuaries. The mixing of strong northern river currents with tidal currents from estuaries resuspended the sedimentary phosphorus stock accumulated at the bottom during periods of calm (Aguar et al., 2011; Coelho et al., 2004). Moreover, the low concentrations obtained at the Manzan tributary (0.020–0.032 mg/L P; station CO2-Manzan during the flood season), can be explained by a greater dilution effect, given the rising water levels during flooding.

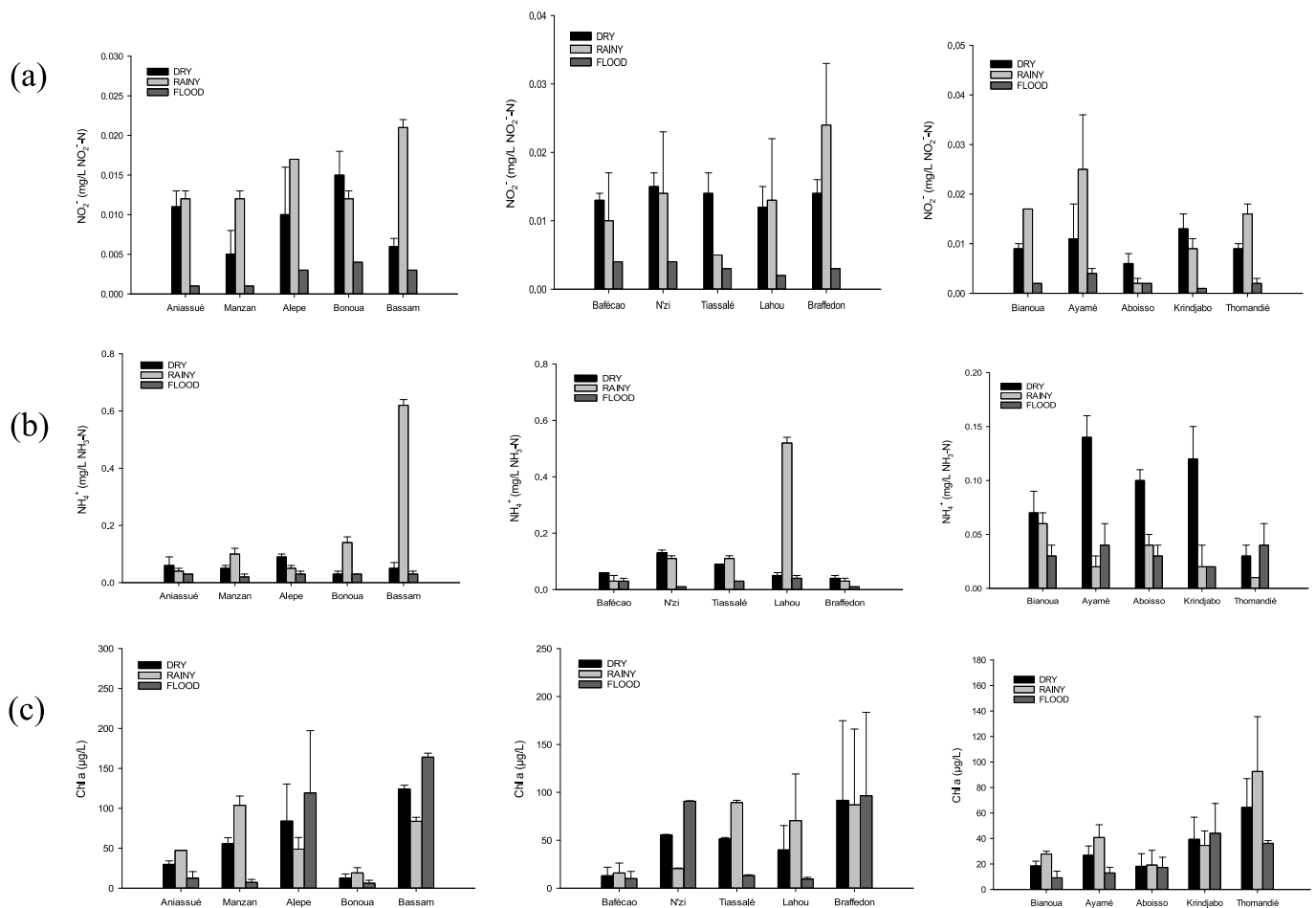


Fig. 5. Seasonal variations of (a) nitrite ions, (b) ammonium ions, and (c) Chlorophyll-a, in the Comoé, Bandama, and Bia Rivers from March 2016 to March 2018 during the dry, rainy, and flood seasons.

PO_4^{3-} concentrations in the Bia River were also in the highest range (0.101–0.110 mg/L P) upstream (station BIA1) during the dry season and near the mouth stations (BIA4-Krindjabo and BIA5-Thomandié). Moreover, the BIA2-Ayamé dam and BIA3-Aboisso city stations had intermediate PO_4^{3-} concentrations (0.093–0.096 mg/L P) during the dry season. Land use around the upstream watershed (e.g. cocoa-rubber cultures) and at the Bia River estuary (e.g. palm grove-rubber cultures) appeared to provide more PO_4^{3-} than urban area. This highlights the definite impact of farming areas on this stream and its consequences such as algae bloom. Moreover, the hunting flow rates of the Ayamé dam lake during its emptying and its great depth influence the nutrients supply downstream of the Bia River as shown by Aguiar et al. (2011) in their works. The lowest PO_4^{3-} concentrations range (0.030–0.090 mg/L P) obtained in the rainy season, reflected a very marked dilution effect. Therefore, rainfall played a regulatory role in the phosphorus load in the Bia River (Pearson $r = 0.39$, Table S4). However, runoff and erosion processes, especially during flood episodes, were the main mode of phosphorus transfer in this river, as evidenced by the values which gradually increased in the direction of the current (Le Noë et al., 2018).

As for the Bandama River, the lowest PO_4^{3-} concentrations were obtained in the dry and rainy seasons (0.010–0.090 mg/L P), while the flood season recorded the highest values (0.099–0.120 mg/L P). Land use around the watershed (Farming/pasture and urban activities) did not have a great impact on the phosphorus input in the Bandama River, during the dry and rainy seasons. Moreover, during the rainy season, the dilution and transport effects due to a strong surface water current appear to occur from upstream to downstream and create a high peak (0.120 mg/L P) at the river estuary BA5-Braffedon (Amano et al., 2010).

Released phosphorus from sediments promoted by the mixing of strong northern river currents with the tidal currents of the estuary can also cause high PO_4^{3-} concentrations at the mouth of the Bandama River during the rainy season (Negrin et al., 2011). PO_4^{3-} concentrations in the Comoé, Bandama, and Bia Rivers coincided with the results reported by Mbaye et al. (2016) (0.00–0.130 mg/L P) in the Senegal River, and by Arimoro et al. (2007) (0.05–0.14 mg/L P), in the Orogodo River (Nigeria) impacted by slaughterhouse effluents. Therefore, the Comoé, Bandama, and Bia Rivers were impacted by human agricultural and urban activity.

4.2.2. Nitrate ions dynamic

The nitrate ions dynamic in the Comoé, Bandama, and Bia Rivers, during the three hydrological seasons, are presented on maps of Fig. 4. The nitrate concentrations in the Comoé River (at all stations) were in the highest range (0.71–1.90 mg/L NO_3^- -N) in the dry season, then kept substantially the same distribution in the rainy season, except at the CO1-Aniasssué and CO3-Alépe stations where the lowest range was reached (0.26–0.53 mg/L NO_3^- -N). Nitrogen fertilizer runoff from agricultural land and in situ organic transformations can be considered nitrates sources in the dry season (Han et al., 2020). A gradual dilution effect was perceptible during floodings, from the confluence area of the CO2-Manzan (0.76 mg/L NO_3^- -N) to the mouth of the Comoé River (0.59 mg/L NO_3^- -N). Nitric nitrogen is found in the aquatic environment mainly through agricultural processes (nitrogenous fertilizers such as sodium nitrate and ammonium nitrate). Nitrogen losses from agroecosystems occur through leaching mainly of nitrate (Rütting et al., 2018). The Comoé, Bandama, and Bia Rivers watersheds were subjected

to an intensification of cash crop cultivation (rubber, cocoa, coffee, etc.) over the past two decades, requiring more fertilizers to increase their productivity. This has contributed to enriching upstream waters in nitrates, especially at the CO2-Manzan, BA1-Bafécao, and BIA1-Bianoua stations, during the dry and rainy seasons. Just as in the Comoé River, nitrate concentrations in the Bia River during the dry season were in the highest range (0.74–1.40 mg/L NO_3^- -N); then they decreased slightly during the rainy season, upstream at Bianoua and downstream at stations near the mouth (BIA4 and BIA5) (0.65–0.73 mg/L NO_3^- -N). Stations BIA2 (Ayamé dam) and BIA3 had the lowest nitrate concentrations (0.27–0.47 mg/L NO_3^- -N) probably due to the Ayamé Dam. The flushing rates of the dam lake and its great depth influenced the supply of nitrates upstream of the reservoir (Mohsenpour et al., 2021; Aguiar et al., 2011). During the flood season, nitrate concentrations were in the intermediate range upstream (0.56–0.64 mg/L NO_3^- -N); then, gradually increased compared to the trend of the rainy season, in the direction of the currents to the mouth. Nitrate concentrations in the Bandama River were in the highest ranges (0.61–1.20 mg/L NO_3^- -N) in the dry season and (1.21–3.60 mg/L NO_3^- -N) in the rainy season. Those of the flood season throughout the river were in the lowest range (0.33–0.54 mg/L NO_3^- -N), with a slight increase at the Lahou station (0.57–0.60 mg/L NO_3^- -N). Nitrates appeared to limit algal growth, hence their low availability during the flood season (Ngatia and Taylor, 2019). The sediments could allow the removal of nitrogen from the water by permanently burying nitrogenous organic compounds (Venkatesh and Anshumali, 2020). In addition, dilution and transport effects from strong surface waters appeared to occur in the water body downstream during the flood season (Amano et al., 2010).

4.2.3. Chlorophyll-*a* dynamic

The chlorophyll-*a* (Chl-*a*) dynamic in the Comoé, Bandama, and Bia Rivers, during the three hydrological seasons, are presented on Fig. 5c. The higher Chl-*a* concentration (164 $\mu\text{g/L}$) and lower one (6.20 $\mu\text{g/L}$) were observed downstream of the Comoé River during the flood season, respectively at the river mouth (CO5-Bassam) and the CO4-Bonoua station. Generally, all three rivers' mouths exhibited high concentrations of chlorophyll-*a* during the three hydrologic seasons. The hydrological profiles and activities along the upstream rivers' watersheds make them important sources of nutrients to downstream habitats (Yasin et al., 2010). As an example, during the dry and flood seasons, Chl-*a* concentrations were low upstream, except at the CO2-Manzan station where runoff water loaded with nitrates led to an increase in phytoplankton activity (Barroso et al., 2016). The associations between the chlorophyll-*a* abundance with the nitrate ions and reactive phosphorus dynamics were performed using Pearson correlation (Table S4). Chlorophyll-*a* was positively correlated with PO_4^{3-} in the Bandama ($r = 0.30$) and Bia ($r = 0.43$) Rivers, and with NO_3^- in the Comoé River ($r = 0.37$). Furthermore, chlorophyll-*a* was negatively correlated with river discharge ($r = -0.24$) in the Bandama River, and with dissolved oxygen (DO) ($r = -0.18$) in the Bia River. The Pearson correlation coefficients suggest that the chlorophyll-*a* abundance in the three rivers varied linearly with nutrients (PO_4^{3-} , NO_3^-) and physicochemical parameters (river discharge, DO). The chlorophyll-*a* concentrations increased with the input of PO_4^{3-} in the Bandama and Bia Rivers. Similarly, nitrate inputs increased with chlorophyll-*a* concentrations in the Comoé River, mainly during the rainy season. These results could indicate a limitation of primary production by nitrogen in the Comoé River, and by phosphorus in the Bandama and Bia Rivers, respectively, during the rainy season (Van der Zee and Chou, 2005). The lower nitrate concentrations obtained during the flood season, combined with the increase in PO_4^{3-} concentrations during the same period, seemed to indicate greater uptake of nitrate by algae. Therefore, nitrate seemed to have a significant regulatory effect on the algal population during the flood season (Horne, 2001). During the dry season, the higher ranges of PO_4^{3-} and nitrate concentrations in the Comoé and Bia Rivers, promoted an increased algal proliferation. This high availability of PO_4^{3-} and nitrate is probably

linked to the biogeochemical cycles of these nutrients in the different rivers (nitrification, release of phosphorus and nitrogen from the sediments) and the low renewal of water during this period (Cruz et al., 2019; Nguyen et al., 2019). Overall, the mapping distributions and the presence of associations between the abundance of chlorophyll-*a* and the environmental parameters measured show that the chlorophyll-*a* dynamic in rivers could be dictated by the availability of nitrate ions and reactive phosphorus, from point sources (urban discharges) and diffuse sources (agricultural), as well as river discharge (Hao et al., 2019).

4.2.4. Nitrite and ammonium ions dynamics

The spatio-temporal distributions of the nitrite ions (NO_2^-) in the Comoé, Bandama, and Bia Rivers during the dry, rainy, and flood seasons are presented on Fig. 5a. NO_2^- was the least abundant dissolved nitrogen nutrient during the study period. The rainy season had the highest concentrations, with an average concentration of 0.013 ± 0.006 mg/L NO_2^- -N, while the lowest concentrations of nitrite were recorded in the flood season with an average concentration of 0.002 ± 0.001 mg/L NO_2^- -N. The nitrite ion is an intermediate in the oxidation of ammonia to nitrate. High levels of nitrite in river waters may indicate pollution and a risk of toxicity to aquatic life at relatively low concentrations (> 0.01 mg/L NO_2^- -N) (Corriveau, 2009). This form of nitrogen can be used as a source of nutrients for algae and its presence promotes their proliferation (Xia et al., 2018). The threshold of 0.01 mg/L NO_2^- -N is generally exceeded in the Comoé, Bandama, and Bia Rivers, particularly during the dry and rainy seasons. Thus; the river waters were polluted by nitrite ions. Many effluent discharges, including wastewater, are rich in ammonia, which in turn can lead to increased nitrite concentrations in rivers water (Harter et al., 2012; Wakida and Lerner, 2005).

The spatio-temporal distributions of the ammonium ions (NH_4^+) in the Comoé, Bandama, and Bia Rivers during the dry, rainy, and flood seasons are presented on Fig. 5b.

The flood season showed the lowest NH_4^+ concentrations in all rivers, with an average concentration of 0.03 ± 0.01 mg/L NH_3 -N. NH_4^+ concentrations did not show a clear trend during the dry and rainy seasons in the Comoé and Bandama Rivers ($p > 0.05$), although two high peak concentrations (0.62 and 0.52 mg/L NH_3 -N, respectively) were observed at the mouths stations (CO5-Bassam and BA5-Lahou) of the Comoé and Bandama Rivers, in June. As for the Bia River, NH_4^+ concentrations were higher during the dry season than during the rainy one. The low NO_2^- and NH_4^+ concentrations in October can be attributed to the dilution effect generated by the increase in the rivers water volume, as a result of precipitation. This has also been observed by Schenone et al. (2007, 2008) in the lower part of the Salado River which empties into the Samborombón bay. Natural waters (unpolluted) contain relatively low amounts of ammonium ions, typically < 0.02 mg/L NH_3 -N (Acero, 2019). This threshold was generally exceeded in the Comoé, Bandama, and Bia Rivers during the three seasons. Thus, the river waters were subject to prolific algal blooms, which had adverse effects on aquatic life. Along the rivers' watersheds, numerous discharges of effluents and organic waste, including domestic wastewater or animal manure, rich in ammonium ions, arrived directly in the water bodies. These releases, combined with the microbiological decomposition of nitrogen compounds in organic matter, resulted in increased NH_4^+ concentrations in the rivers' waters.

4.2.5. Comparison to rivers and lakes in the world

Data from the present study were compared with those from the literature (Table 4). The ammonium ions, reactive phosphorus, and chlorophyll-*a* concentrations of this study were much lower than those of Karla Lake in Greece (Papadimitriou et al., 2013). This could be explained by the length of stay and the low turnover of the Lake Karla waters, which results in more nutrient accumulation and high concentrations. In contrast, except during the dry season, the Côte d'Ivoire Rivers benefit a constant water renewal leading to a dilution effect on the one hand (low nutrient concentrations upstream generally), and

Table 4
Comparison of nutrients and chlorophyll-*a* concentrations in the Comoé, Bandama, and Bia Rivers with other studies in the world.

Nutrient	River/lake	Area	Min–max	References	Nutrient	River/lake	Area	Min–max	References			
NH ₄ ⁺ (mg/L NH ₃ -N)	Karla Spercheios Cape Fear	Temperate Greece Greece USA	0.16–2.95	Papadimitriou et al. (2013)	NO ₃ ⁻ (mg/L NO ₃ ⁻ -N)	Karla Spercheios Cape Fear	Temperate Greece Greece USA	0.10–1.00	Papadimitriou et al. (2013)			
			0.02–1.22	Markogianni et al. (2017)				0.07–1.68	Markogianni et al. (2017)			
			0.01–0.22	Mallin et al. (2006)				0.19–1.58	Mallin et al. (2006)			
	Guaxindiba Yellow Congo Mara Senegal Comoé Bandama Bia	Tropical Brazil China RDC Kenya Senegal	–	Aguiar et al. (2011)	Guaxindiba Yellow Congo Mara Senegal Comoé Bandama Bia	Tropical Brazil China RDC Kenya Senegal	0.04–0.28	Aguiar et al. (2011)				
			0.02–0.15	Wang et al. (2017)			0.03–0.91	Wang et al. (2017)				
			0.00–0.28	Descy et al. (2017)			0.00–1.24	Descy et al. (2017)				
			0.02–0.04	Masese et al. (2017)			1.00–6.10	Masese et al. (2017)				
			0.01–0.03	Mbaye et al. (2016)			0.00–0.35	Mbaye et al. (2016)				
			0.02–0.62	Our study			0.26–1.90	Our study				
			0.01–0.52				0.33–3.60					
	0.01–0.14		0.27–1.40									
	NO ₂ ⁻ (mg/L NO ₂ ⁻ -N)	Karla Spercheios Cape Fear	Temperate Greece Greece USA	0.001–0.071	Papadimitriou et al. (2013)	NO ₂ ⁻ (mg/L NO ₂ ⁻ -N)	Imbuaçu Yellow Senegal Comoé Bandama Bia	Tropical Brazil China Senegal	0.005–0.215	Aguiar et al. (2011)		
				0.005–0.051	Markogianni et al. (2017)				0.008–0.043	Wang et al. (2017)		
				–	Mallin et al. (2006)				0.000–0.005	Mbaye et al. (2016)		
Karla Spercheios Cape Fear		Temperate Greece Greece USA	0.25–5.25	Papadimitriou et al. (2013)	Karla Spercheios Cape Fear	Temperate Greece Greece USA	47.0–729	Papadimitriou et al. (2013)				
			0.01–1.08	Markogianni et al. (2017)			0.15–2.81	Markogianni et al. (2017)				
			0.03–0.26	Mallin et al. (2006)			0.40–15.2	Mallin et al. (2006)				
			Imbuaçu Guaxindiba Gbako Senegal Yellow Comoé Bandama Bia	Tropical Brazil Brazil Nigeria Senegal Chine			0.13–2.67	Aguiar et al. (2011)	Imbuaçu Guaxindiba Mara Congo Yellow Comoé Bandama Bia	Tropical Brazil Brazil Kenya RDC Chine	5.34–190	Aguiar et al. (2011)
							0.53–1.83	Aguiar et al. (2011)			7.63–8.21	Aguiar et al. (2011)
							0.06–0.20	Arimoro and Keke (2017)			6.10–37.5	Masese et al. (2017)
0.00–0.13	Mbaye et al. (2016)	0.01–7.68	Descy et al. (2017)									
0.00–0.02	Wang et al. (2017)	2.98–15.53	Wang et al. (2017)									
0.02–0.10	Our study	6.21–164	Our study									
0.01–0.12		9.45–96.4										
0.03–0.11		9.18–92.6										
PO ₄ ³⁻ (mg/L P)	Imbuaçu Guaxindiba Gbako Senegal Yellow Comoé Bandama Bia	Tropical Brazil Brazil Nigeria Senegal Chine	0.13–2.67	Aguiar et al. (2011)	Chl- <i>a</i> (µg/L)	Imbuaçu Guaxindiba Mara Congo Yellow Comoé Bandama Bia	Tropical Brazil Brazil Kenya RDC Chine	5.34–190	Aguiar et al. (2011)			
			0.53–1.83	Aguiar et al. (2011)				7.63–8.21	Aguiar et al. (2011)			
			0.06–0.20	Arimoro and Keke (2017)				6.10–37.5	Masese et al. (2017)			
	0.00–0.13	Mbaye et al. (2016)	0.01–7.68	Descy et al. (2017)								
	0.00–0.02	Wang et al. (2017)	2.98–15.53	Wang et al. (2017)								
	0.02–0.10	Our study	6.21–164	Our study								
	0.01–0.12		9.45–96.4									
	0.03–0.11		9.18–92.6									

then a nutrient transport effect towards the mouths of the rivers on the other hand (hypereutrophic areas). The reactive phosphorus and ammonium ions concentrations were within the ranges of some rivers in West Africa: Senegal River (0.00–0.13 mg/LP, [Mbaye et al., 2016](#)); Gbako River (0.06–0.20 mg/LP, [Arimoro and Keke, 2017](#)); and streams from China: Yellow River (0.00–0.02 mg/L P, [Wang et al., 2017](#)) and Wuli lake (0.03–0.12 mg/L P, [Wang et al., 2019](#)). The nitrite ion concentrations were lower than those from some temperate rivers: the Karla Lake (0.001–0.071 mg/L NO₂-N, [Papadimitriou et al., 2013](#)) and the Spercheios River (0.005–0.051 mg/L NO₂-N, [Markogianni et al., 2017](#)) in Greece; the Guaxindiba River (0.006–0.269 mg/L NO₂-N) and the Imbuaçu River (0.005–0.215 mg/L NO₂-N) in Brazil ([Aguiar et al., 2011](#)); and the Yellow River (0.008–0.043 mg/L NO₂-N, [Wang et al., 2017](#)) in China. However, the nitrite ions concentrations in some West-African rivers were similar to the values of the Côte d'Ivoire Rivers, referring to the works of [Mbaye et al. \(2016\)](#) in the Senegal River (0.000–0.005 mg/L NO₂-N) and of [Houssou et al. \(2017\)](#), in the Ouémé River Benin (0.08–0.016 mg/L NO₂-N).

The nitrate concentrations ranges of the Comoé River (0.26–1.90 mg/L NO₃-N) and the Bia River (0.27–1.40 mg/L NO₃-N) were generally found in the same range as the rivers of some temperate areas: Greece (0.07–1.68 mg/L NO₃-N, [Markogianni et al., 2017](#)); USA (0.19–1.58 mg/L NO₃-N, [Mallin et al., 2006](#)). On the other hand, nitrate ion concentrations were higher than most tropical ones, such as the Guaxindiba River in Brazil (0.04–0.28 mg/L NO₃-N, [Aguiar et al., 2011](#)), the Yellow River in China (0.03–0.91 mg/L NO₃-N, [Wang et al., 2017](#)), the Congo River in RDC (0.00–1.24 mg/L NO₃-N, [Descy et al., 2017](#)), and the Senegal River in Senegal (0.00–0.35 mg/L NO₃-N, [Mbaye et al., 2016](#)). However, the Mara River in Kenya (1.00–6.10 mg/L NO₃-N, [Masese et al., 2017](#)) had greater nitrate ion concentrations than the Bandama River ones (0.33–3.60 mg/L NO₃-N).

As for the chlorophyll-*a* concentrations from this study, they were much higher than those in other rivers in tropical areas (Guaxindiba River, Brazil 7.63–8.21 µg/L, [Aguiar et al., 2011](#); Mara River, Kenya 6.10–37.5 µg/L, [Masese et al., 2017](#); Congo River, RDC 0.01–7.68 µg/L, [Descy et al., 2017](#)) and those of the rivers in temperate areas (Spercheios River, Greece 0.15–2.81 µg/L, [Markogianni et al., 2017](#); Cape Fear River, USA 0.40–15.2 µg/L, [Mallin et al., 2006](#)). These results indicated a strong proliferation of algae in the Côte d'Ivoire Rivers. Ultimately, the Comoé, Bandama, and Bia Rivers seemed to be strongly impacted by human activity along their watersheds. The nutrient concentrations (nitrogen/phosphorus) in the Côte d'Ivoire Rivers are among the highest in the world tropical areas and contribute to water eutrophication.

Table 5

The principal component analysis (PCA) of various parameters studied in the dry, rainy, and flood seasons.

	Dry season			Rainy season			Flood season		
	F1	F2	F3	F1	F2	F3	F1	F2	F3
Pluviometry	0.90^a	-0.36	0.03	0.59	-0.69	-0.07	0.59	-0.64	0.37
Temperature	-0.75	0.32	0.26	0.34	-0.59	-0.21	-0.13	0.83	0.07
pH	0.28	0.90	-0.09	0.18	-0.25	0.29	0.48	-0.47	-0.09
TDS	-0.72	-0.47	0.16	0.95	0.07	-0.16	-0.87	-0.30	-0.13
EC	-0.79	-0.44	0.01	0.95	0.13	-0.21	-0.88	-0.30	-0.14
DO	0.04	0.78	-0.46	-0.70	-0.17	-0.46	-0.15	0.14	0.66
Salinity	-0.78	-0.34	-0.19	0.93	0.13	-0.27	-0.88	-0.30	-0.14
TP	-0.65	0.31	-0.58	-0.05	0.08	-0.42	0.55	-0.26	-0.53
Chl- <i>a</i>	-0.25	-0.48	-0.20	0.37	0.21	0.35	-0.44	0.22	0.18
NH ₄ ⁺	0.06	0.28	0.50	0.25	-0.27	0.88	0.49	-0.01	-0.22
PO ₄ ³⁻	0.55	-0.04	-0.36	0.43	0.74	-0.22	0.57	0.20	-0.61
TKN	0.84	0.06	0.09	0.19	0.36	0.63	-0.38	-0.35	-0.55
NO ₃ ⁻	0.00	-0.18	-0.73	0.18	-0.62	0.52	-0.30	-0.88	0.13
NO ₂ ⁻	-0.49	0.51	0.39	0.46	0.47	0.16	0.07	0.81	0.00
Discharge	-0.86	0.45	-0.05	0.47	-0.60	-0.45	-0.62	0.62	-0.35
Eigenvalues	5.69	3.10	1.81	4.54	2.74	2.50	4.60	3.70	1.82
Cumulative %	37.9	58.6	70.6	30.3	48.5	65.2	30.7	55.4	67.5

pH hydrogenionic potential, TDS total dissolved solids, EC electrical conductivity, DO dissolved oxygen, TP total phosphorus, Chl-*a* chlorophyll-*a*, NH₄⁺ ammonium ion, PO₄³⁻ reactive phosphorus, TKN total Kjeldahl nitrogen, NO₃⁻ nitrate ion, NO₂⁻ nitrite ion.

^a Bold value represents strong loadings.

4.3. Factors influencing nutrients loads

One of the factors that influence the nutrient dynamics and hydrology of rivers is rainfall. We have thus linked the total concentrations of nitrite ions, nitrate ions, and reactive phosphorus in the Comoé, Bandama, and Bia Rivers to the average monthly precipitation. (Fig. S2).

The peaks of nitrite concentrations in the three rivers coincided with the maximum precipitation in June (Rainy season > Dry season > Flood season). These concentrations fell sharply during the flood season, indicating nitrification promoted by bacterial activity breaking down organic matter ([Cui et al., 2020](#)). Nitrate levels were decreasing in the waters with the drop in rainfall from June to October. These levels were on average higher during the dry season in the rivers water because of the low water renewal, especially in the upstream stations. The low rainfall recorded during the flood and dry seasons favored an increase in phosphate levels in rivers waters. It seems that the leaching effect of soils during the rainy season provided more ammonia compounds (NH₄⁺, TKN) and nitrate (NO₃⁻) than phosphates (PO₄³⁻). The soils located along the river basins would therefore be more enriched in nitrogenous elements and would indicate frequent use of fertilizers rich in nitrogen elements ([Dalal et al., 2003](#)). Domestic discharges, especially from cities bordering rivers, also added to the phosphorus and nitrogen load in the waters. Nitrogen inputs were dominant, especially during the dry and rainy seasons. However, the dilution effect was more pronounced for nitrite and nitrate concentrations in October, whereas the higher flow rates during this period had an increased effect on phosphate concentrations as demonstrated by [Gao et al. \(2018\)](#).

Factorial analysis was performed with the measured parameters and the results are presented in [Table 5](#).

Three factors (F1, F2, and F3) accounted for 70.6 % of the cumulative percentage of the total variability in the dry season. Factor 1 explained 37.9 % of the total variance with an eigenvalue of 5.69. This factor seems to have strong positive loadings with rainfall and total Kjeldahl nitrogen (TKN), but negative loadings with water temperature, total dissolved solids (TDS), electrical conductivity (EC), salinity, total phosphorus (TP), and river discharge. The second factor accounted for 20.6 % of the total variance with an eigenvalue of 3.10. Positive loadings were found with pH and dissolved oxygen (DO). Factor 3 contributed to 12.0 % of the total variance with an eigenvalue of 1.81 and had negative loadings with nitrate. The relationships between factor 1 parameters suggest that the low precipitation added to the low flow rate in the dry season induced an increase in the TP and TKN levels. Factors 2 and 3 suggest that nitrate ions mainly controlled algal blooms. Their

availability for photosynthetic activity was accompanied by a slight increase in pH and oxygenation of the aquatic environment (Aguiar et al., 2011).

In the rainy season, the three factors (F1, F2, and F3) explained 65.2 % of the cumulative percentage of the total variability. Factor 1 accounted for 30.3 % of the total variance with an eigenvalue of 4.54. Factor 1 indicated positive loadings with total dissolved solids (TDS), electrical conductivity (EC) and salinity, but negative loadings with dissolved oxygen (DO).

The second factor accounted for 18.2 % of the total variance with an eigenvalue of 2.74. Factor 2 showed a strong positive loading with phosphates but negative loadings with rainfall, nitrate ions and river flow. Factor 3 represented 16.7 % of the total variance with an eigenvalue of 2.50, and had positive loadings with ammonium ions and total Kjeldahl nitrogen. The relationships among parameters under factor 1 reflected a high ionic and particulate charge (solid debris), a consequence of soils leaching during heavy rains. Water oxygenation was strongly associated with the transport of particles and debris from runoff water flowing into the aquatic environment. The relationships among parameters under factors 2 and 3 suggested that precipitations and river discharges are the main regulators of the levels of nutrient bioavailability for algae (phosphate and nitrate) in rivers during the rainy season (Gao et al., 2018).

Likewise, three factors accounting for 67.5 % of the cumulative

percentage of total variance controlled nutrient loads in rivers during the flood season. Factor 1 accounted for 30.7 % of the total variance with an eigenvalue of 4.60 and showed negative loadings with total dissolved solids (TDS), electrical conductivity (EC), salinity and river discharge. The ionic and solid charge in river waters was greatest during the flood season because it accounted for all the variance of this factor. Factor 2 represented 24.7 % of the total variance with an eigenvalue of 3.70. Positive charges were found with water temperature, nitrite ions and river discharge, while precipitation and nitrate ions exhibited negative charges. This suggested a phenomenon of nitrification induced by the rising rivers waters. Factor 3 representing 12.2 % of the total variance with an eigenvalue of 1.82 gave positive charges with dissolved oxygen (DO) and then negative with orthophosphates. This factor shows that the assimilation of phosphates by algae during the flood season was accompanied by an increase in oxygenation of the aquatic environment. Photosynthetic activity increased therefore during this period (Abbott et al., 2018).

4.4. Sources of the nutrient inputs

The hierarchical analysis (dendrograms Fig. 6) made it possible to identify three statistically significant groups per season: G_1^a , G_2^a , G_3^a for the dry season; G_1^b , G_2^b , G_3^b for the rainy season, and G_1^c , G_2^c , G_3^c for the flood season.

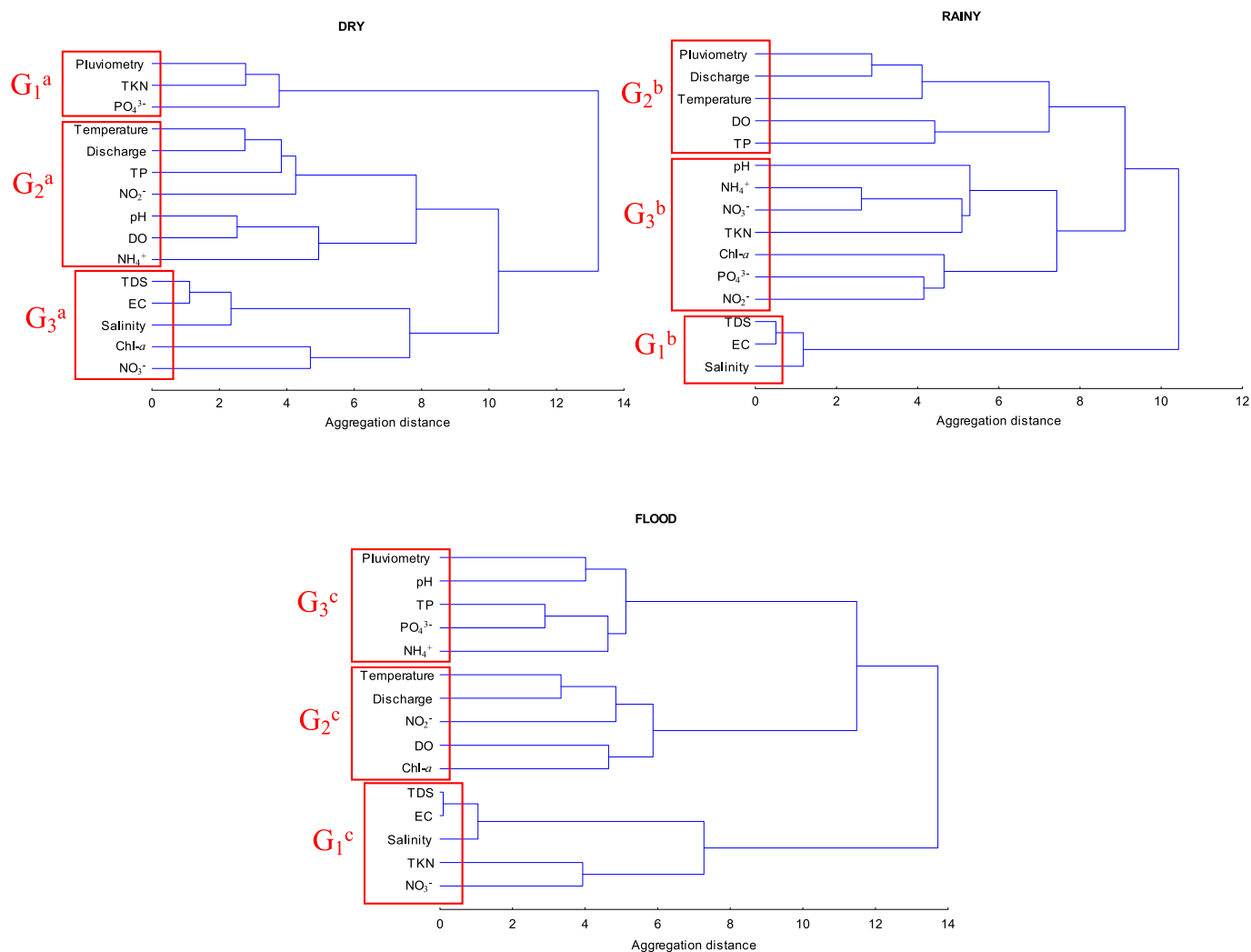


Fig. 6. Results of hierarchical cluster analysis (shown as dendrogram) for the variables studied in the three rivers for all seasons (^aDry season, ^bRainy season, and ^cFlood season).

Nutrient concentrations in the G_3^a , G_3^b , and G_1^c groups were mainly attributable to external sources. Among these, the increase in domestic discharges, agricultural slurry, and fertilizer runoff were prominent (Liu, 2015; Wang et al., 2017). The NO_3^- and TKN (Total Kjeldahl Nitrogen) contents contributed to the nutrient enrichment of the aquatic environment, due to their anthropogenic sources. These sources were mainly of agricultural origin such as fertilizer inputs and to a lesser extent urban inputs. This could be explained by the frequent proximity of plantations along the river watersheds. Thus, nitrate ions availability in the three rivers water impacted algae proliferation (Aguiar et al., 2011; Subha et al., 2014).

Nutrient concentrations in the G_2^a , G_1^b , and G_2^c groups were mainly due to internal sources. Water temperature and rivers discharges influenced strongly aquatic organic decomposition and nitrite (NO_2^-) levels. The sources of orthophosphates appeared to be sedimentary. Factors such as phosphorus particles adsorption/desorption and nutrients released from sediments should be considered (Liu, 2015). A low renewal of waters and low flow rates accentuated the inorganic phosphorus fraction (PO_4^{3-}) availability and contributed to rivers eutrophication (Li et al., 2018). The high organic phosphorus content (representing up to 93.7 % of total phosphorus) in the rivers water, could be deposited at the bottom and form an important reservoir of phosphorus in the sediments (Boukemara et al., 2017; Orihel et al., 2017).

Nutrients concentrations in the G_1^a , G_2^b , and G_3^c groups were mainly attributable to external sources. Among these, the leaching of soils along the rivers' catchments and agricultural erosion constituted a preponderant place (Le Noë et al., 2018). Pluviometry favored soils leaching enriched with fertilizers (nitrogen and phosphate) along the rivers watershed, agricultural runoff, and natural erosion (Lopes et al., 2019). Intensive export crops (cocoa, rubber, coffee, palm oil, etc.) near rivers basins, requiring large inputs of fertilizers for obvious yield needs, loaded the soils with phosphorus and nitrogen, which were then leached by meteorite drainage waters (McKergow et al., 2003; Vanlauwe et al., 2015). Furthermore, precipitation strongly affected the phosphorus inputs (TP, PO_4^{3-}) to the aquatic environment, suggesting that algae growth was mainly controlled by this nutrient during rainy periods (Le Noë et al., 2018).

Moreover, the high ionic load (EC, TDS, salinity) reflected significant anthropogenic inputs (urban discharges) to the aquatic environment. Cluster analysis (Fig. 6 Dry) suggests that nitrate ions mainly controlled algal proliferation and contributed by its diffuse sources with phosphate to the ionic charge of the rivers. Relations among parameters under factors 2 and 3 suggest that nitrate consumption by algae for growth was accompanied by an increase in pH and oxygenation of the aquatic environment related to photosynthesis activity.

4.5. Water quality of rivers

We evaluated the water quality of the Comoé, Bandama, and Bia Rivers according to the classification established by the CONAMA resolution 357/2005 for the freshwater quality (class 1, class 2, and class 3) (Cunha et al., 2013b). The results suggested that the water quality of the Comoé River was in class 3, generally intended for human consumption after advanced treatment. More, the water quality of the Bandama and Bia Rivers was in class 2, generally intended for human consumption after conventional treatment (Table 6). These waters can also be used for crop irrigation, hobbyist fishing, secondary contact recreation, and animals consumption.

The water quality of the Comoé, Bandama, and Bia Rivers was also assessed by the Water Quality Index (WQI) proposed by Pesce and Wunderlin (2000). Fig. S3 gives the WQI values of each station during the dry, rainy, and flood seasons. These values ranged from 76 to 87 during the dry season, from 76 to 91 during the rainy season, and from 82 to 97 during the flood season. According to the classification proposed by Wu et al. (2018), the water quality of all the stations can be considered good ($71 < WQI < 90$). Results presented on Fig. S3 show all the WQI index values of the rivers beyond 71 (see red line on Fig. S3). Given the two water quality assessment methods, it appears that rivers waters used by the indigenous rural populations, without advanced prior treatment, could constitute a human health risk.

Moreover, the WQI index proposed by Pesce and Wunderlin (2000) does not take into account the contents of chlorophyll-*a*, metal(oid)s, and pesticides that affect the water quality of these rivers. For example, Ouattara et al. (2018) found that, during the flood season, 80 and 100 % of the water samples from the Comoé and Bia Rivers, respectively, had arsenic concentrations above the WHO recommendation (10 $\mu\text{g/L}$).

Investigations in the N'zi tributary of the Bandama River revealed clandestine artisanal gold mining which inexorably degrades the water quality of this river. The video titled "Illegal gold panning threatens the fishery resources of the N'zi River" is an illustration (<https://web.facebook.com/RTIinfo225/videos/412758705827659/>) (RTI Info, 2018). Moreover, most of the local communities use the water from these rivers for drinking, washing, and cooking without any prior treatment. The health of at least 9 million people in the South-East of Côte d'Ivoire is therefore threatened. In comparison with the results of Table 6, the WQI index values obtained were not sufficiently representative of the pollution status of the Comoé, Bandama, and Bia Rivers. Taking into account the chlorophyll-*a* and metal(oid)s contents in the WQI index calculation would allow a better assessment of the water quality of these rivers.

Table 6

Assessment of the water quality of the Comoé, Bandama, and Bia Rivers according to CONAMA resolution 357/2005 for the freshwater quality classification.

Classes	Treatment before consumption	pH	DO (mg/L)	TDS (mg/L)	NO_3^- (mg/L NO_3^- -N)	TN (mg/L N)	TP (mg/L P)	Chl- <i>a</i> ($\mu\text{g/L}$)	
^a Concentrations limits established by CONAMA 357/2005 for the freshwater quality classification (Cunha et al., 2013b)									
Class 1	Simplified	6.0–9.0	≥ 6	500	10	3.7 for $pH \leq 7.5$	0.025	10	
Class 2	Conventional	6.0–9.0	≥ 5	500	10	3.7 for $pH \leq 7.5$	0.050	30	
Class 3	Advanced	6.0–9.0	≥ 4	500	10	13.3 for $pH \leq 7.5$	0.075	60	
Classes	Treatment before consumption	River	pH	DO (mg/L)	TDS (mg/L)	NO_3^- (mg/L NO_3^- -N)	TN (mg/L N)	TP (mg/L P)	Chl- <i>a</i> ($\mu\text{g/L}$)
Average concentrations of parameters in sampled sites from March 2016 to March 2018									
Class 3	Advanced	Comoé	7.22	4.78	29,87	0.60	1.67	0.20	45.44
Class 2	Conventional	Bandama	7.38	5.04	37,63	0.98	1.64	0.54	43.32
Class 2	Conventional	Bia	7.52	5.46	22,70	0.58	1.35	0.45	25.77

pH hydrogenionic potential, TDS total dissolved solids, NO_3^- nitrate ion, TN total nitrogen, TP total phosphorus, Chl-*a* chlorophyll-*a*.

^a Except for dissolved oxygen (DO), the concentration limits are the minimum values.

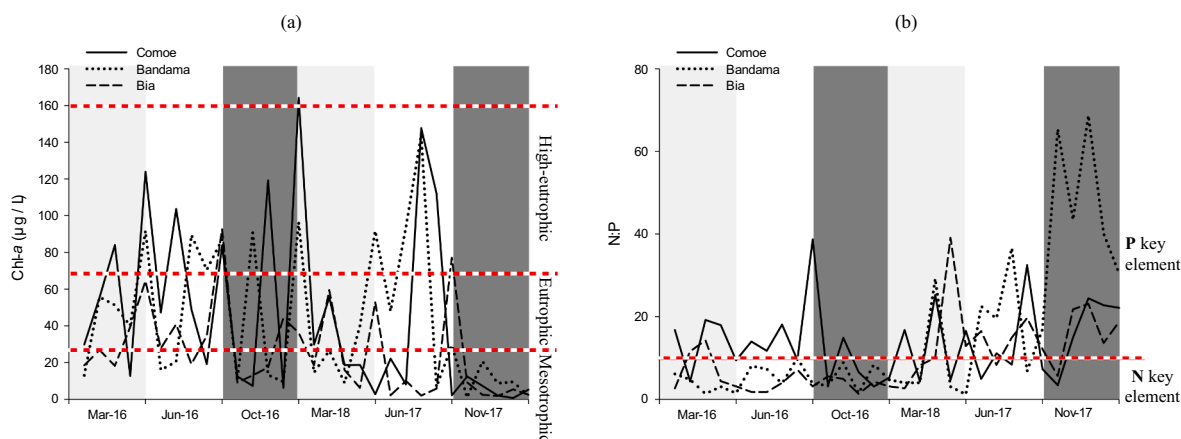


Fig. 7. Seasonal variations of the trophic status (a) and the N:P mass ratios (b) in the Comoé, Bandama, and Bia Rivers during March 2016 to March 2018 periods. The red dashed line delineates the concentration ranges of the trophic status (Fig. a) and the limiting factor for algal growth (Fig. b). Gray color presents the dry seasons, white color presents the rainy seasons and black color presents the flood seasons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.6. Eutrophication assessment in rivers

4.6.1. Chl-a classification and limiting factors

Eutrophication assessment of river waters in Côte d'Ivoire has become essential given the challenges of use, management, and drinking water. Although many methods have been developed for assessing and monitoring eutrophication trends, we used the classification scheme for Chl-a biomass (EEA, 2001). The water quality of the Comoé, Bandama, and Bia Rivers was most often under the mesotrophic state during the three seasons (Fig. 7a).

To identify the principal limiting factor of algal blooms in the system, we used the N:P mass ratio presented in Fig. 7b. A mass ratio of N:P lower than 10 indicates that N is the limiting factor for algal growth, while a ratio higher than 10 shows that P is the key element (Redfield et al., 1963).

Over the sampling campaigns, all the waters were in a hyper-eutrophic state, and in general, nitrogen was the limiting nutrient during the flood period (an average of N:P $\sim 5.3 < 10$, Redfield et al. (1963)). The strong floods of the rivers seemed to favor the phosphate enrichment of the waters to the detriment of nitrate ions as shown in Fig. S2. This explains the low average values of the N:P ratio during this period. Phosphorus, on the other hand, limited phytoplankton production in a third of the sampling stations in March (dry season) and in the two-thirds in June (rainy season). The Comoé River, in this case, had high N:P values during the dry and rainy seasons. These two seasons showed the highest levels of nitrate in the Comoé River. The high availability of nitrogen (urban waste, leaching of soils enriched with fertilizers) probably helped to limit phosphorus in the Comoé River during the dry and rainy seasons. Phosphorus is the factor limiting eutrophication during the low water period (dry season), due to the slowness of water renewal. It was sometimes observed that the Comoé River had dried up in the stations upstream. We must not also neglect the water-sediment exchanges favored by certain specific conditions of the aquatic environment according to the biogeochemical cycle of this nutrient (Wang and Liang, 2016).

N was the least available nutrient in the Bandama River during 2016 (average N:P < 10 , Fig. 7b). In contrast, P became the less available nutrient in the aquatic environment the next year, especially during the period of rising water (Jun-17 to Nov-17, Fig. 7b). There was thus a shift of algal bloom limitation from nitrogen in 2016 to phosphorus in 2017. The Bandama River waters were subject to competitive inputs of N and P during the hydrological seasons. This situation is quite reasonable, considering that around the river watersheds are urban areas and more croplands that discharge nitrogen and phosphorus into the waters

leading to the eutrophication of these natural ecosystems (Fachrul et al., 2021).

Concerning the Bia River, nitrogen seemed to be the least available element in the aquatic environment during the dry and rainy seasons, certainly the most consumed by algae. Low N:P values (~ 4) were recorded in June, which coincided with the high chlorophyll-a (Chl-a) concentrations in the water column. A relatively low N:P ratio had been reported to be associated with the direct and indirect effects of eutrophication (Pavlidou et al., 2015; Yalçın et al., 2017).

4.6.2. The trophic state index (TSI_{tsr})

Temperate and tropical/subtropical aquatic systems have specific sensitivities to eutrophication due to different influences related to climates and land use shifts (Huszar et al., 2006; Ortiz-Jiménez et al., 2006). High rainfall and temperatures make the trophic status prediction in tropical/subtropical freshwater more complex. They induce solid matter intrusions caused by watershed erosion, more environmental constraints controlling nutrient dynamics, and the phytoplankton responses in water masses. Trophic state indices provide clues as to how nutrient availability and light control phytoplankton development. The TSI_{tsr} index developed by Cunha et al. (2013a) for tropical/subtropical systems was thus used to assess the trophic state of the Comoé, Bandama, and Bia Rivers. Results on Fig. 8 showed that throughout the sampling period, all the stations were considered hypereutrophic, with no difference in expression between the years. This can indicate anthropogenic inputs, mainly through agricultural runoff and domestic sewage as shown by Aguiar et al. (2011). The trophic state of the Comoé, Bandama, and Bia rivers according to the TSI_{tsr} index is therefore congruent with the Chl-a classification. The TSI_{tsr} index is proving to be a useful tool in monitoring eutrophication in tropical rivers.

4.7. N and P fluxes

We calculated nitrogen and phosphorus fluxes (i.e. the product of nutrient mean content (mg/L) and the monthly rivers discharge (m^3/s)) exchanged by the Comoé, Bandama, and Bia Rivers in the surface layer (0–0.5 m) for all the sites in March, June, and October from 2016 to 2017 (Table 7). The nutrient flux values ranged from 5.80 to 454 $g\ s^{-1}$ for nitrate ions, from 0.76 to 74.4 $g\ s^{-1}$ for phosphate, and from 0.05 to 2.95 $g\ s^{-1}$ for nitrite ions. The nutrient fluxes showed obvious fluctuations. The ANOVA statistical analysis tests revealed significant differences in phosphate and nitrate ion fluxes between the flood and dry seasons on the one hand in the Comoé and Bandama Rivers and between the flood and rainy seasons on the other in the Comoé River ($p < 0.05$).

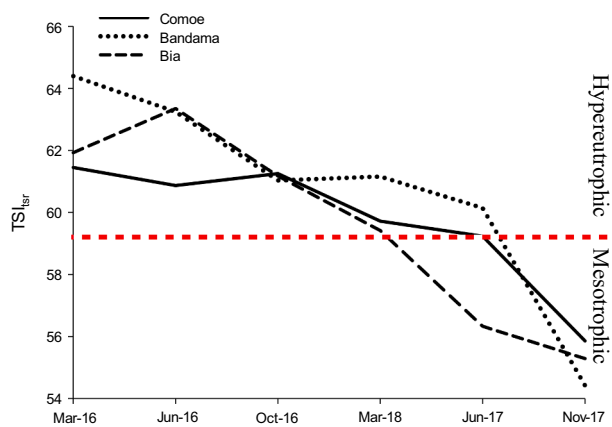


Fig. 8. Seasonal variations of the TSI_{tr} index in the Comoé, Bandama, and Bia Rivers during March 2016 to March 2018 periods. The red dashed line delineates the ranges of the trophic status. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Furthermore, these fluxes were equivalent during the dry and rainy seasons in these rivers ($p > 0.05$). Contributions to aquatic environments related to human activities increased significantly with rising water levels (Yalçın et al., 2017). Phosphorus and nitrogen fluxes were related to fluctuating runoff along the river catchments (Wu et al., 2017). The phosphorus influx was more important because this flood period was marked by a limitation of nitrogen. Added to this, higher dissolved oxygen values during the flood season (6.20 mg/L on average), may reflect an increase in phytoplankton activity; and thus, rivers eutrophication (Markogianni et al., 2017). Nitrite ion fluxes were equivalent during the hydrological seasons of the Bandama and Bia Rivers ($p > 0.05$). It seems that neither the low water period nor even rainfall inputs had a significant impact on the nitrite ions dynamics in these two rivers (Fig. S2).

However, low nitrite ions levels during the flood seasons (Fig. S2), suggested higher nitrification with rising water, as aerobic conditions ($DO > 4$ mg/L) were met (Cao et al., 2015). A portion of nitrite ions was converted to ammonium and nitrate ions and contributed to increasing the photosynthetic process in the Bandama and Bia Rivers. The nitrification process induced the more or less rapid transformation of nitrite to nitrate ions in the aquatic environment (Wu et al., 2013, 2017). Nitrate ions variations in Comoé River are attributed to the intrusions of enriched waters resulting from the heavy rainfall in June when nitrite ions levels were high. Nutrients fluxes observed in the Bia River were linked to its particular hydrological regime with two equivalent flood peaks (July and October) and its two dams (Ayamé 1 and 2). Only phosphorus fluxes varied during the hydrological seasons of the Bia River, which indicated a watershed subject to a significant influx of this element ($p < 0.05$). This was corroborated by the greater phosphate

availability during the dry and flood seasons (peaks in Fig. S2). Nutrient intakes have been influenced by the application of agricultural phosphate fertilizers and urban inputs (Yalçın et al., 2017). In most cases, phosphorus and nitrogen fluxes were related to leaching river catchments and were significant sources of nutrients to the Atlantic Ocean.

5. Conclusions

Monitoring the eutrophication state of river waters in Côte d'Ivoire represents a major challenge for leaders because these rivers are vital for populations' livelihoods. This study made it possible to assess the water eutrophication of the Comoé, Bandama, and Bia Rivers impacted by human activities (agricultural and urban). It emerges that nutrient (N&P) contaminations of rivers are essentially linked to internal sediment inputs during the dry season, and to rainfall inputs during the rising waters periods, particularly during the rainy and flood seasons. Moreover, the chlorophyll-*a* dynamics showed higher levels at the mouths of the three rivers during the three seasons as well as upstream during the rainy season. High chlorophyll-*a* concentrations in rivers mainly resulted from anthropogenic inputs such as agricultural and urban runoff, leading to progressive deterioration of waters quality. The three rivers seemed to act as sources of nutrient transport, causing eutrophication downstream, as the mouths were more impacted by algal activity (hypereutrophic), during the hydrological seasons. The significant associations revealed by Pearson's correlations between nutrients (N&P) and algae (Chl-*a*), explained that the algae proliferation in rivers during the low-flow season was linked to the nutrient enrichment (phosphorus - nitrogen) mainly from sediments, numerous discharges of agricultural manure, domestic wastewater, and organic waste. The high availability of orthophosphates and nitrate ions during this period was linked to the biogeochemical cycles of the streams (nitrification, release of phosphorus and nitrogen from the sediments) and the low renewal of water. Low oxygen levels sometimes close to hypoxia, high temperature, and a slightly acidic character of waters during the dry season, were a consequence of the mineralization process of the organic matter in the rivers and caused the phosphorus and nitrogen release from sediments. Furthermore, nutrient inputs to rivers during rising waters periods were mainly due to external sources, of which leaching of soils along river watersheds and agricultural erosion were taken primary importance. The intensive export crops (cocoa, rubber, coffee, palm oil, etc.) near river basins, requiring large fertilizer inputs for obvious yield needs, loaded the soils with phosphorus and nitrogen. Thus, precipitations favored soils leaching enriched in fertilizers (nitrogen and phosphates) along the river catchments, with agricultural runoff and natural erosion. As a result, the chlorophyll-*a* values increased with N and P inputs and sometimes led to the deterioration of water quality and then reached the hypereutrophic status during the flood seasons. The Comoé, Bandama, and Bia Rivers were strongly impacted by human activity along their watersheds, given that the nutrient contents (N&P) of these rivers are among the highest in tropical areas in the world. Ultimately, the mediocre quality of river water (according to WQI and CONAMA 357/2005)

Table 7
Nitrate ions (NO_3^-), reactive phosphorus (PO_4^{3-}) and nitrite ions (NO_2^-) fluxes in the Comoé, Bandama and Bia Rivers.

Area	Dry season			Rainy season			Flood season			
	NO_3^- flux ($g \cdot s^{-1}$)	PO_4^{3-} flux ($g \cdot s^{-1}$)	NO_2^- flux ($g \cdot s^{-1}$)	NO_3^- flux ($g \cdot s^{-1}$)	PO_4^{3-} flux ($g \cdot s^{-1}$)	NO_2^- flux ($g \cdot s^{-1}$)	NO_3^- flux ($g \cdot s^{-1}$)	PO_4^{3-} flux ($g \cdot s^{-1}$)	NO_2^- flux ($g \cdot s^{-1}$)	
Aniassué	CO1	13.3	0.76	0.10	32.1	1.44	0.83	288	57.5	0.80
Manzan	CO2	9.03	0.81	0.05	59.8	5.05	0.83	454	46.5	0.80
Alepe	CO3	10.9	0.98	0.10	27.1	1.98	1.14	328	49.2	1.60
Bafécao	BA1	101	1.97	0.90	350	6.51	1.94	306	74.4	2.69
N'zi	BA2	24.1	0.91	1.06	152	2.70	2.70	358	65.7	2.93
Tiassalé	BA3	39.8	3.05	0.99	96.8	5.33	0.88	327	66.3	1.96
Bianoua	BIA1	14.9	1.83	0.15	87.7	10.6	2.06	82.5	12.3	0.23
Ayamé	BIA2	5.80	1.55	0.17	32.4	4.99	2.95	64.0	12.6	0.54
Aboisso	BIA3	23.2	1.54	0.09	60.5	3.42	0.24	79.1	13.7	0.23

combined with the usual use of these river waters by indigenous rural populations, without prior treatment, could constitute a real health risk.

CRedit authorship contribution statement

Maley-Pacôme Soro: Conceptualization, Methodology, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Writing - original draft, Writing - review & editing. **Koffi Martin N'goran:** Data curation, Formal analysis, Writing - original draft. **Ahmed Abauriet Ouattara:** Data curation, Formal analysis, Writing - original draft. **Koffi Marcellin Yao:** Data curation, Writing - original draft preparation, Investigation, Methodology, Project administration, Supervision, Validation, review & editing. **N'Guessan Louis Berenger Kouassi:** Data curation, Formal analysis, Visualization & Investigation. **Thomas Diaco:** Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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