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Spatio-temporal characterization of the water quality of the san pedro River (Cote D'ivoire, West Africa)

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Abstract

The San Pedro River is subject to the effect of land use change in its watershed. Originating in the primary forest of the PNT, it flows through a large agricultural area of agro-industrial hevea blocks, palm trees and village plantations, before emptying into the Atlantic Ocean in the urban area of San Pedro. In order to assess the impact of anthropization of its watershed, the San Pedro River was investigated from May 2016 to April 2017. The physico-chemical and ionic variables of the water were collected monthly in three study stations respectively through a multiparameter type Lovibond Senso Direct 150 and miniphotometers brand Hanna. Different statistical approaches (Kruskall-Wallis, Mann-Withney and Principal Component Analysis) were applied to a dataset of 1836 values in order to interpret the spatio-temporal variation of the water quality of this coastal river. Significant spatial variation ($p<0.05$) was observed between data from the forested area and the anthropized area. An increase in water temperature, pH, electrical conductivity, dissolved solids, phosphate and nitrogen compounds, as well as a decrease in dissolved oxygen and transparency were observed from the park to the urban area. This change in the aquatic environment highlighted the impact of the removal of forest cover in favor of agriculture and urbanization in the San Pedro River watershed. This could be an ecological stressor for aquatic species and limit the conservation of aquatic biodiversity. Water quality monitoring programs should be considered for the preservation of aquatic resources.

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Introduction

The conversion of forest areas into agricultural areas and the intensification of agricultural activities is one of the major causes of degradation of terrestrial and aquatic ecosystems in the world (Leigh *et al.*, 2010; Sass *et al.*, 2010). This global phenomenon, which continues to grow, has disastrous ecological repercussions on water bodies and rivers (Tilman *et al.,* 2001; Glücker *et al.,* 2009; Hepp *et al.,* 2010). Several studies have highlighted the negative impacts of the use of pesticides and chemical fertilizers on aquatic communities (Chambers *et al.,* 2001; Lawani *et al.,* 2017). These chemicals, once dispersed, affect the different compartments of the environment. The aquatic ecosystems remain for the most part the ultimate receptacle of these residues. This constitutes a real threat for aquatic ecosystems with a watershed with strong agricultural activity. In addition to affecting the quality of water, these chemicals strongly disturb the stability of aquatic populations by intoxication and ecological stresses up to the extinction of certain species (Youes-Barailli *et al.,* 2005 ; Agbohessi *et al.,* 2011)

The southwest of Côte d'Ivoire remains one of the largest agricultural areas. Indeed, the establishment of many agro-industrial firms such as the Société des Caoutchoucs de Grand Béréby (SOGB), the Société Africaine de Plantation d'Hévéa (SAPH), the Société de production de palm à huile de Côte d'Ivoire (PALMI-CI) increases their production capacity every year (OIPR, 2014). This agricultural development observed in this Ivorian region is mainly due to a favorable climate caused by the forest massif of the Taï National Park. This primary forest under strict protection provides enormous ecosystem services to the region. Indeed, at least 3.2% of Côte d'Ivoire's gross domestic product (GDP) emanates from this area through the production of cocoa, coffee, rubber, and oil palm representing a turnover of 492 billion FCFA in 2014 (Berger *et al.,* 2015). Unfortunately, this agricultural prowess has negative impacts on aquatic resources. The San Pedro River is one of the main rivers in the southwest region of Côte d'Ivoire. It originates in the Taï National Park and flows into the Atlantic Ocean at the level of the town of San Pedro after having crossed a vast domain of agricultural occupation. About 17% of its basin (556 km^2) is under strict protection within the park and the rest (112 km; 3310 km2) under anthropic pressure.

Several studies have been conducted on the San Pedro River. Most of these studies focus on the ichthyofauna of the peripheral zone (Koné *et al.,* 2014; Kamelan *et al.,* 2014; Kamelan *et al.,* 2018) and benthic macroinvertebrates (Diarassouba, 2014). However, no data on the physico-chemical quality of the water exist. This study aims to characterize the physico-chemical environment of the San Pedro River in order to provide a first database of environmental parameters to contribute to the conservation of aquatic resources of this important coastal basin of Côte d'Ivoire.

Materials and methods

Study area

The San Pedro River is located in the southwest of Côte d'Ivoire. It is 112 km long with a catchment area of 3310 km2 (Molinier, 1972) and originates in the primary forest of the Taï National Park. After passing through several industrial and village plantations, the San Pedro River empties into the Atlantic Ocean in the town of San Pedro. This river has a sub-equatorial climate with dense forest vegetation and a rainfall of up to 2100 mm/year. A total of 3 stations were selected for this river, including 2 stations in the Park (SP1 - 05°19'31.790'' N and 006°52'08.465'' W ; SP2 - 05°13'53.241'' N ; 006°52'26.795'' W) and 1 station in the urban area (SP3 - 04°47'11.838'' N ; 006°38'49.263'' O) (Fig. 1).

Measurement of environmental variables

The physico-chemical variables of the water (water temperature, dissolved oxygen rate, pH, electrical conductivity, TDS and oxidation-reduction potential) were measured using a multi-parameter Lovibond Senso Direct 150. Ionic compounds (nitrite, nitrate, phosphate, total phosphorus, free chlorine, total chlorine and ammonium) were measured with Hana mini-photometers. For each of the water variables, three in situ measurements were made at each station between 7 and 8 am, 12 and 1 pm and between 3 and 4 pm. Data collection were performed according to the methods described by (Rodier *et al.,* 2009).

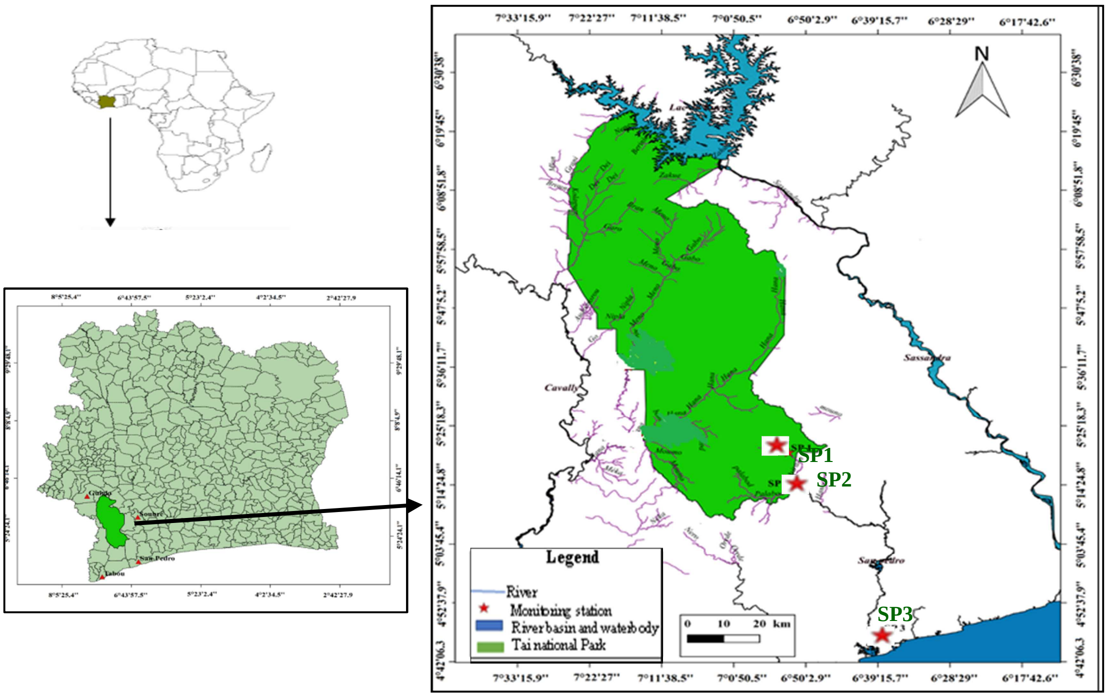


Fig. 1. Map of the stations of measurement of physico-chemical parameters in the San Pedro River in the NTP from May 2016 to April 2017.

The depth and width of the stream were assessed at each mission using a graduated string immersed to the substrate for depth and from bank to bank for width expressed in meters (m). To measure transparency, the Secchi disk is immersed in water until it disappears completely. Then it is slowly raised until it is visible. The graduated wire is then used to determine the thickness of the euphotic zone in cm. The velocity was measured according to (McMahan *et al.,* 1996) using a half-filled 0.5 liter plastic bottle and is expressed in m/s. All these variables were measured each month from May 2016 to April 2017.

Data analysis

A descriptive analysis was applied to all the data collected in order to assess the position and dispersion parameters of the different variables in the waters of the San Pedro River. In order to highlight the spatio-temporal variation, an inferential analysis based on the Kruskall-Wallis and Mann-Withney tests, associated with multiple comparison tests, was performed at the critical threshold of 0.05.

A principal component analysis with a varimax rotation was applied to all the water variables collected to visualize the typology of environmental characteristics of the study stations of the San Pedro River. All these analyses were performed using Statistica and XLStat version 2014 software.

In order to estimate the organic pollution of the different study stations and to visualize the spatio-temporal evolution of this pollution, the Organic Pollution Index (OPI) was used. The details of this index are shown in Table I.

Table 1. Class limits of the Organic Pollution Index (Leclercq, 2001).

Class	NH_4^+ (mg/L)	NO_2^- (mg/L)	PO_4^{3-} (mg/L)
5	< 0.1	< 0.005	< 0.015
4	0.1- 0.9	0.006- 0.01	0.016- 0.075
3	1- 2.4	0.011- 0.05	0.078- 0.25
2	2.5- 6	0.051- 0.15	0.251- 0.9
1	< 6	< 0.15	< 0.9

(5): no organic pollution, (4) : low organic pollution, (3): moderate organic pollution, (2) : high organic pollution, (1) : very high organic pollution.

In order to determine the oxidizing or reducing character of the river water, the oxidizing power (RH) of the water was calculated from the following equation:

$$R_H = \frac{E_h}{0992 \times T} + 2\,pH$$

E_h: Average redox potential; T: Temperature in degrees Kelvin (273 + T°C); pH = Hydrogen potential.

The value obtained for the oxidizing power allows the water to be placed in the following categories according to (Rejset, 2002): RH ≥ 23, the medium is said to be oxidizing; 15 < RH < 23, the medium is described as anoxic; RH < 15, the medium is said to be reducing.

Results

Spatial variation of environmental parameters of the San Pedro River

The descriptive analysis showing the annual mean values of the physico-chemical and hydromorphological variables of the San Pedro River is shown in Table 2. The spatial variation of these physico-chemical parameters of the San Pedro River is shown in Fig. 2. The Kruskall-Wallis H-test showed statistically significant differences ($p < 0.05$) for the parameters temperature, dissolved oxygen level, conductivity and TDS. Temperature values differed significantly between stations SP3 and SP1 on the one hand and between stations SP3 and SP2 on the other.

The mean annual temperature of the San Pedro River is 26.76 ± 1.97 °C. It follows an increasing gradient from the interior to the periphery of the park with maximum values at station SP3 (29.03 °C) and minimum at stations SP1 (25.58 °C) and SP2 (25.67 °C). Dissolved oxygen levels differed significantly between stations SP3 and SP1 and between stations SP3 and SP2. The average annual oxygen level in the San Pedro River is 6.36 ± 1.33mg/L.

It is very low at station SP3 (4.57mg/L) and very high at stations SP1 (7.10mg/L) and SP2 (7.42mg/L). For conductivity and TDS, the values differ significantly in all stations taken in pairs.

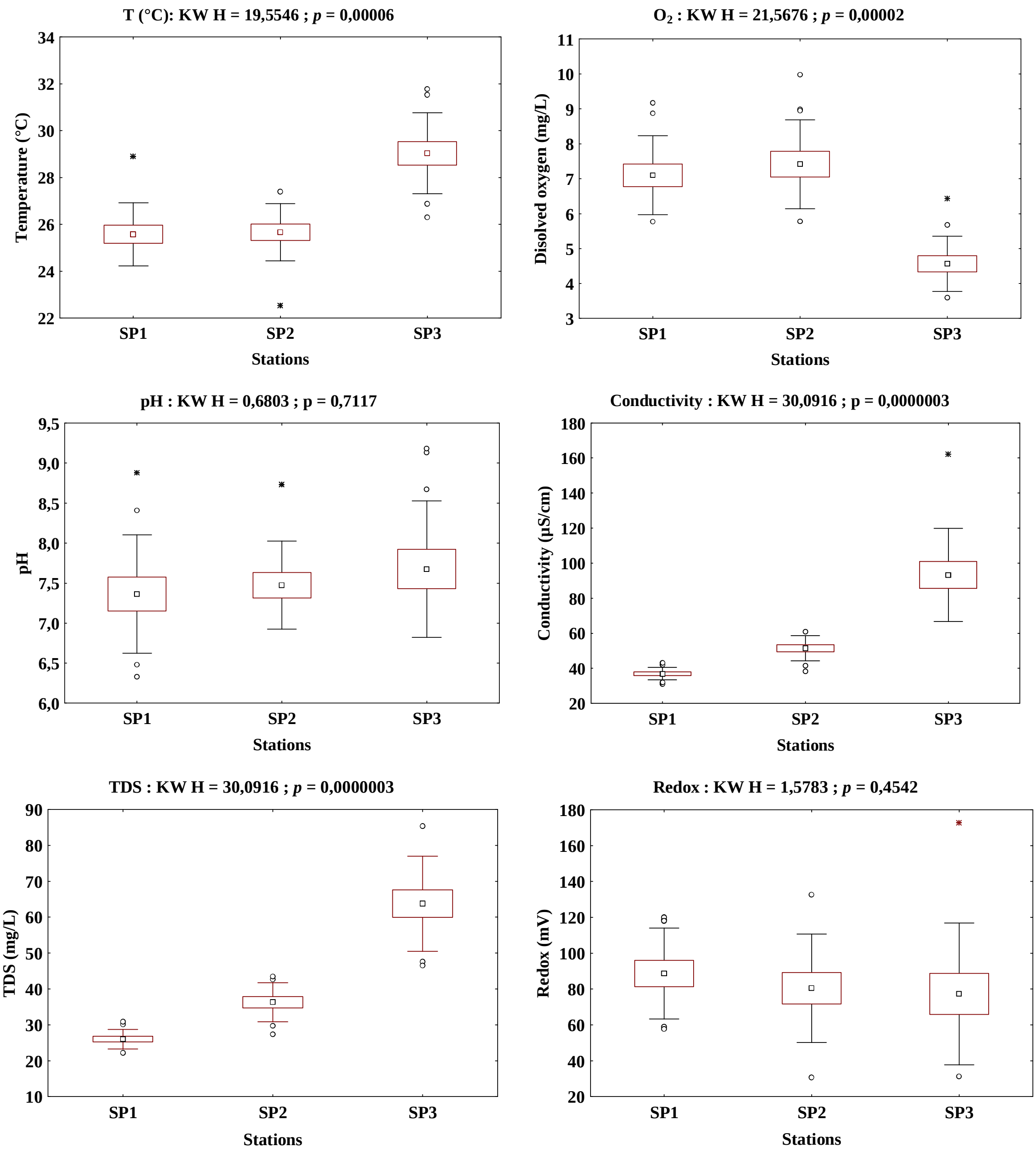
The conductivity and TDS readings follow an increasing upstream-downstream gradient. Values are highest at station SP3 (Conductivity = 93.29 µS/cm and TDS =63.71mg/L) and lowest at stations SP1 (36.96 µS/cm and 26.03mg/L) and SP2 (51.46 µS/cm and 36.33mg/L). As for the redox potential values, the maximum is obtained at station SP3 (172.7 mV) and the minimum at station SP2 (30.67 mV) with an average of 82.154 ± 31.734 mV in the San Pedro River.

Of the ionic compounds measured in the San Pedro River, only ammonium and free chlorine do not show significant variation between stations (Fig. 3).

Thus, the values of nitrite, nitrate and phosphate differ between station SP3 and SP1. The annual mean values for nitrite, nitrate and phosphate are 0.012 ± 0.006mg/L, 3.48 ± 1.97mg/L and 0.313 ± 0.16mg/L, respectively. At station SP3, these values are 0.009mg/L, 2.60mg/L and 0.380mg/L while at station SP1 the measured concentrations are 0.015mg/L, 4.38mg/L and 0.195mg/L respectively.

Table 2. Annual average values of physico-chemical variables of the San Pedro River waters measured from April 2016 to May 2017.

Variables	Observations	Minimum	Maximum	Mean	Std. deviation
Température (°C)	36	22.53	31.77	26.761	2.153
pH	36	6.33	9.18	7.505	0.716
Oxygen (mg/L)	36	3.6	9.98	6.361	1.667
Conductivity (µS/cm)	36	31.07	162.2	60.567	28.798
Dissolved solids (mg/L)	36	22.19	85.4	42.045	18.11
Redox (mV)	36	30.67	172.7	82.154	31.734
Nitrites	36	0.002	0.024	0.011	0.005
Nitrates	36	0.5	7.1	3.33	1.595
Phosphates	36	0.013	0.71	0.322	0.186
Total phosphorus	36	0.045	6.5	1.197	1.675
Ammonium	36	0.533	8.33	3.138	1.674
Total Chlorine	36	0.027	0.72	0.128	0.12
Free Chlorine	36	0.017	0.19	0.086	0.031
Velocity	36	0	1.325	0.555	0.335
Transparency	36	26	73	51.015	12.547
Depth	36	0.41	4.42	1.724	1.124
Width	36	5	58.54	38.757	12.483



K. H test: Kruskall-Wallis H test at the 0.05 threshold.

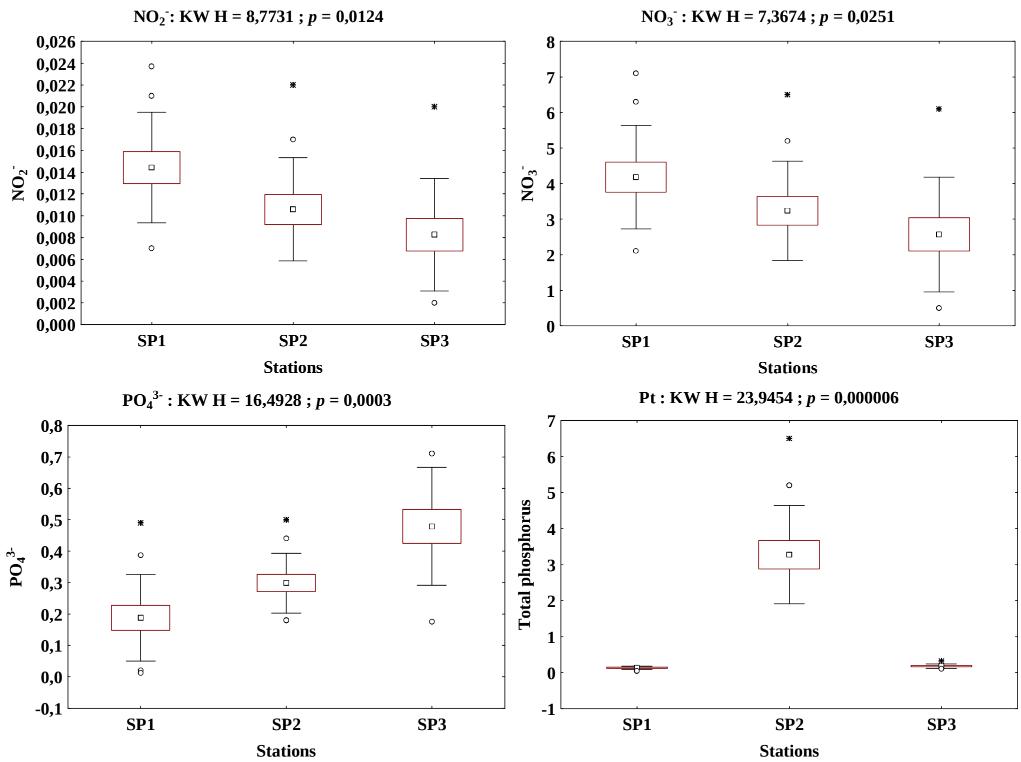
Fig. 2. Spatial variation of physico-chemical parameters measured in the San Pedro River stations of the NWP from May 2016 to April 2017.

Total phosphorus differs between stations SP2 and SP1 on the one hand and between SP2 and SP3 on the other. It is higher at station SP2 (3.73mg/L) and lower at stations SP1 and SP3 (0.13mg/L and 0.17mg/L respectively). Total chlorine readings differed from station SP1 to SP2. The concentration of total chlorine is higher at station SP1 with 0.256mg/L compared to station SP2 with 0.048mg/L. The analysis of hydro-morphological parameters showed a significant difference ($p < 0.05$) for velocity, depth and width (Fig. 4). The average velocity of the San Pedro River is 0.55 ± 0.34 m/s with higher values (0.77 m/s) at station SP2 and lower (0.41 m/s) at station SP3. The maximum depth (3.12 ± 0.50 m) of the stream was observed at station SP3 and the most depth value was determined upstream (SP1; 0.614 ±

0.17 m). This same gradient was observed for stream width (SP3: 51.51 m; SP1: 25.99 m).

Seasonal Variation of Environmental Parameters in the San Pedro River

Apart from pH and redox potential, the Mann-Withney U test showed no significant variation in the measured water parameters (Table 3). Thus, in the dry season, the water is more basic (pH=7.53) with a low redox potential than in the rainy season (pH=7.11) with a high redox potential.



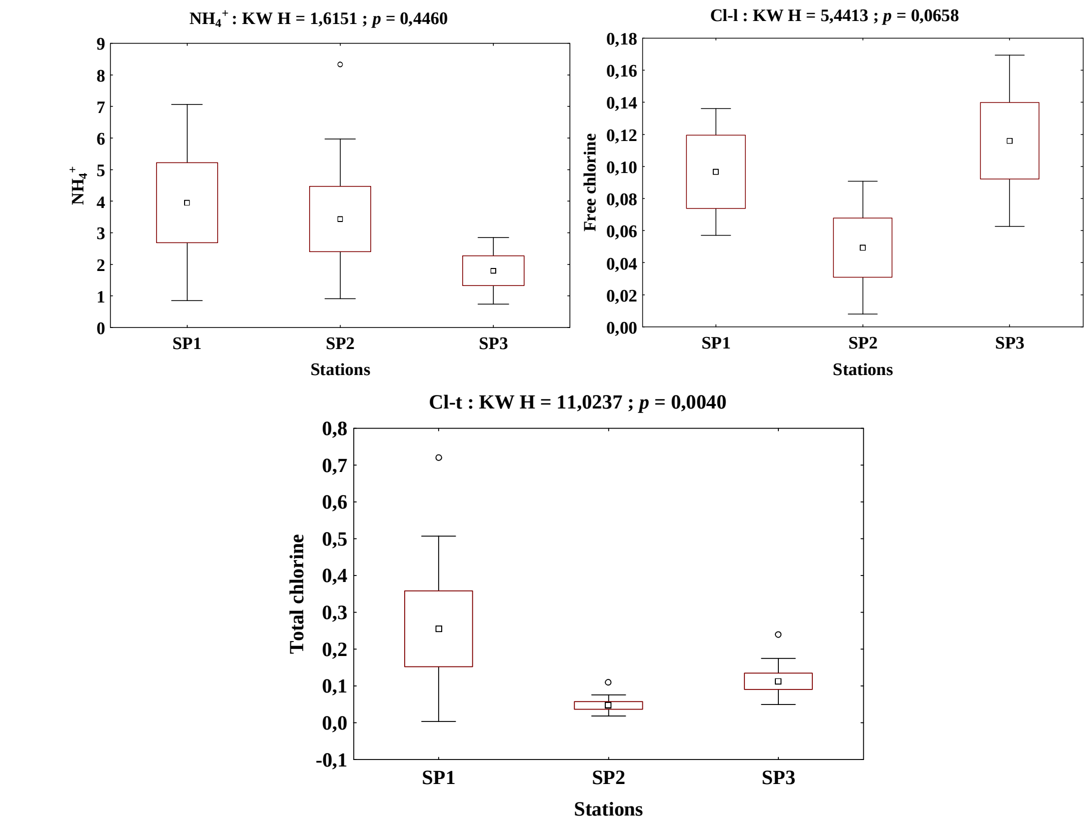


Fig. 3. Spatial variation of ionic compounds measured at stations in the San Pedro River from May 2016 to April 2017.

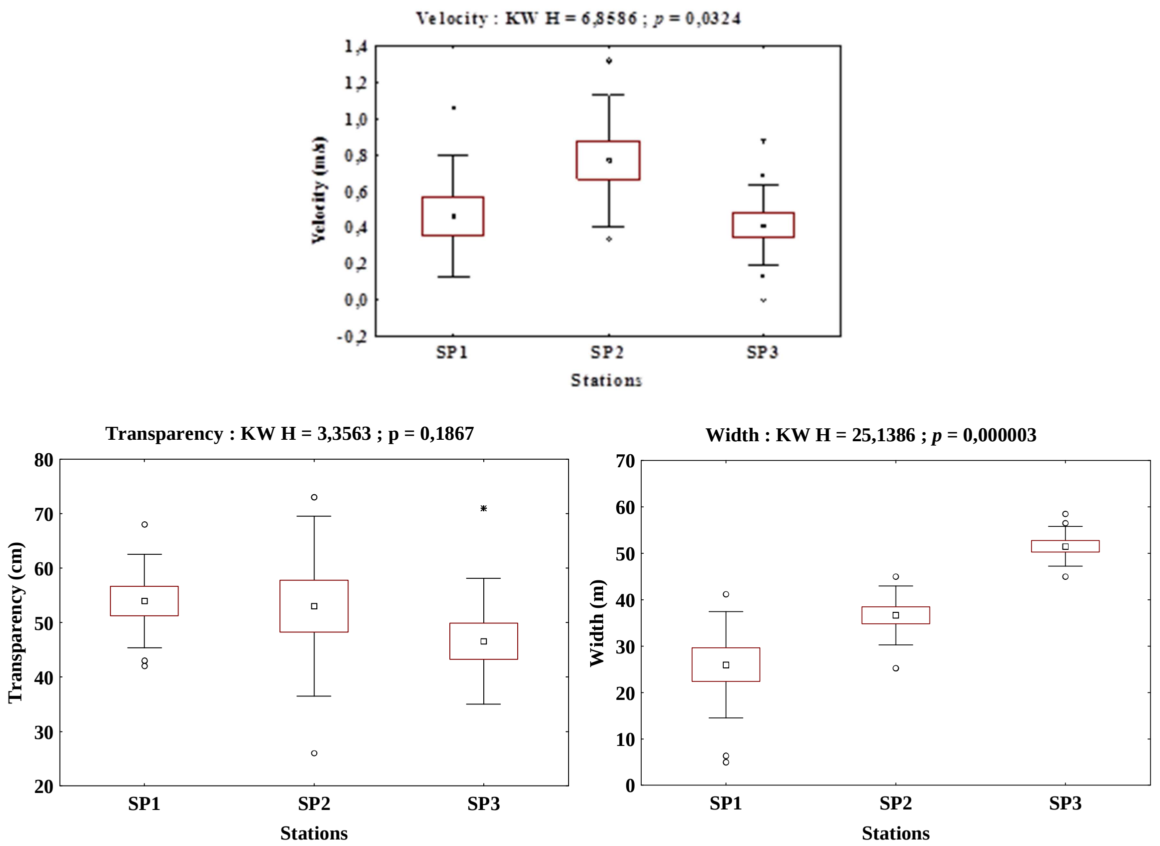


Fig. 4. Spatial variation of hydro-morphological parameters measured in the stations of the San Pedro River of the NWP from May 2016 to April 2017.

Table 3. Seasonal variations in environmental parameters of the San Pedro River surveyed from May 2016 to April 2017.

Seasons	Rainy			Dry		
Parameters	Mini	Max	Méd	Mini	Max	Méd
Physico-chemical parameters						
T (°C)	22.53	31.77	26.37	24.43	31.53	25.94
pH*	6.33	9.18	7.11	6.88	9.13	7.53
O_2 (mg/L)	3.6	9.98	6.48	4.1	7.75	5.79
Cond (µS/cm)	35.17	162.2	61.75	32.1	107.2	66
TDS (mg/L)	23.47	85.4	44.105	23.21	76.57	47.14
Redox* (mV)	49	172.7	91.84	30.67	118	62.42
Ionic compounds (mg/L)						
NO_2^-	0.002	0,024	0,008	0,006	0,022	0,012
NO_3^-	0.5	7.1	2.5	1.8	6.5	3.4
PO_4^{2-}	0.02	0.5	0.297	0.173	0.71	0.384
TP	0.045	5.2	0.153	0.124	6.5	0.25
NH_4^+	0.53	8.33	1.98	1.9	7.9	2.78
TCL	0.03	8.33	0.13	0.03	2.6	0.11
FCL	0.017	0.14	0.055	0.047	0.19	0.12
Hydro-morphological parameters						
Velocity (m/s)	0.37	1.32	0.56	0.132	1.33	0.45
Transparency (cm)	26	73	44	35.5	73	58
Depth (m)	0.41	4.42	1.99	0.43	3.07	1.08
Width (m)	25.26	58.54	41.23	5	56.28	38.9

*: Data showing statistically significant variations between rainy season and dry season values at $p < 0.05$

Calculation of pollution indices

The pollution index analysis indicates values between 2 and 3.33. These values range from 2.33 to 3.33 during the rainy season and 2 to 3 2.33 to 3.33 during the dry season (Fig. 5).

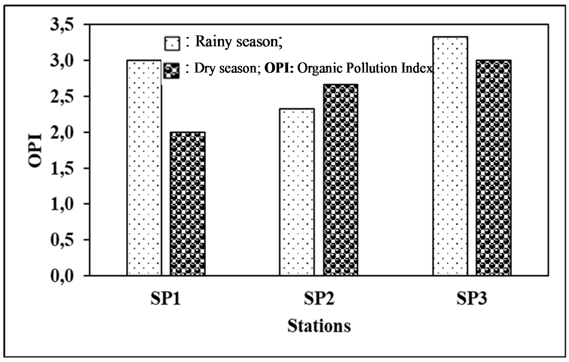


Fig. 5. Spatial and temporal variation in the Organic Pollution Index (OPI) of the San Pedro River from May 2016 to April 2017.

This reflects a moderate to high range of organic pollution during both seasons. Spatially, this index is lower in the urban area (SP3; 4: low organic pollution) and relatively high in the park (SP1; 1: very high organic pollution). The average annual value of the oxidizing power of the waters of the San Pedro River is 17.79 (Table 4). This parameter ranges from 17.34 to 18.03 in the rainy season and from 17.43 to 17.84 in the dry season.

Table 4. Seasonal variation in water oxidizing power (R_H) in the San Pedro River from May 2016 to April 2017.

	R_H			
	SP	Nature of the environment	SS	Nature of the environment
SP1	17.34	Anoxic	18.1	Anoxic
SP2	17.9	Anoxic	17.43	Anoxic
SP3	18.03	Anoxic	17.84	Anoxic

Typology of the stations

A principal component analysis (PCA), carried out on 17 environmental variables, made it possible to highlight the typology of the stations of the San Pedro River. In this ordination, axis 1 (eigenvalue F1= 73.06%) and axis 2 (eigenvalue F2= 26.94%) expressed 100% of the cumulative variance of the collected data (Fig. 6). Water temperature (r = 0.97), pH (r = 0.96), dissolved oxygen (r = 0.92), electrical conductivity (r = 0.99), TDS (r = 0.99), nitrite (r = 0.78), nitrate (r = 0.81), phosphate (r = 0. 95), ammonium (r = 0.99), width (r = 0.94), depth (r = 0.77), and transparency (r = 0.80) recorded the highest values (r > 0.7) for the I axis ordination. This axis separates station SP3 on its negative end characterized by an increase in water temperature, pH, electrical conductivity, dissolved solids, phosphate, depth and stream width as well as a decrease in dissolved oxygen, nitrogen compounds (nitrate, nitrite, ammonium) and water transparency. Stations SP1 and SP2 are grouped on the positive part of Axis I characterized by an increase in dissolved oxygen, nitrogen compounds (nitrate, nitrite, ammonium) and water transparency and a decrease in the other water variables. The variables total phosphorus (r = 0.89), total chlorine (r = 0.85) and current velocity (r = 0.80) recorded the highest values (r > 0.7) for the axis II ordination. This factor separates station SP1 characterized by high total chlorine from SP2 characterized by high current and high total phosphorus.

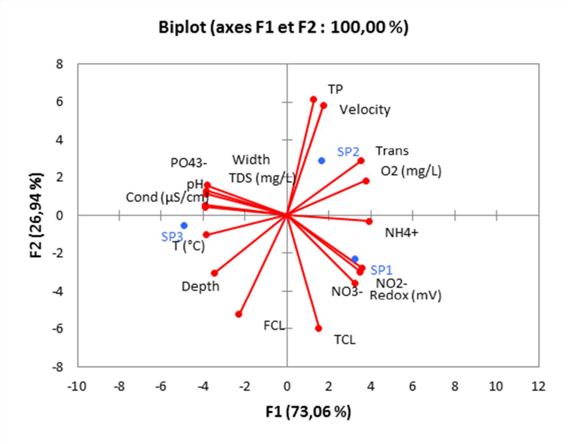


Fig. 6. Factor map of San Pedro River sampling stations from May 2016 to April 2017.

Discussion

Analysis of the environmental characteristics of the San Pedro River indicates an annual water temperature above 25°C. This water temperature value increases progressively from the forest area of the park towards San Pedro town. This was observed by Diomandé *et al.* (2019) in the Meno River, which originates in the forest of Taï National Park and flows into the Hana River at the town of Djouroutou. The increase in water temperature from forested areas to urban areas highlights the impact of land use in the watersheds of continental rivers. Indeed, in agreement with several authors (Ometto *et al.*, 2000; Mckee *et al.*, 2000 ; Likens, 2004 ; Thomas *et al.*, 2004 ; Silva *et al.*, 2012) land use change modifies the basic functioning of aquatic ecosystems. This is reflected in an increase in water temperature, electrical conductivity, dissolved solids and a decrease in dissolved oxygen, as observed at the SP3 station located in the urban area of San Pedro. In fact, urbanization is the main land use in the town of San Pedro. In addition to the elimination of the forest for the benefit of urbanization, the continental aquatic ecosystems are the places of discharge of untreated wastewater from urban areas of developing countries. This untreated wastewater is a real source of heavy metals, pathogens and drugs, including carcinogenic compounds (Sañudo-Wilhelmy *et al.*, 1999 and Wethé *et al.*, 2003).

These anthropogenic inputs therefore promote an increase in the electrical conductivity of aquatic environments, the rate of dissolved solids in the water and a decrease in the rate of dissolved oxygen due to the high wastewater load. The decrease in dissolved oxygen is thought to be related to the intense activity of aerobic bacteria in the mineralization of organic matter and the release of carbonic acid into the environment (CRE, 2009).

In the presence of a high wastewater load, these aerobic bacteria consume sufficient oxygen for the degradation of organic matter, thus leading to an oxygen deficit in the watercourse (Diaz, 2009; Hulla *et al.*, 2008). In addition, the increase in nitrate levels observed downstream of the San Pedro River could be attributed to runoff water that drains agricultural effluents from industrial and village plantations observed along the San Pedro River.

In fact, after leaving the forest of the PNT, the San Pedro River crosses huge agricultural areas of cocoa, hevea and palm trees mostly belonging to multinational companies such as SAPH, PALMCI and SOGB. These agro-industrial blocks of monocultural regime require large quantities of chemical inputs to improve crop productivity.

Chiapo and Adja (2015) have indicated that the majority of chemical inputs used in the plantations around the park are of chemical origin and consist of NPK fertilizers. The input of these effluents changes the chemistry of the contaminated water. These changes have been reported by Rai *et al.* (2015) and Kamisako *et al.* (2008) in temperate rivers, Silva *et al.* (2011) and Andrade *et al.* (2011) in tropical waters. Seasonal analysis of environmental variables indicates significant variation in pH and redox potential during this study. Indeed, the pH and redox potential values change inversely from one season to another. The pH values oscillate between 7.06 in the rainy season and 7.91 in the dry season and remain around neutrality throughout the year. Such a trend has been observed by Mounjid *et al.* (2018) in the Merzeg River in Casablanca, Morocco and Tohozin *et* *al.* (2018) in the Sô River in Benin. The latter authors state that values close to neutrality are characteristic of the majority of surface waters. The relatively lower pH values during the rainy season compared to the dry season could be explained by the acidification of water due to rainfall and runoff from more acidic arable soils. According to Konan *et al.* (2017), the hydration of CO_2 produces carbonic acid, the ionization of which releases H^+ ions that contribute to the decrease in water alkalinity.

Principal component analysis highlights a gradient of impact of land use change on the water chemistry of the San Pedro River along axis 1. From the forest of Taï National Park to the town of San Pedro, a set of changes in environmental water variables were observed. These modifications were favored by the elimination of vegetation cover in favor of the creation of agro-industrial blocks and the intensification of urbanization in the town of San Pedro, which hosts one of the main ports in West Africa. Thus, a strong environmental pressure is expressed at the level of the SP3 station through an increase in the temperature and mineralization of the water associated with a decrease in the oxygen level. This would constitute a real threat to the aquatic biodiversity of this area of the San Pedro River. Within the Taï National Park, a decreasing gradient of organic pollution from SP1 to SP2 has been maintained. This organic pollution would be due to a significant degradation of organic matter through plant debris released into the aquatic environment. The decomposition of this organic matter by aerobic bacteria leads to a high consumption of oxygen in the environment, making the environment anoxic (IBGE, 2005). This phenomenon explains the rather low values of the oxidizing power (RH) measured during the two seasons. The increase in phosphorus content at station SP2 suggests an endogenous source of phosphorus input to the river. Kleeberg and Kozerski (1997) demonstrated a benthic release of phosphorus into surface waters. In agreement with these authors, the high value of phosphorus in this station would be related to the nature of the sediment and the geomorphology of this station. Indeed, this station is characterized by an abundance of substrate and rocky outcrops making this area quite atypical. In addition, several other factors such as redox potential, nitrate concentration, mineralization, release, bioturbation, the effects of phytoplankton and macrophytes (Mama, 2010) could promote the desorption of phosphorus in the waters of the San Pedro River.

Conclusion

All the investigations carried out on the physico-chemical characteristics of the San Pedro River have made it possible to highlight the impact of the change in land use on the quality of the waters of the aquatic ecosystems. These modifications related to water temperature, dissolved oxygen rate, mineralization and ionic composition of the waters could negatively impact the conservation of aquatic species. In addition, seasonal variations in the pH of the waters of the San Pedro River were observed in the different stations visited. This seasonal variation would be related to the runoff of water from agricultural ponds that influences the aquatic environment of the river. The data from this work could be considered as a baseline for developing a management plan for the San Pedro River.

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