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Spatio-temporal dynamics of physico-chemical parameters in a forest stream: The Hana river, Taï national park, Côte d'Ivoire

Diomande Abou*[1], Kouassi Koumoin Henry-Delmas[2], Fofana Nahon Mamadou[3], Kouame K. Augustin[4], Kamelan Tanoh Marius[4]

[1]*Université Peleforo Gon Coulibaly de Korhogo, Département de Biologie Animale, Côte d'Ivoire*
[2]*Université Alassane Ouattara de Bouaké, UFR Sciences et Technologie, Côte d'Ivoire*
[3]*Université de San Pedro, UFR Agriculture Ressources Halieutiques Agro-industrie, Côte d'Ivoire*
[4]*Université Félix Houphouet Boigny de Cocody Abidjan, Laboratoire des Milieux Naturels et Conservation de la Biodiversité, UPR Hydrobiologie et eco-Technologie des Eaux, Côte d'Ivoire*

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ABSTRACT

This study aimed to assess the spatial and seasonal variation of physicochemical parameters in the Hana River within Taï National Park in order to strengthen monitoring of its aquatic environment and support biodiversity conservation. Monthly measurements were conducted from May 2016 to April 2017 at three stations—upstream, midstream, and downstream—during three daily intervals. Using a LOVIBOND SENSO DIRECT 150 multiparameter meter, the annual mean values recorded were: temperature (26.89 ± 2.17 °C), pH (7.14 ± 0.51), dissolved oxygen (5.70 ± 1.67 mg/L), conductivity (52.28 ± 17.33 µS/cm), total dissolved solids (37.07 ± 12.46 mg/L), and redox potential (75.08 ± 41.33 mV). Nutrient concentrations measured with HANA mini-photometers included nitrites (0.011 ± 0.008 mg/L), nitrates (3.18 ± 2.27 mg/L), phosphates (0.273 ± 0.24 mg/L), total phosphorus (0.890 ± 1.39 mg/L), ammonium (2.927 ± 1.82 mg/L), total chlorine (0.088 ± 0.04 mg/L), and free chlorine (0.111 ± 0.11 mg/L). Hydromorphological parameters—velocity (0.361 ± 0.20 m/s), transparency (45.3 ± 17.62 cm), depth (2.179 ± 1.43 m), and width (19.29 ± 8.79 m)—were also recorded. Seasonal patterns showed that most parameters peaked during the dry season across all stations. Principal Component Analysis suggested that observed variations and local impairments were largely linked to agricultural and rural activities, with natural watershed processes contributing to a lesser extent. Overall, the Hana River exhibited lower physicochemical levels than typically reported in similar ecosystems, and nutrient concentrations remained within acceptable limits. However, areas influenced by rural activities displayed higher pollution indicators. These findings highlight the need to establish a standardized chemical monitoring framework to ensure long-term protection of the Hana River.

***Corresponding author:** Diomande Abou ✉ diomandeabout@gmail.com
https://orcid.org/0009-0004-2907-5708

INTRODUCTION

Ivory Coast is drained by a dense hydrographic network extending from the north to the south, comprising rivers, streams, lakes, and lagoons. Unfortunately, this vast water resource potential is subject to anthropogenic pressures related to agro-industrial activities, agricultural exploitation, and illegal gold mining. Like many developing countries, Ivory Coast lacks reliable and comprehensive data on its water resources.

Taï National Park (TNP), as the largest protected primary rainforest in West Africa, harbors a high diversity of flora and fauna, which has been the subject of numerous scientific studies on plant species (Adou *et al*., 2005; Guillaumet, 1994; Aké-Assi and Pfeffer, 1975; Bakayoko, 2005) and wildlife (Roth and Merz, 1986, in Riezebos *et al*., 1994; Gartshore, 1989, in Tropenbos, 1994; TNP, 2006). In contrast, its hydrographic potential remains poorly documented, with existing data being sparse and scattered, mainly limited to studies on fish by Kamelan *et al.* (2014), benthic organisms by Diarrassouba *et al.* (2012), and physicochemical parameters by Grell *et al.* (2012). Therefore, monitoring the water quality of these rivers is essential both for the health of local communities and for the preservation and conservation of biological diversity.

The Hana River is one of the main watercourses crossing the TNP. It originates outside the protected forest and flows from east to west, receiving several tributaries, including the Pama River, which traverses the conservation area. This study, conducted within the framework of ecological monitoring of rivers in the TNP, involved monthly measurements of physicochemical parameters of the Hana River over a one-year period. Following the analytical techniques described by Rodier *et al.* (2009), water temperature, pH, conductivity, total dissolved solids, redox potential, dissolved oxygen, as well as four physical parameters (transparency, depth, velocity, and width) were measured. In addition, nine nutrients (nitrites, nitrates, phosphate, total phosphorus, ammonium, ammonia, ammoniacal nitrogen, free chlorine, and total chlorine) were quantified at each sampling station.

MATERIALS AND METHODS

Study area presentation

The Taï National Park (PNT) is located in West Africa, in the southwestern region of Côte d'Ivoire, near the border with Liberia, between 5°08' and 6°24' N latitude and 6°47' and 7°25' W longitude (OIPR, 2006). The park extends over about 536,000 hectares of primary forest. The Hana River (5°24′–6°02′ N and 6°78′–7°35′ W) represents one of the principal rivers of PNT. It extends diagonally across the central section of the park, with a northeast–southwest flow direction (Kamelan, 2014). After traversing the park, it discharges into the Cavally River, with 77% of its basin (3,310 km²) located inside Taï National Park (Kamelan, 2014). The upper course of the Hana River is influenced by anthropogenic activities, particularly agricultural practices. Along the Hana River, three stations were selected based on gradients of anthropogenic pressure potentially altering its ecological condition: (i) Hana Mont Niénoukoué (Ha2), located in the midstream section at the park's core, free from human disturbance and serving as a reference site; (ii) Hana Ecotel (Ha3), positioned near Ecotel Touraco at the downstream outlet of the river outside the park; and (iii) Hana (Ha1), situated upstream at point O, where the river enters the park through the Soubré sector (Fig. 1).

Monitoring of physico-chemical parameters and data analysis

At each sampling station, physico-chemical parameters were recorded using digital meters of the Lovibond SensoDirect 150 model. Analytical procedures were carried out according to Rodier *et al.* (2009). For each station, three in situ measurements were performed monthly at specific intervals: 07:00–08:00, 12:00–13:00, and 15:00–16:00, over the study period from May 2016 to April 2017. During each sampling event, the river's depth and width were evaluated using a graduated rope. Depth measurements were taken by immersing the rope to the riverbed, and width was recorded from one bank to the other, expressed in meters (m).

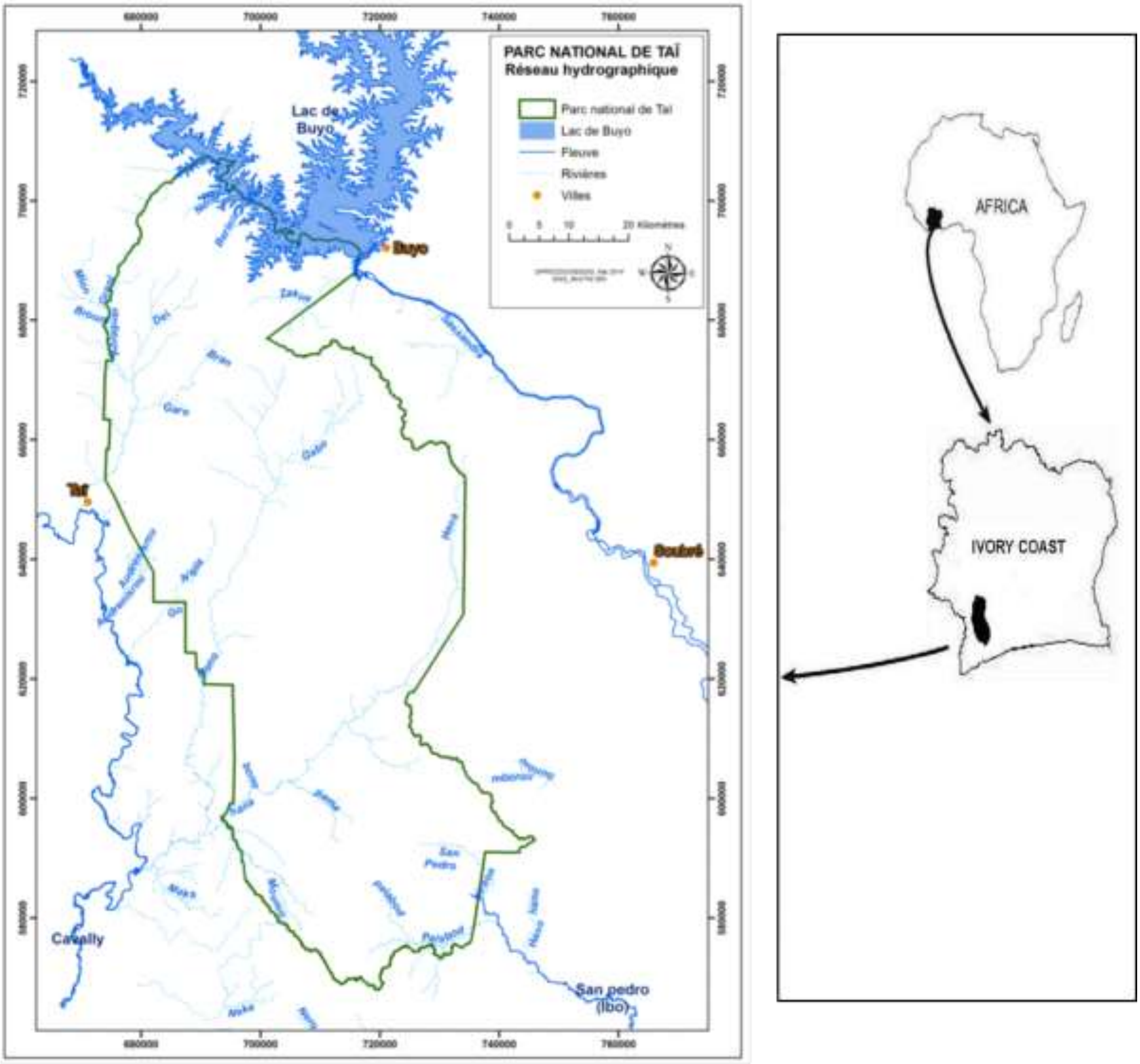

Fig. 1. Location of physicochemical sampling stations along the Hana River in Taï National Park (TNP).
Sampling stations Ha1 : Hana Point O ; Ha2 : Hana Mont Nienonkoué ; Ha3 : Hana Ecotel Touraco

Hence, the depth corresponds to the portion of the rope that was immersed in the water. For transparency measurements, the Secchi disk was placed into the water until it disappeared completely, and then carefully lifted until it could be seen again. The graduated line was used to quantify the euphotic zone depth, expressed in cm. Flow rate was measured according to McMahon *et al.* (1996) using a 0.5-liter plastic bottle filled to half its volume, with results reported in m/s. Data were analyzed using Statistica 7.1. Principal Component Analysis (PCA) with Varimax transformation was applied, and parameters showing significant correlations along each axis were used to infer potential sources of pollution in the river. Analysis of variance (ANOVA) was used to study the spatio-temporal variability of physico-chemical parameters, with statistical significance set at $p < 0.05$.

RESULTS

Physical parameters

In general, no statistically significant differences ($p > 0.05$) were observed in the daily variations of environmental parameters at any station. Therefore, only seasonal averages will be considered in describing the spatiotemporal variations of the physicochemical parameters of the Hana River. Overall, water temperatures at the sampled stations in the park were highest in the dry season (28.35°C), and Hana Point O (Ha1) recorded the maximum temperature of 29°C (Fig. 2A).

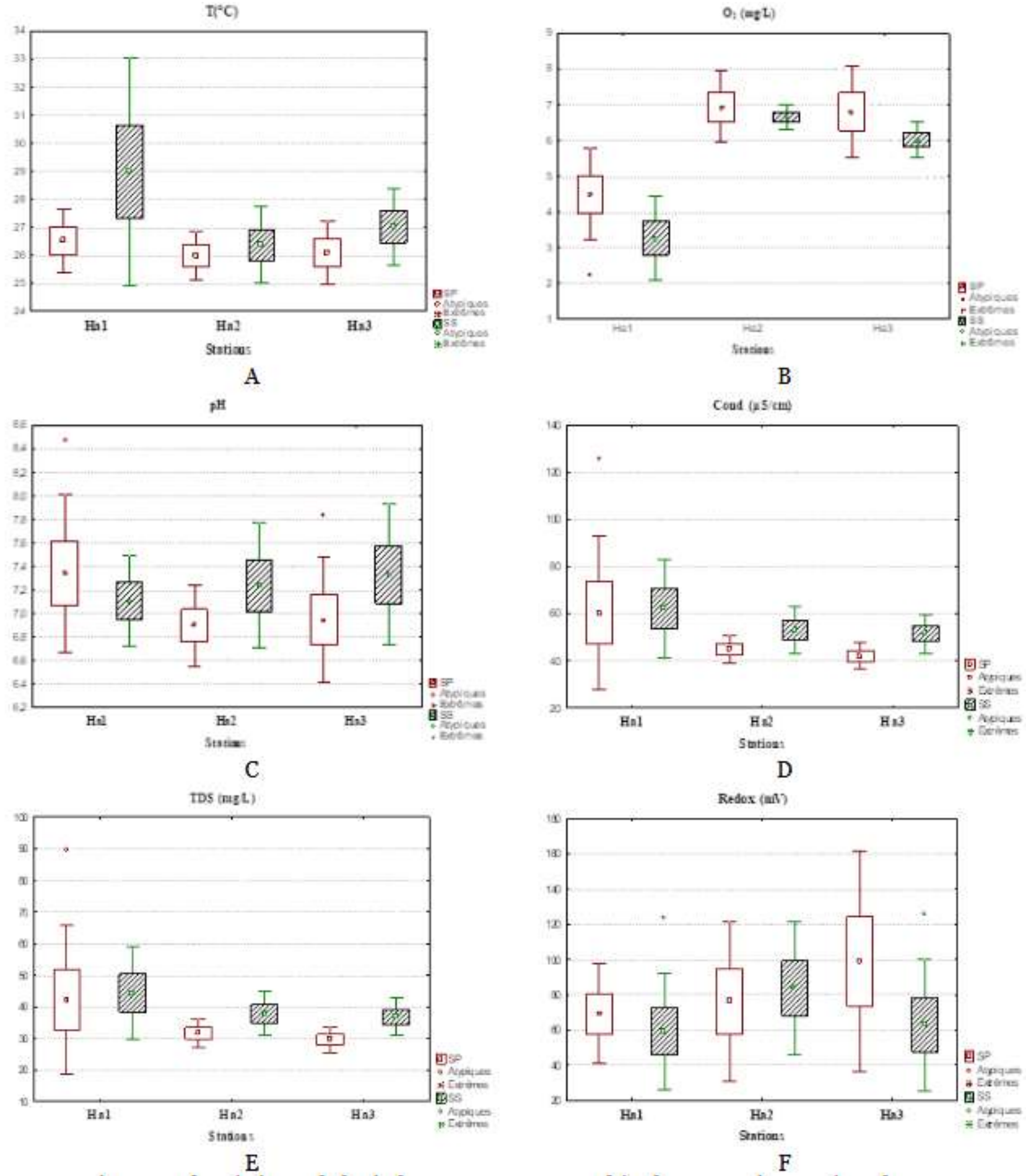

Fig. 2. Spatiotemporal variations of physical parameters measured in the Hana River stations from May 2016 to April 2017.

Ha1 : Hana Point O ; Ha2 : Hana Mont Nienonkoué ; Ha3 : Hana Ecotel Touraco ; SP : Rainy Season ; SS : Dry Season

The lowest seasonal mean temperature was observed during the dry season (26.20°C), with the lowest station-specific value recorded at Hana Mont Nienonkoué (Ha2) (25.99°C). Temperature variation corresponded inversely to oxygen concentrations across the stations during the four seasons. Hence, the highest water oxygen concentrations were recorded during the major rainy season (6.30 mg/L), whereas the lowest values occurred during the dry season (5.1 mg/L) (Fig. 2B). Hana Mont (Ha2) presented the maximum mean oxygen concentration (6.78 mg/L), whereas the minimum value was obtained at Ha1 (3.99 mg/L). The pH values measured across all sampled stations (Fig. 2C) generally indicated alkaline conditions (pH > 7), ranging from 6.90 at Ha2 during the rainy season to 7.34 at Ha3 in the dry season. Conductivity values (Fig. 2D) varied from 41.90 µS/cm at Ha3 in the rainy season to 62.14 µS/cm at Ha1 during the dry season, corresponding respectively to 29.60 mg/L and 44.39 mg/L of TDS. Conductivity measurements were proportional to TDS values (Fig. 2E). The mean conductivity and TDS across all stations were 52.28 µS/cm and 37.04 mg/L, respectively. Mineralization of the Hana River was higher during the dry season, with conductivity of 55.56 µS/cm and TDS of 39.68 mg/L, whereas the lowest seasonal means were observed in the rainy season (40.00 µS/cm and 34.46 mg/L). Regarding redox potential (Fig. 2F), values were relatively high in both the rainy season (81.53 mV) and dry season (68.63 mV), peaking at 198.50 mV during the rainy season at Ha3. Ha3 exhibited the highest annual mean redox potential (99.03 mV) in the rainy season, while Ha1 recorded the lowest annual mean (59.23 mV) during the dry season.

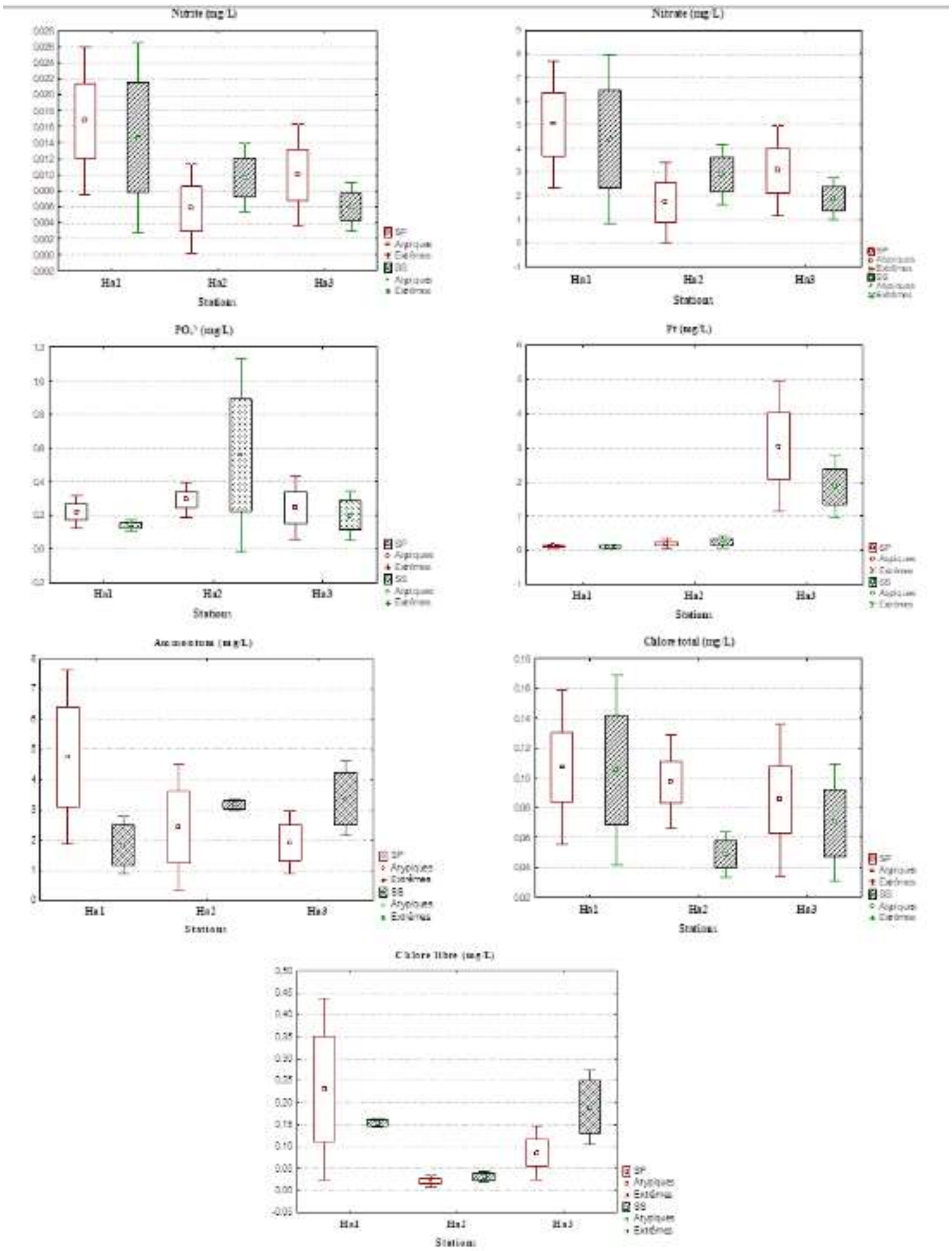

Fig. 3. Spatio-temporal variation of chemical parameters at Hana River stations from May 2016 to April 2017

Chemical parameters

The Kruskal–Wallis comparison test applied to the chemical parameter data from the three stations revealed a statistically significant difference ($p < 0.05$) for only two parameters (total phosphorus and free chlorine). Significant differences in total phosphorus were found between stations Ha3 and Ha1, and between Ha3 and Ha2, while free chlorine differed significantly between Ha2 and Ha1, and between Ha2 and Ha3. Most values were higher during flood periods across all stations. Thus, the Hana River stations showed higher concentrations of total phosphorus, phosphate, and total chlorine during the rainy season than in the dry season. Nitrite and nitrate levels at Ha1 and Ha3 were elevated in the rainy season and lower in the dry season, whereas at Ha2 the lowest seasonal means were observed in the dry season. Regarding free chlorine and ammonium, concentrations were relatively high at Ha1 during the rainy season and lower in the dry season, in contrast to stations Ha2 and Ha3 (Fig. 3).

Hydro-morphological parameters

The Kruskal-Wallis test applied to the seasonal data revealed no statistically significant differences among seasonal values of hydro-morphological parameters. However, measurements across stations showed significant statistical differences between sites. Only water velocity (Fig. 4A) did not vary significantly among stations. Water was more transparent (Fig. 4B) at station Ha3, where the highest transparency (75.1 cm) was recorded during the dry season. In contrast, the lowest transparency (29.5 cm) was observed at Ha1, also during the dry season. The river basin becomes progressively deeper (Fig. 4C) from upstream to downstream, as does its width (Fig. 4D). Upstream, the Hana River (Ha1) is a small stream, with a maximum depth of 0.80 m and a width of 9.49 m during the dry season. In the middle course (Ha2), depths reached 3.14 m during the rainy season, and the width extended up to 26 m. Downstream, at the outlet of the Hana Park (Ha3), the river resembles a fully developed watercourse, reaching a width of approximately 30 m and a depth of 3.80 m during the rainy season.

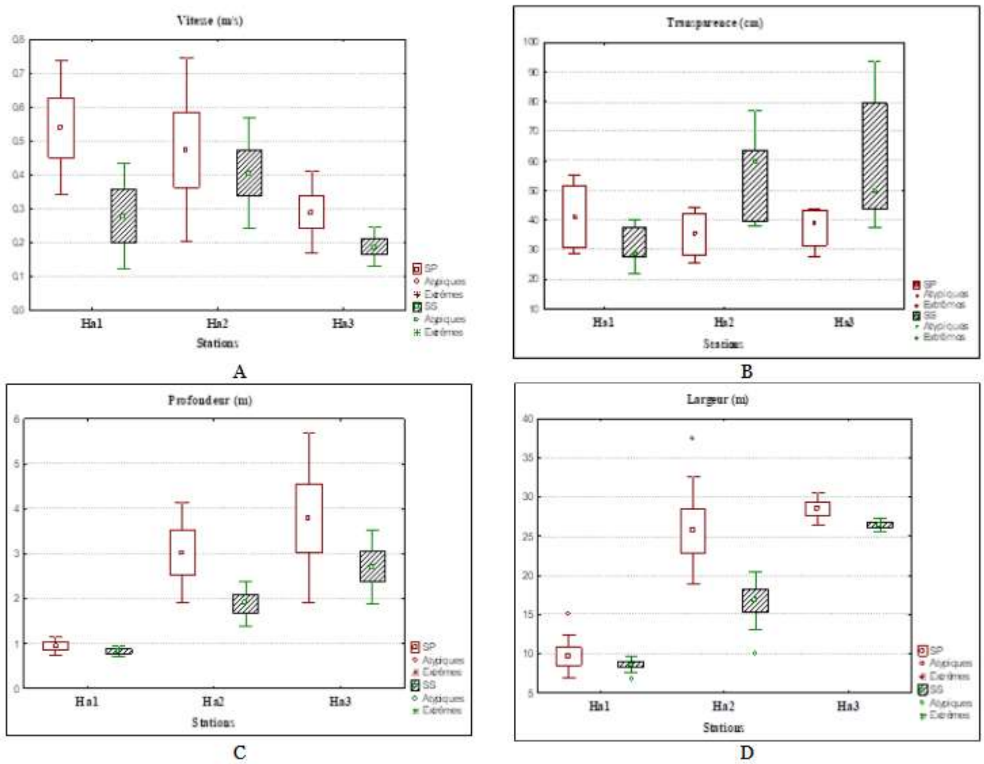

Fig. 4. Spatio-temporal variation of hydro-morphological parameters at Hana River stations from May 2016 to April 2017.

Abiotic typology of hana river waters

A Principal Component Analysis (PCA) was performed on data collected from the Hana River to assess potential sources of water pollution and to identify the major factors or parameters responsible for variations in water physico-chemical quality (Table 1). Seven (07) factors were identified, accounting for 74.13% of the total variance in water quality during the study period. A varimax rotation was applied to the principal components (F) with eigenvalues greater than 1 to obtain the varimax factors (D). The identification of pollution sources was based on different activities occurring within the watershed, supported by previous literature and field observations. Factors D1 and D3 explained 19.98% and 11.69% of the total variance, respectively. D1 showed strong positive correlations with Ammonium (r= 0.978), Ammonia (r= 0.977), and Ammoniacal nitrogen (r= 0.978), while D3 exhibited strong positive correlations with Nitrate (r= 0.979) and Nitrite (r= 0.977), which likely reflect nitrogenous pollution of mineral origin. Axis D2 accounted for 14.58% of the variance and was positively correlated with Dissolved Oxygen (O_2) (r= 0.750), Width (r= 0.821), and Depth (r= 0.715). In contrast, it was negatively correlated with Temperature (r= −0.471), Conductivity (r= −0.589), and TDS (r= −0.589). The parameters associated with Axis D2 suggest organic pollution. pH (r= 0.921) and Total Chlorine (r= 0.377) were positively correlated with Axis D4 (8.63% of the variance), whereas Redox potential (r= −0.558) and Phosphate (r= −0.243) were negatively correlated. These parameters defined by Axis D4 indicate physico-chemical pollution. Factors D5 (6.31%) and D6 (5.94%) were positively correlated with Free Chlorine (r= 0.902) and Total Phosphorus (r= 0.864), respectively. The variation in these parameters may be attributed to diffuse pollution throughout the watershed. Finally, Axis D7 (7%) was negatively correlated with Velocity (r= −0.856) and positively with Transparency (r= 0.429), corresponding to pollution associated with climatic variability.

Table 1. Factor loadings after varimax rotation

	D1	D2	D3	D4	D5	D6	D7
T (°C)	-0,320	-0,471	0,026	0,101	-0,259	-0,209	0,394
pH	0,173	-0,052	0,132	0,921	0,023	-0,086	0,039
O_2	0,020	0,750	0,015	0,161	0,081	0,277	0,183
Cond	0,563	-0,589	-0,281	0,244	-0,123	0,115	0,224
TDS	0,555	-0,589	-0,303	0,224	-0,113	0,129	0,236
Redox	-0,067	0,094	0,011	-0,558	0,358	0,230	-0,125
Nitrites	0,106	0,001	0,977	0,056	0,036	0,019	-0,063
Nitrates	0,111	0,002	0,979	0,060	0,039	0,031	-0,067
Phosphates	0,080	0,055	-0,097	-0,243	-0,029	-0,077	0,141
Total phosphorus	-0,215	0,155	0,074	-0,161	-0,014	0,864	-0,056
Ammonium	0,978	0,000	0,104	0,045	-0,029	-0,067	-0,071
Ammoniaque	0,977	-0,003	0,107	0,052	-0,027	-0,070	-0,069
Azote ammoniacal	0,978	0,000	0,104	0,045	-0,029	-0,067	-0,071
Total chlorine	-0,186	-0,201	0,039	0,377	0,319	-0,193	0,120
Free chlorine	-0,098	0,002	0,084	-0,014	0,902	-0,009	-0,043
Velocity	0,183	-0,032	0,155	-0,047	0,054	0,064	-0,856
Transparency	0,097	0,165	-0,144	0,279	0,139	0,311	0,429
Width	0,060	0,821	-0,090	-0,053	-0,064	0,108	0,150
Depth	-0,044	0,715	-0,103	-0,101	-0,142	0,049	-0,130
Variability (%)	19,98	14,58	11,69	8,63	6,31	5,94	7,00

DISCUSSION

The water samples collected during the measurement campaigns were of an instantaneous type; thus, they only reflect water quality at a given moment and demonstrate the local influence of pollution sources (domestic and agricultural activities). The average temperatures recorded in this study ranged from 24.90°C to 30.29°C, indicating that the water in the portion of the Hana River located within the park is favorable for aquatic life. In contrast, the high temperature observed at station Ha1 can be attributed to the absence of vegetation cover and a sparse canopy, unlike station Ha2, located in a primary forest with canopy cover ranging from approximately 60% to 75%. According to Welcomme (1985), factors that determine water temperature variation in aquatic ecosystems include latitude, solar radiation, substrate composition, precipitation, wind, and vegetation cover. Temporal variations in temperature at all stations indicate that water temperature closely follows air temperature. The lowest values recorded during the dry season are explained by the Harmattan period, a dry north-to-south wind characterized by very low humidity.

The mean pH values ranged from 6.55 to 7.62, with an average of 7.14, showing no significant variation. They remained slightly basic to neutral, reflecting the alkalinity of the different stations (upstream to downstream). The pH values recorded are higher than those reported by Konan (2014) in the Tanoé-Ehy swamp forest (5.1–6.7) and Camara (2013) in Banco National Park (4.46–7.07), where waters are more acidic. Several processes can influence water pH, the most important being photosynthesis and respiration balances, the presence of weak organic acids in water, and runoff from the watershed (Groleau *et al.*, 2008; Bertrin *et al.*, 2009; CRE, 2009a), as is likely the case in the PNT. According to CRE (2009b), pH variations suitable for the development and protection of aquatic life should range between 6 and 9. Outside this range, organisms may experience stress that compromises vital functions. Therefore, the PNT waters appear favorable for aquatic life throughout the year.

Water conductivity is a measure of its ability to conduct electrical current. It provides a rapid, albeit approximate, assessment of water mineralization and its temporal evolution. Recorded values were below 100 µS/cm, indicating very low mineralization in the rivers of the PNT.

Across all Hana River stations, conductivity ranged from 39.59 to 73.42 µS/cm during the measurement periods. This low mineralization is likely linked to the river's location within the PNT forest. Moss (2007) reports that low mineralization in forest rivers is partly due to the rapid cycling of biogenic elements within the forest ecosystem.

Dissolved oxygen (DO) concentrations provide information about metabolic activity in the environment. DO was lowest at station Ha1, not exceeding 5 mg/L, yet still above the 3 mg/L threshold considered unfavorable for aquatic life, indicating good aeration in PNT waters.

The highest oxygen concentration (7.24 mg/L) was recorded at Ha3 during the rainy season.

Redox potential is a measure that quantifies the presence of oxidizing agents in a fluid under certain conditions. Positive values indicate low electron activity and a capacity to accept electrons (oxidizing power), whereas negative values suggest a high capacity to accept electrons (Youssef *et al.*, 2015). During this study, almost all redox values in the Hana River were positive, with seasonal averages ranging from 41.59 to 123.50 mV. These results indicate that PNT waters are oxidizing and can be characterized as oligotrophic.

Nitrates (NO_3^-) are naturally occurring ions found throughout the environment. They result from the microbial oxidation of nitrogen in plants, soil, or water, and to a lesser extent from electrical discharges such as lightning (Beatson, 1978). Nitrate sources in water include decomposing plant and animal matter, agricultural fertilizers, manure, domestic wastewater, and geological formations containing soluble nitrogen compounds (Adam, 1980; Egboka, 1984). In this study, nitrate concentrations ranged from 1.65 to 5.03 mg/L, corresponding proportionally to nitrite levels (0.006–0.017 mg/L), which can be explained by nitrite denitrification processes carried out by autotrophic bacteria (Nitrosomonas and Nitrobacter), converting ammonium to nitrite and nitrite to nitrate, thus consuming dissolved oxygen from upstream to downstream (Pauwels, 1996). Considering reference surface water quality levels defined by Nisbet and Vernaux (1970), the recorded nitrate concentrations indicate a risk of eutrophication (nitrates ≥ 0.3 mg/L) across all stations.

PCA analyses revealed five probable sources of pollution in the Hana River based on parameter distribution along the different axes after varimax rotation. These statistical analyses align with the observations described above. Mineral nitrogen pollution likely originates from upstream agricultural activities in the watershed where the Hana River enters the PNT (Soro *et al.*, 2021; Afrifaun *et al.*, 2022). Organic pollution appears to result from litterfall and decomposition (dead leaves, wood, and other plant matter) within the primary forest represented by the PNT (Costa *et al.*, 2017). Alteration of minerals in the upper course of the Hana River may explain the physico-chemical pollution indicated by Axis D4 (Su *et al.*, 2011). Additionally, this physico-chemical pollution may derive from natural changes in aquatic environmental conditions and ionic properties of the water mass (Xiaoxue *et al.*, 2020). Agricultural activities in the Hana River watershed may also contribute to diffuse pollution detected along Axis D5. During the rainy season, increased precipitation and runoff from tributaries bring suspended solids (SS) into the river. Consequently, variations in hydro-morphological parameters may pose a threat to the aquatic ecosystem's balance. Climatic conditions, therefore, could become a factor affecting water quality in the Hana River.

CONCLUSION

The investigations carried out on the physico-chemical properties of the Hana River allowed the assessment of seasonal variations across the different stations surveyed. From a physical and chemical perspective, monitoring of this fluvial system highlighted low concentrations of nutrients. It was found that the Hana River receives nutrient inputs primarily of exogenous origin, linked to rainfall-induced leaching from the watershed, with peaks occurring during the rainy season. Overall, the river waters were well-aerated during both main seasons, with the highest concentrations observed in the rainy season. Consequently, special attention should be given to stations near river mouths and areas under strong anthropogenic influence, where pollution indices are the highest.

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