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SEASONAL VARIATION IN THE PHYSICO-CHEMICAL PARAMETERS OF THE WATERS OF THE GNINTCHI RIVER (CÔTE D'IVOIRE): CONTRIBUTIONS OF A PRINCIPAL COMPONENT ANALYSIS

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ABSTRACT

This study examines the seasonal variation in fourteen physico-chemical parameters (pH, temperature, electrical conductivity, dissolved oxygen, total dissolved solids, turbidity, alkalinity, ammonium, nitrates, nitrites, phosphates, total phosphorus, silica and residual chlorine) in the waters of the Gnintchi River (Côte d'Ivoire), based on twelve monthly sampling campaigns conducted from August 2021 to July 2022. The results revealed acidic waters (mean pH: 5.58 ± 0.51), low mineralization (mean conductivity: 40.90 µS/cm; TDS: 20.54 mg/L) and good oxygenation (mean: 6.19 mg/L). Seasonal analysis (t-test) showed that conductivity (50.10 versus 31.69 µS/cm; p = 0.0056), TDS (25.18 versus 15.90 mg/L; p = 0.0045) and nitrites (21.33 versus 3.67 µg/L; p = 0.0111) were significantly higher during the rainy season, whereas dissolved oxygen tended to decrease (p = 0.0515). Principal component analysis (PCA), performed on centered and standardized data, highlighted two complementary environmental gradients: a mineralization and particulate-load gradient (PC1, 28.09% of the variance) and an oxygenation gradient (PC2, 20.18%). Together, these two axes explained 48.27% of the total variance. These findings provide baseline information on the seasonal dynamics of water quality in the Gnintchi River and highlight the importance of rainfall-driven runoff in shaping its physico-chemical characteristics.

Keywords: Physico-Chemical Parameters, Seasonal Variation, Gnintchi River, Water Quality, Principal Component Analysis, Côte d'Ivoire.

1 INTRODUCTION

Surface water quality is a major public health and sustainable development issue in West Africa, where rivers meet most of the domestic, agricultural and industrial needs of riparian populations [1]. In Côte d'Ivoire, the physico-chemical parameters of rivers (temperature, pH, electrical conductivity, dissolved oxygen, turbidity and nutrients) are largely governed by hydroclimatic conditions, which alternate between dry and rainy seasons, as well as by increasing anthropogenic pressures on watersheds, including extensive agriculture, illegal gold mining, and domestic and industrial discharges [2, 3]. Numerous studies conducted in recent years on Ivorian aquatic systems have shown that these parameters undergo substantial seasonal fluctuations. In the Upper Bandama Basin, Soro et al. [4] observed that seasonal variations in physico-chemical parameters were more pronounced than spatial variations, with dissolved oxygen, temperature and nutrient ions (nitrate, nitrite, phosphate and ammonium) being higher during the rainy season, whereas conductivity and pH were higher during the dry season. A similar trend was reported for the Lobo River at Daloa, where conductivity and ammonium increase during the dry season, while dissolved oxygen and nitrites are higher during the rainy season [5]. Monitoring of the Sassandra River revealed a direct influence of the hydrological regime on the dynamics of major elements and turbidity [3]. In south-eastern Côte d'Ivoire, the coastal rivers Mé and Agnéby also exhibit marked seasonality in turbidity and suspended solids, exacerbated by illegal gold mining [2, 6]. More recently, a study of the Bia River reported higher concentrations of major ions (HCO_3^-, NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+} and Na^+) during high-water periods, whereas electrical conductivity reached its maximum during low-water periods [7]. These dynamics reflect mineralization of both natural and anthropogenic origin, which has also been documented in the N'Zi River [8] and in heavily altered peri-urban rivers such as the Djibi, where discharges threaten adjacent lagoon resources [1, 9].

However, to the best of our knowledge, no study published to date has specifically focused on the Gnintchi River. Available studies on small rivers in central and southern Côte d'Ivoire concern other aquatic systems (Bia, N'Zi, Sassandra, Lobo, Mé, Agnéby and Djibi) and indicate that baseline data for small watersheds remain fragmentary [10]. Furthermore, most of these studies rely on univariate descriptions; multivariate analytical methods, such as principal component analysis (PCA), are still not routinely used, although they make it possible to synthesize information from numerous parameters and identify the main gradients structuring water quality. In this context, the present study aims to assess the seasonal variation in fourteen physico-chemical parameters in the Gnintchi River in order to (i) characterize water quality during the dry and rainy seasons, (ii) identify, using correlation analysis, the relationships among the measured parameters, and (iii) determine the main environmental gradients structuring water quality through PCA.

2 MATERIALS AND METHODS

2.1 Study area

The Gnintchi River (Figure 1) is a watercourse in Côte d'Ivoire that drains a watershed subject to a humid tropical, sub-equatorial climate characterized by four alternating seasons: two rainy seasons (the long rainy season from May to July and the short rainy season from September to November) and two dry seasons (December to April and August). [To be completed by the authors: precise location (geographical coordinates), administrative subdivision, watershed area, geological substrate, land use, and main uses of the water by riparian communities.]

2.2 Sampling and analyzed parameters

2.2.1 Twelve sampling campaigns were conducted, at a rate of one per month, using a

portable HANNA multiparameter meter, model HI9829010 GPS, a HANNA HI 98703 turbidimeter and a HANNA HI 83300-01 photometer, from August 2021 to July 2022, thus covering a complete hydrological year. Fourteen parameters were measured in situ or in the laboratory: hydrogen potential (pH), temperature (T, in °C), electrical conductivity (Cond, in µS/cm), dissolved oxygen (DO, in mg/L), total dissolved solids (TDS, in mg/L), turbidity (NTU), alkalinity (mg/L), ammonium (NH_4^+, in mg/L), nitrates (NO_3^-, in mg/L), nitrites (NO_2^-, in µg/L), phosphates (PO_4^{3-}, in mg/L), total phosphorus (P, in mg/L), silica (SiO_2, in mg/L) and total residual chlorine (mg/L). [To be completed: instrument types and specifications, measurement stations, sampling procedure, and standardized methods used (AFNOR, HACH, etc.).]

2.3 Descriptive statistics and seasonal analysis

For each parameter, the mean, standard deviation and extreme values were calculated. Months were grouped into two categories—rainy period (September to November and May to July) and dry period (August and December to April)—and an independent-samples Student's t-test ($\alpha = 0.05$) was applied to compare seasonal means for each parameter. Relationships among parameters were explored using a Pearson correlation coefficient matrix.

2.4 Principal component analysis (PCA)

PCA was performed on the individuals × variables data matrix (12 months × 14 parameters), after centering and scaling the data (Z-score transformation), which was necessary because the variables had very different units and orders of magnitude. Principal components were retained according to the Kaiser criterion (eigenvalues ≥ 1) and inspection of the scree plot (elbow criterion). The axes were interpreted based on variable–axis correlations (loadings) and squared cosines (cos^2) of the variables, while the position of the individuals (months) was examined on the PC1–PC2 factorial plane. All calculations were performed using the scikit-learn library (Python 3.12).

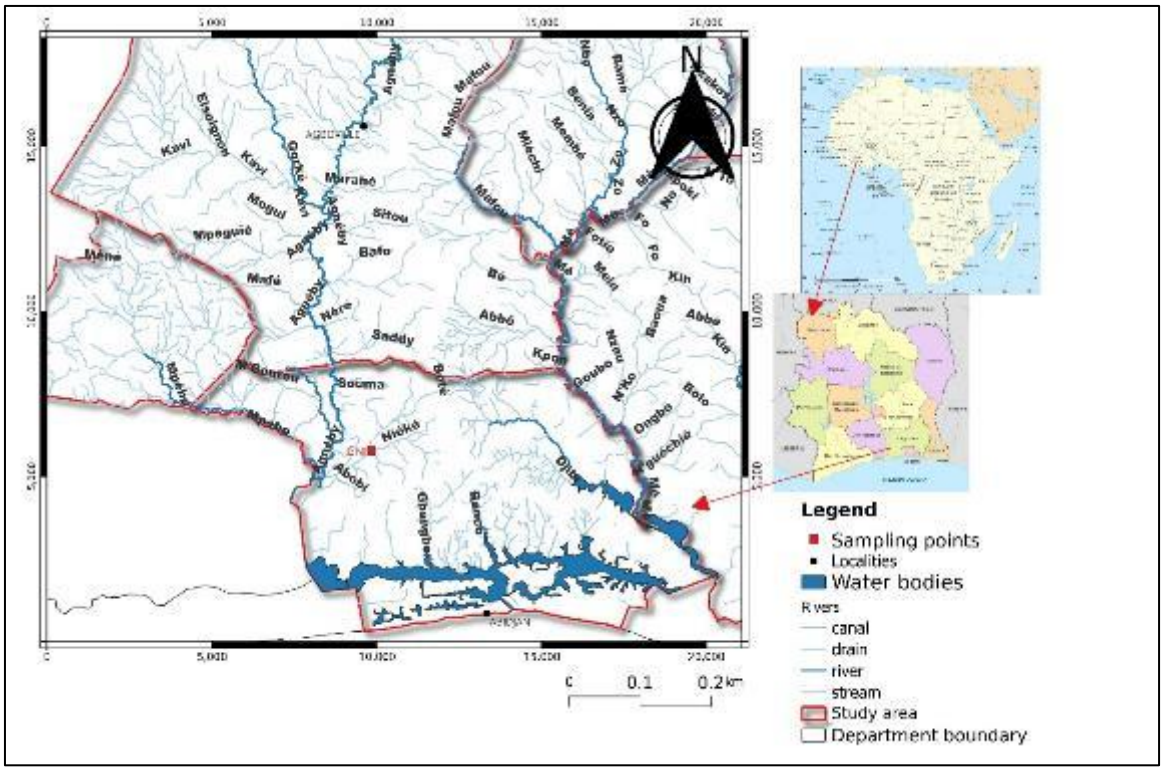


Figure 1: Location of the Gnintchi River (Côte d'Ivoire). [5°28'24,1''N and 4°12'14,6''O]

3 RESULTS

3.1 Descriptive statistics

Table 1 presents all monthly values measured in the Gnintchi River, while Table 2 summarizes the descriptive statistics. The waters of the Gnintchi River are acidic (mean pH: 5.58 ± 0.51), weakly mineralized (Cond.: 40.90 ± 12.94 µS/cm; TDS: 20.54 ± 6.41 mg/L) and adequately oxygenated (DO: 6.19 ± 1.15 mg/L). Temperature is nearly constant (24.21 ± 0.64 °C). Among the nutrients, nitrates are predominant (6.93 ± 5.51 mg/L), nitrites remain at moderate levels (12.50 ± 13.17 µg/L), and total phosphorus is highly variable (1.15 ± 1.84 mg/L; range: 0.13–6.50 mg/L).

Table 1: Monthly values of the 14 physico-chemical parameters of the Gnintchi River (August–July).

Month	pH	T	Cond	OD	TDS	TURB	ALC	NH4	NO3	NO2	PO4	P	SiO	ClRe
August	6.23	23.46	30.67	7.60	15.22	15.90	120.00	0.17	4.40	8.00	0.40	0.93	3.00	0.40
September	6.14	23.31	58.86	5.84	29.28	16.20	100.00	0.16	5.70	40.00	0.23	0.30	6.00	0.31
October	4.88	23.83	69.00	6.22	34.50	26.30	40.00	0.13	5.60	23.00	0.02	0.15	6.00	0.27
November	5.44	24.17	48.00	5.37	24.11	17.90	165.00	0.02	17.00	17.00	0.11	0.13	6.00	0.25
December	4.54	23.86	37.17	8.15	18.67	16.40	20.00	0.21	3.70	4.00	0.10	0.17	9.00	0.49

January	5.59	23.91	33.28	5.96	16.71	18.60	55.00	0.10	11.70	4.00	0.13	0.48	9.00	0.18
February	5.55	24.76	31.25	6.31	15.62	16.50	55.00	0.09	3.30	2.00	0.20	0.85	9.00	0.33
March	5.53	23.79	30.00	6.74	15.20	26.20	45.00	0.26	3.90	2.00	0.21	0.30	5.00	0.38
April	5.93	25.46	27.75	6.16	14.00	15.70	45.00	0.24	16.70	2.00	0.35	0.60	4.00	0.40
May	6.01	24.75	44.33	3.66	22.50	29.60	45.00	1.23	1.20	8.00	0.13	0.50	3.00	0.27
June	5.29	24.90	47.43	5.39	23.71	25.60	65.00	0.21	1.00	34.00	0.03	2.90	2.00	0.32
July	5.88	24.30	33.00	6.88	17.00	17.40	85.00	0.29	9.00	6.00	0.88	6.50	4.00	0.29

Table 2: Descriptive statistics of the physico-chemical parameters (n = 12).

Parameter	Mean	Standard deviation	Minimum	Maximum
pH	5.58	0.51	4.54	6.23
Température (°C)	24.21	0.64	23.31	25.46
Cond. (µS/cm)	40.90	12.94	27.75	69.00
O.D. (mg/L)	6.19	1.15	3.66	8.15
TDS (mg/L)	20.54	6.41	14.00	34.50
Turbidité (NTU)	20.19	5.13	15.70	29.60
Alcalinité (mg/L)	70.00	40.90	20.00	165.00
NH4+ (mg/L)	0.26	0.32	0.02	1.23
NO3- (mg/L)	6.93	5.51	1.00	17.00
NO2- (µg/L)	12.50	13.17	2.00	40.00
$PO4^{3}$- (mg/L)	0.23	0.23	0.02	0.88
P total (mg/L)	1.15	1.84	0.13	6.50
SiO2 (mg/L)	5.50	2.47	2.00	9.00
Chlore résiduel (mg/L)	0.32	0.08	0.18	0.49

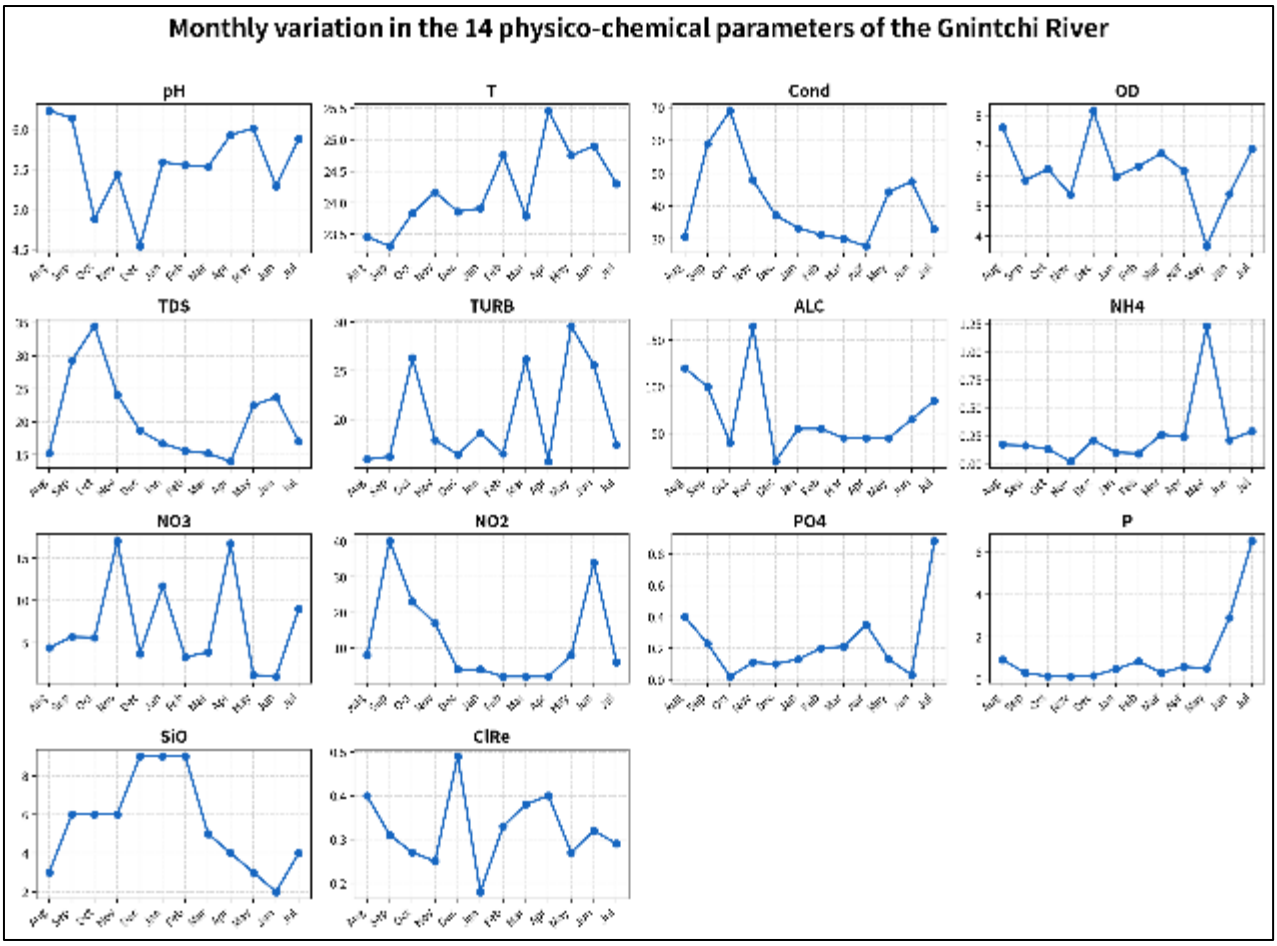


Figure 2: Monthly variation in the 14 physico-chemical parameters of the Gnintchi River (August–July).

3.2 Seasonal patterns in the parameters

Comparison of seasonal means (Table 3) revealed three parameters that were significantly higher during the rainy season: conductivity (50.10 versus 31.69 µS/cm; t = 3.52; p = 0.0056), TDS (25.18 versus 15.90 mg/L; t = 3.65; p = 0.0045) and nitrites (21.33 versus 3.67 µg/L; t = 3.11; p = 0.0111). Dissolved oxygen was close to the significance threshold and decreased during the rainy season (5.56 versus 6.82 mg/L; t = −2.21; p = 0.0515). The other parameters (pH, temperature, turbidity, alkalinity, NH_4^+, NO_3^-, PO_4^{3-}, P, SiO_2 and residual chlorine) showed no significant seasonal differences, although mean turbidity tended to increase during the rainy season (22.17 versus 18.22 NTU).

Table 3: Seasonal comparison of the parameters (Student's t-test; rainy period: September–November and May–July; dry period: August and December–April).

Parameter	Rainy-season mean	Dry-season mean	t	p	Significance
pH	5.61	5.56	0.15	0.8859	ns
Température (°C)	24.21	24.21	0.01	0.9933	ns
Cond. (µS/cm)	50.10	31.69	3.52	0.0056	**
O.D. (mg/L)	5.56	6.82	-2.21	0.0515	ns
TDS (mg/L)	25.18	15.90	3.65	0.0045	**
Turbidité (NTU)	22.17	18.22	1.39	0.1949	ns
Alcalinité (mg/L)	83.33	56.67	1.15	0.2788	ns
NH4+ (mg/L)	0.34	0.18	0.88	0.4003	ns
NO3- (mg/L)	6.58	7.28	-0.21	0.8378	ns
NO2- (µg/L)	21.33	3.67	3.11	0.0111	*

$PO4^{3}$- (mg/L)	0.23	0.23	0.01	0.9908	ns
P total (mg/L)	1.75	0.56	1.13	0.2836	ns
SiO2 (mg/L)	4.50	6.50	-1.48	0.1704	ns
Chlore résiduel (mg/L)	0.29	0.36	-1.79	0.1033	ns

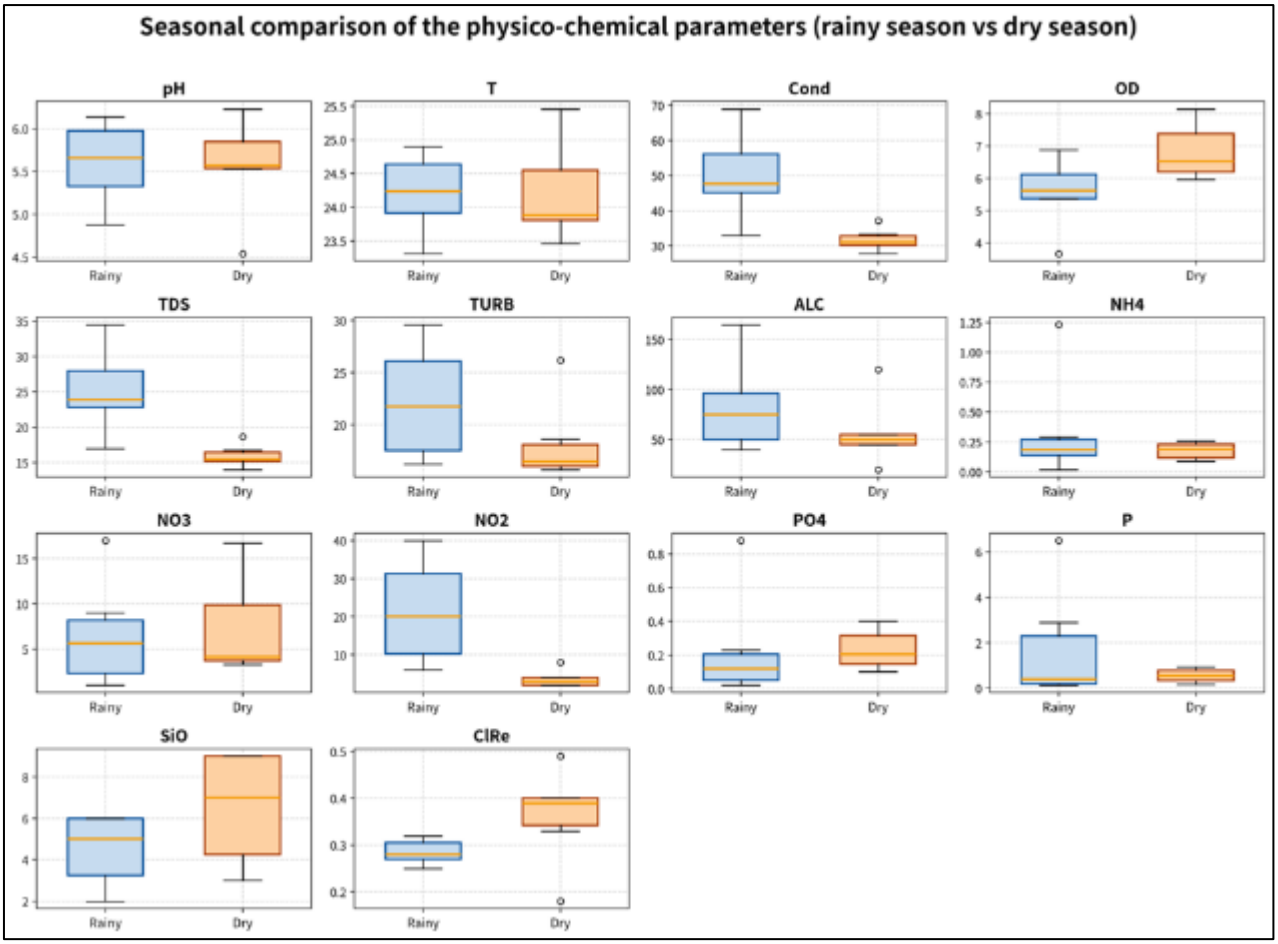


Figure 3: Seasonal comparison of the 14 physico-chemical parameters of the Gnintchi River (box plots: rainy season in blue, dry season in orange).

3.3 Correlations among parameters

The correlation matrix (Figure 4) reveals several strong associations. Conductivity and TDS are perfectly correlated (r = 1.00), and both are strongly correlated with nitrites (r = 0.80 and 0.79, respectively); these three parameters therefore reflect a similar dissolved load of external origin. Dissolved oxygen is positively correlated with residual chlorine (r = 0.64) and negatively correlated with ammonium (r = −0.60) and turbidity (r = −0.57), indicating that oxygenation decreases as particulate matter and ammoniacal organic matter increase. Phosphates and total phosphorus are strongly correlated (r = 0.77), suggesting a common source of phosphorus. Finally, pH is positively correlated with phosphates (r = 0.51) and negatively correlated with silica (r = −0.47).

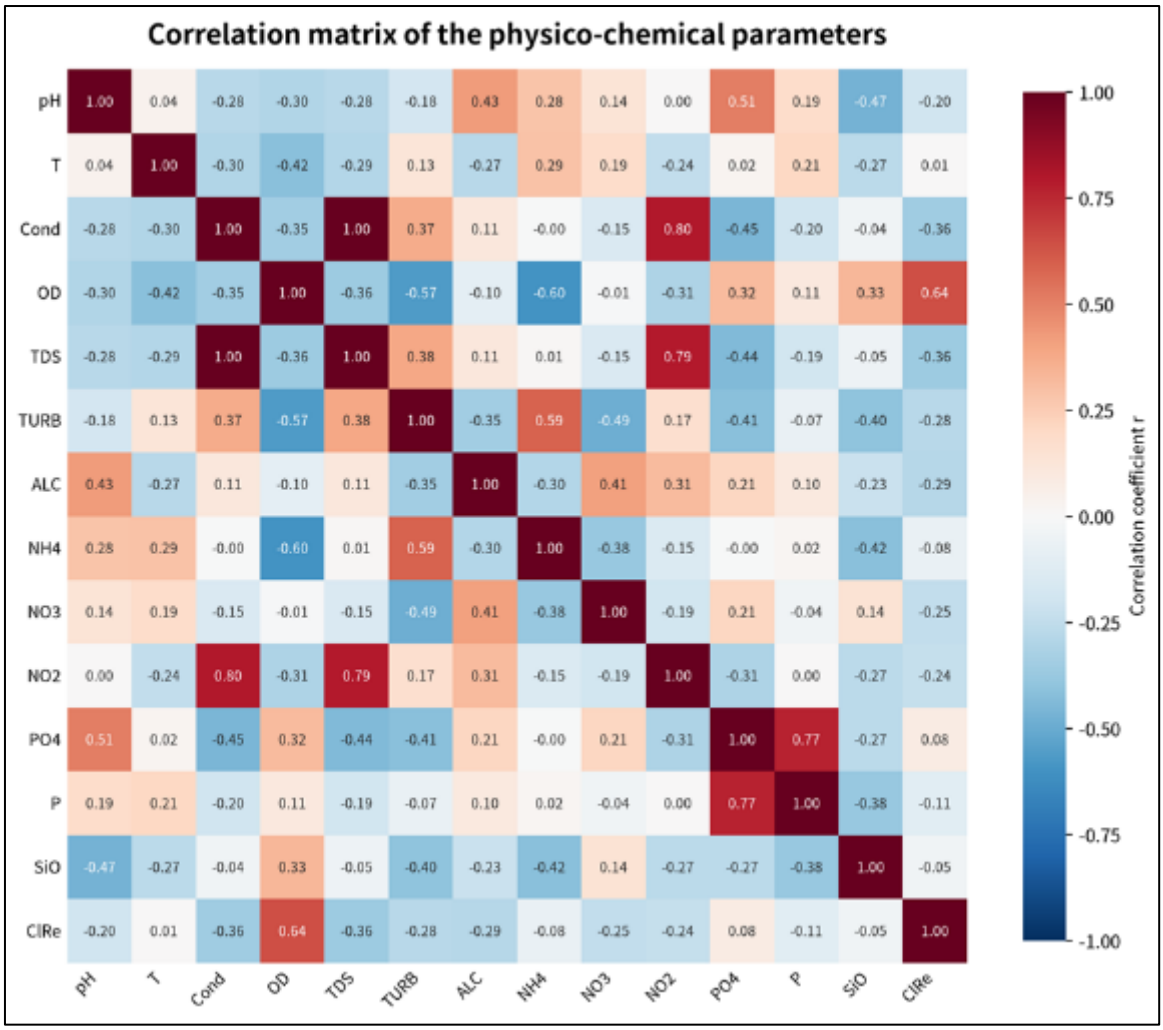


Figure 4: Pearson correlation matrix of the 14 physico-chemical parameters of the Gnintchi River (red: positive correlation; blue: negative correlation).

3.4 Principal component analysis

3.4.1 Variance structure

Five principal components have eigenvalues greater than 1 (Kaiser criterion) and account for 84.61% of the variance. However, inspection of the scree plot (Figure 5A) reveals a clear elbow after the second axis. The first two components (PC1 = 4.29; PC2 = 3.08), which explain 28.09% and 20.18% of the variance, respectively (48.27% cumulatively), were retained for interpretation, supplemented by PC3 (2.67; 17.47%), which is mainly associated with alkalinity (r = 0.89).

3.4.2 Interpretation of the axes

PC1 (28.09%) represents a mineralization and particulate-load gradient. It is strongly and positively correlated with TDS (r = 0.93), conductivity (r = 0.93), nitrites (r = 0.75) and turbidity (r = 0.70), and negatively correlated with phosphates (r = −0.68) and dissolved oxygen (r = −0.66). The squared cosine values confirm that these variables are well represented ($\cos^2$ Cond = 0.86; $\cos^2$ TDS = 0.86; $\cos^2$ NO_2 = 0.57). This axis therefore expresses a gradient of inputs from the watershed: the higher its value, the more the water is loaded with dissolved salts and particles, and the lower its oxygen content.

PC2 (20.18%) contrasts dissolved oxygen (r = 0.63) and silica (r = 0.77) with the pH (r = −0.68)–ammonium (r = −0.73) pair. It represents an oxygenation and organic-enrichment gradient: positive values correspond to well-oxygenated waters with low ammonium concentrations, whereas negative values indicate months with high oxygen demand (decomposition of ammoniacal organic matter) and more acidic pH.

3.4.3 Position of the individuals (months)

On the factorial map (Figure 6), rainy-season months—October (PC1 = 3.47), May (2.43), June (2.12) and September (1.97)—are grouped on the positive side of PC1, confirming that mineralization and particulate loading peak during the

rainy period. Dry-season months are positioned in the opposite direction: April (−2.36), July (−2.52) and August (−1.98). On PC2, December (3.09), the month with the highest dissolved oxygen concentration (8.15 mg/L), is opposed to May (−3.51), which combines the lowest dissolved oxygen concentration (3.66 mg/L) with the highest ammonium concentration (1.23 mg/L)—a pattern typical of summer organic stress. The hydrological year is thus structured by two complementary gradients: an input gradient (PC1) and an oxygenation gradient (PC2).

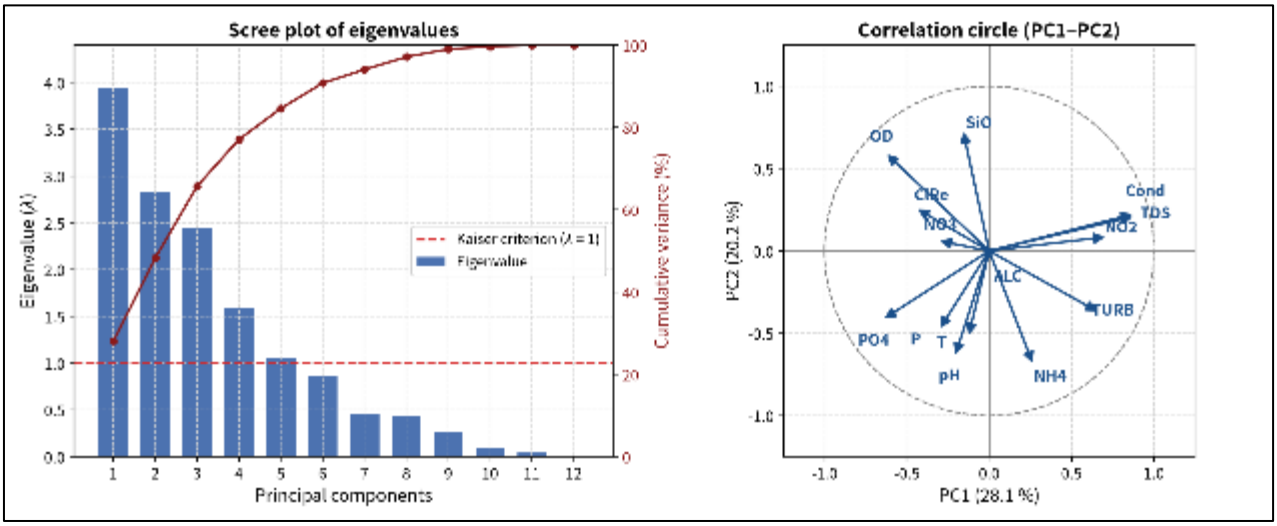


Figure 5: PCA of the physico-chemical parameters of the Gnintchi River: (A) scree plot of eigenvalues and cumulative variance (red line: Kaiser criterion, λ = 1); (B) correlation circle of the variables on the PC1–PC2 plane.

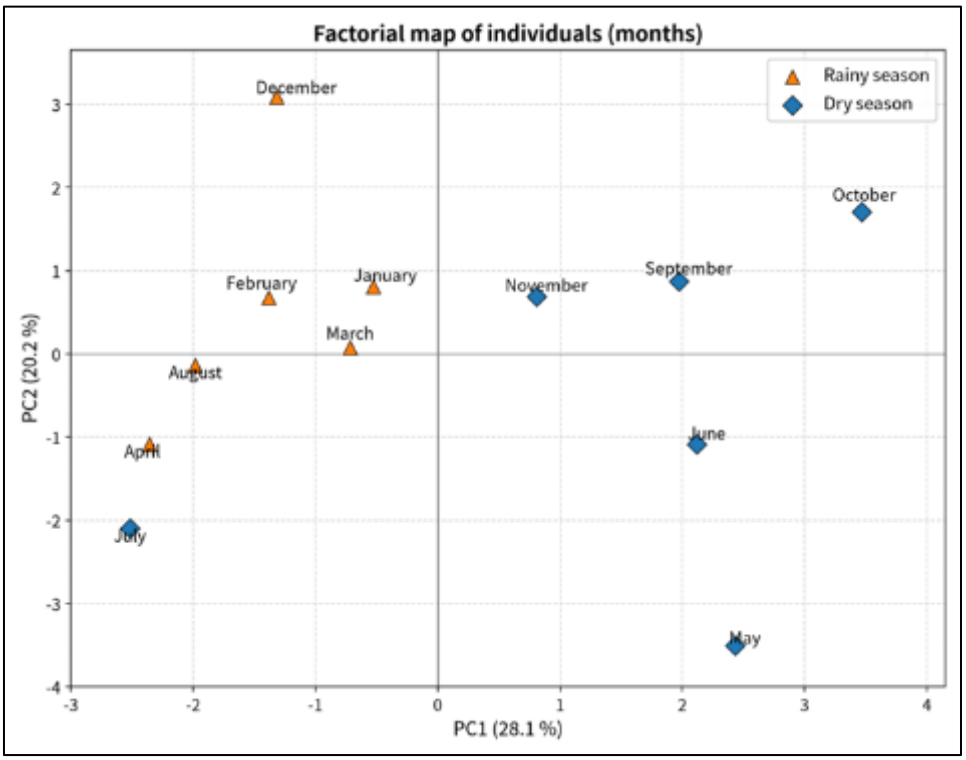


Figure 6: Factorial map of individuals (months) on the PC1–PC2 plane (blue diamonds: rainy season; orange triangles: dry season).

4 DISCUSSION

The combined analysis of seasonal statistics, correlations and PCA reveals three major dynamics in the Gnintchi River. First, water mineralization (conductivity, TDS) and dissolved and particulate loads (nitrites, turbidity) increase

concomitantly and significantly during the rainy seasons. This pattern results from intensified runoff across the watershed, which leaches soils and transports dissolved salts and fine particles into the river. This is precisely what is summarized by PC1 of the PCA, which separates rainy months (October, May, June and September) from dry months. This pattern is consistent with the observations of Soro et al. [4] in the Upper Bandama, where nutrient ions increase during the rainy season, and with those of Aka et al. [2], who reported strong rainfall-driven seasonality in suspended solids and turbidity in the Mé and Agnéby coastal rivers. The increase in major ions during high-water periods is also consistent with the findings of Kra et al. [7] for the Bia River. Second, PCA highlights an oxygenation gradient (PC2) that was not clearly apparent in the univariate analyses: months with the highest dissolved oxygen concentration (December, 8.15 mg/L) contrast with those in which it drops sharply (May, 3.66 mg/L), while ammonium reaches its peak (1.23 mg/L). This pattern suggests oxygen consumption through the decomposition of organic matter transported by runoff, potentially exacerbated by anthropogenic inputs. A comparable mechanism has been proposed for the Djibi, a peri-urban river in the Abidjan District where organic loads impair water oxygenation [9], and for nutrient and faecal-bacteria inputs documented in Ivorian estuarine areas [1]. Third, the persistent acidity of the water (mean pH: 5.58; 100% of values below the lower limit of the WHO range [11], 6.5–8.5) and its very low mineralization (mean conductivity: 40.90 µS/cm, far below the 500 µS/cm often cited as a guideline value) are characteristic of rivers in southern Côte d'Ivoire draining substrates poor in weatherable minerals, as described for the south-eastern coastal rivers [6] and the Bia River [7]. Temperature, which remained nearly constant (amplitude: 2.15 °C), had only a negligible influence on the observed variability, most of which was hydroclimatic in origin, as also concluded by Gboko et al. [3] for the Sassandra River. Finally, it should be emphasized that the high turbidity (mean: 20.19 NTU, with no value below the WHO threshold [11] of 5 NTU) and acidic pH make the Gnintchi River water unsuitable for direct consumption without treatment, while the oxygen minimum recorded in May could be a stress factor for aquatic fauna. The combination of univariate and multivariate analyses places the Gnintchi River within the same functional group as other small Ivorian coastal rivers investigated over the past decade [2, 6, 7, 8, 10].

5 CONCLUSION

Monthly monitoring of fourteen physico-chemical parameters in the Gnintchi River from August 2021 to July 2022 revealed acidic waters (mean pH: 5.58), low mineralization (mean conductivity: 40.90 µS/cm; TDS: 20.54 mg/L) and generally good oxygenation (6.19 mg/L), with stable temperature. Seasonality was the main source of variation: conductivity, TDS and nitrites were significantly higher during the rainy season ($p < 0.05$), whereas dissolved oxygen decreased. PCA summarized this pattern through two complementary gradients accounting for 48.27% of the variance: a mineralization and particulate-load gradient associated with runoff (PC1), and an oxygenation gradient contrasting well-oxygenated waters with months characterized by a high ammoniacal organic load (PC2). These results, which are consistent with trends reported for Ivorian rivers over the past decade, provide an initial reference dataset for this river. They also highlight the need for continued monitoring (heavy metals, microbiological indicators and flow rates) and for integrated watershed management to preserve this essential resource for riparian communities.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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