

Research Article

Physico-chemical Assessment and Environmental Quality of the Waters of Lake Buyo During the Low-water Period of the River Sassandra (South-west Côte d'Ivoire)

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Abstract

In Côte d'Ivoire, almost a dozen hydroelectric dams have been built since 1965, with the opening of the Ayamé 1 dam. These dams, in addition to their primary vocation of generating electricity, also serve other functions such as recreation, tourism, flood control and supplying drinking water to local populations. Lake Buyo is a natural resource of considerable interest for the economic development of Côte d'Ivoire. The Buyo dam, built on the Sassandra River in 1980, is no exception. The aim of this study was to assess the water quality of Lake Buyo during low-water periods of the Sassandra River. To do this, water samples and measurements were taken in the lake in March 2021. In situ measurements showed that the waters were warm, with an average temperature of 32.4 °C. The waters were alkaline, with fairly low electrical conductivity. These waters were relatively well oxygenated at the surface and deoxygenated at depth during the dry season. On the other hand, the average concentration of suspended solids (SS) was 4.8 mg/L, and the transparency of 1.48 m showed that the lake's waters were not very loaded. Based on the nitrate (1.56 mg/L) and ammonium (0.13 mg/L) concentrations, the raw water analyzed complies with the WHO 2017 guidelines for drinking water production, with overall good quality in terms of nitrogen pollution.

Keywords

Physico-chemical, Assessment, Water Quality, Low-water, Lake Buyo, Dam

1. Introduction

Dams are an essential part of any national water resources management strategy, particularly in countries facing water supply uncertainties, such as those in West Africa.

In fact, hydroelectric dams are built to serve one or more functions, including electricity production, irrigation and water supply. Côte d'Ivoire has a vast hydrographic network with seven (7) major hydroelectric dams (Ayamé 1, Ayamé 2,

Kossou, Taabo, Buyo, Fayé and Soubré). However, the reservoirs of these dams, which provide water supply, are increasingly faced with pollution. Indeed, problems linked to water degradation and the proliferation of aquatic plants have been highlighted by several hydrological and physicochemical characterization studies [1-4]. Furthermore, the transport of sediments and the resulting input of nutrients accelerates the

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processes of silting, siltation and eutrophication of lakes [5].

Lake Buyo, the subject of our study, is not immune to the problem of pollution. Despite the dangers inherent in the degradation of the lake's water quality over time, very few hydrological studies have been carried out there. Indeed, the last hydrological studies carried out. Indeed, the last hydrological studies carried out on Lake Buyo date back more than twenty (20) years [2]. This does not allow good monitoring of water quality,

knowing that the lake is used to supply water to the region.

It is in this context that the present study has been undertaken. Its aim to determine the characteristics of the physico-chemical parameters of the downstream sector of Lake Buyo in order to assess the quality of the water in the environment during the low-water period of the Sassandra River, to which it is tributary.

2. Materials and Methodes

2.1. Presentation of Study Area

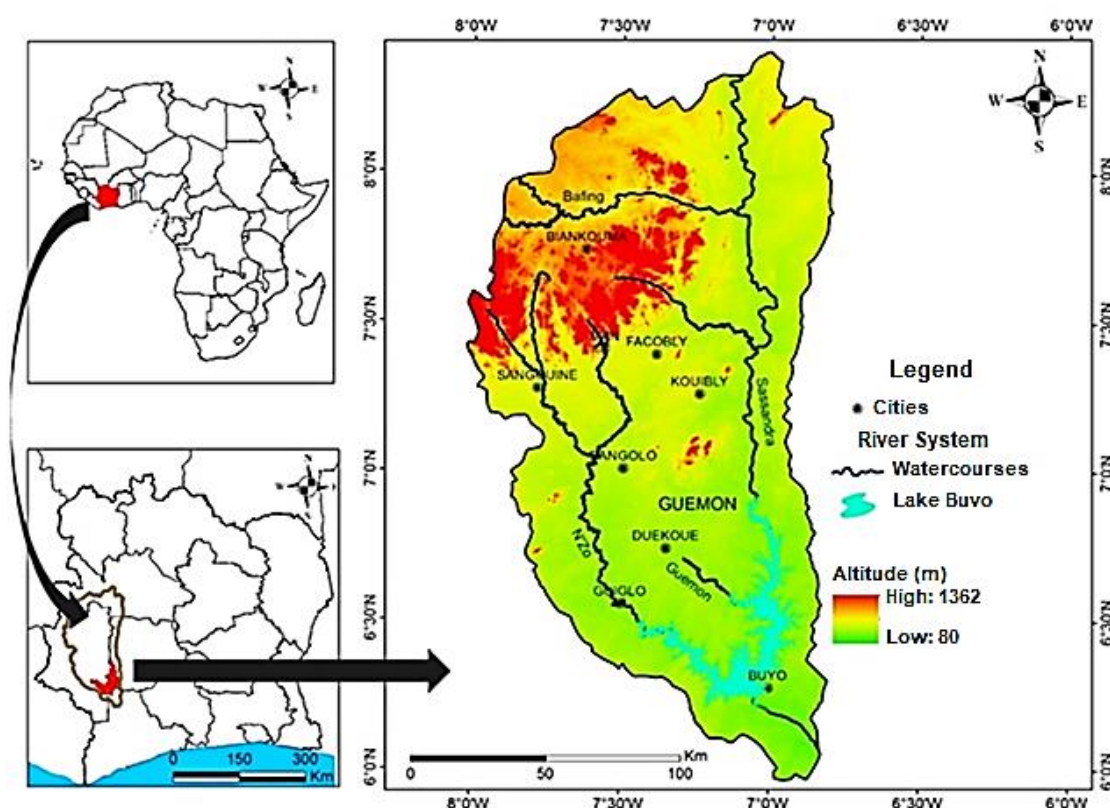


Figure 1. Geographical location of Lake Buyo.

Lake Buyo, the study area, is located in the southwest of Côte d'Ivoire in the town of Buyo. It belongs to the department of Soubré in the Nawa region, 513 km from Abidjan (economic capital). The lake is located between latitudes $6^{\circ}10'00''$ N and $6^{\circ}20'00''$ N and longitudes $7^{\circ}00'0''$ W and $7^{\circ}10'0''$ W with a surface area of 920 km² (Figure 1). The water reservoir, under investigation is the downstream sector of Lake Buyo. The Buyo zone, corresponding to the reservoir area created by the hydroelectric installations of the Compagnie Ivoirienne d'Electricité (CIE). The lake's water regime depends on rainfall. Low and high water levels depend essentially on

inflows from the Sassandra River and its tributary, the N'zo. Annual rainfall ranges from 1.250 to 1.643 mm.

2.2. Physical-chemical Analysis Equipment

Sampling of physico-chemical parameters was carried out at ten (10) stations during the dry season (March 2021), corresponding to the low-flow period of the Sassandra River. Sampling was carried out on the surface and then in the water column at each station (Figure 2).

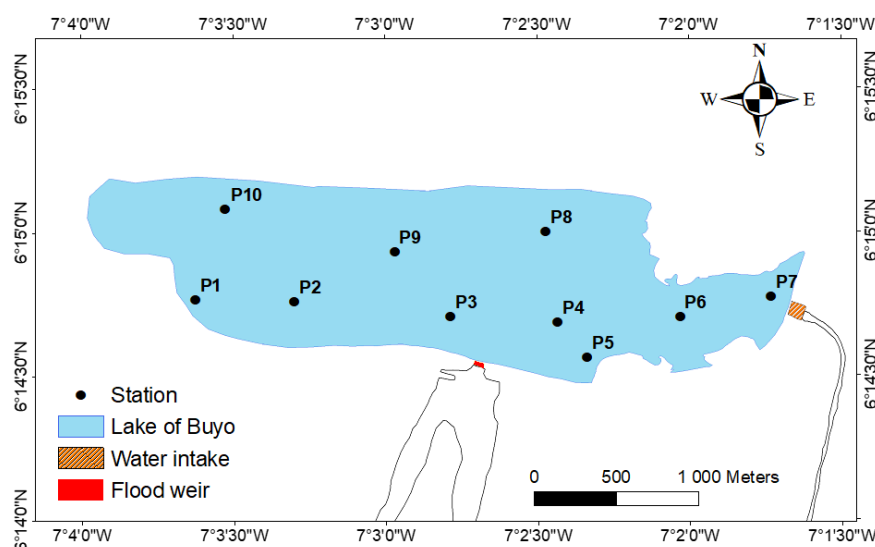


Figure 2. Distribution of sampling points.

The equipment used in the field consisted mainly of a METTLER TOLEDO type multiparameter, a pH meter, a GPS and a Secchi disk. Composed of a probe and a screen, the multiparameter was used for the in-situ measurement of physicochemical parameters (Temperature, Dissolved Oxygen, Conductivity). pH was determined using the pH meter. GPS was used to locate the sampling stations. As for the Secchi disk, was used to measure water transparency.

2.3. Acquisition of Physical-chemical Data

To measure these parameters (pH, Temperature, Dissolved Oxygen, Conductivity, Turbidity) in the field, the multiparameter was calibrated from the boat and then placed in the water at each sampling station. The values obtained were displayed on screen carefully recorded by the operator. To measure transparency, the Secchi disk was lowered into the water using a graduated rope until it disappeared. The height of water above which the disc is no longer visible to the operator is noted in meters (m). Suspended solids (SS) were determined by membrane filtration (Wattman GF/C microfiber). Nutrient salts were determined using a DR 6000 mass spectrometer, plus the HACH 8155 silicate method and the HACH 8171 cadmium reduction method respectively.

Creation of distribution maps

ArcGIS software was used to produce spatial distribution maps for the various physico-chemical parameters. The pro-

duction of the distribution maps is summarized in two (02) phases. In the first phase, an Excel spreadsheet was used to create a CVS file of numerical data for the various physico-chemical parameters for each station, together with data collected in the field. The Google Earth contour was added to this file. The second phase involved interpolating the spatial distribution maps for the various parameters. The interpolation method used is Inverse Distance Weighted (IDW).

Correlation of physico-chemical parameters by principal component analysis

The data collected during the sampling campaign were subjected to statistical analyses with Statistica 7.1 software for better interpretation of the results. Principal component analysis (PCA), which is an exploratory tool, consisted of looking for linear combinations of quantitative variables with a view to forming factorial axes in order to detect similar individuals, then to highlight a typology of individuals and finally to detect the relationships between the different variables.

Environmental quality assessment

The World Health Organization's drinking water quality guidelines recommend 50 mg/L for nitrates and 0.5 mg/L for ammonium [6]. Nitrate and ammonium levels in the downstream sector of Lake Buyo were compared with the [6] guide values to assess water quality. Ecological status, on the other hand, was assessed against the standards of the European Water Framework Directive [7] (Table 1).

Table 1. Classification according to the [7] of water bodies in [8].

(mg/l)	Very good	Good	Medium	Poor	Bad
Max. Mineral Nitrogen	< 0.2	0.2 à 0.4	0.4 à 1	1 à 2	> 2

3. Results

3.1. Spatio-temporel Variability and Depth Trends in Physico-chemical Parameters of the Waters of Lake Buyo

i. Lake temperature trends

During low water periods, water temperature ranged from

31.4 to 33.7 °C, with an average of $32.4\text{ °C} \pm 0.76$ (Figure 3). High values (32.6 - 33.7 °C) covered practically $\frac{3}{4}$ of the lake surface. The low values (31.4 - 32.5 °C) were located to the east of the reservoir on the water intake side. The thematic map showed a negative West-East horizontal gradient. However, the temperature variation in depth showed a negative surface-bottom gradient (Figure 4).

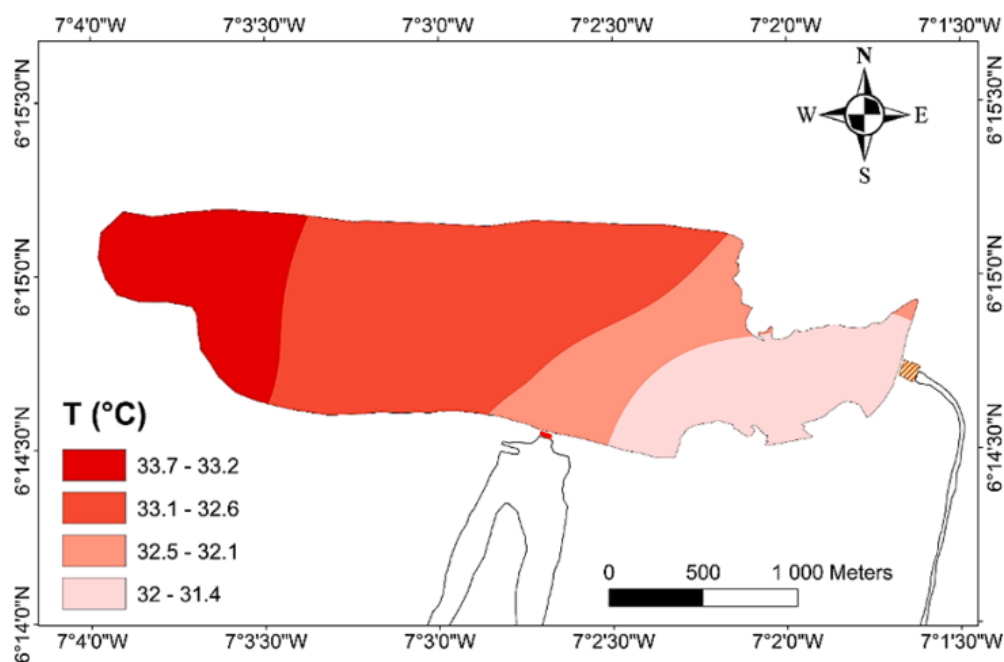


Figure 3. Spatial distribution of temperature in Lake Buyo during low water periods.

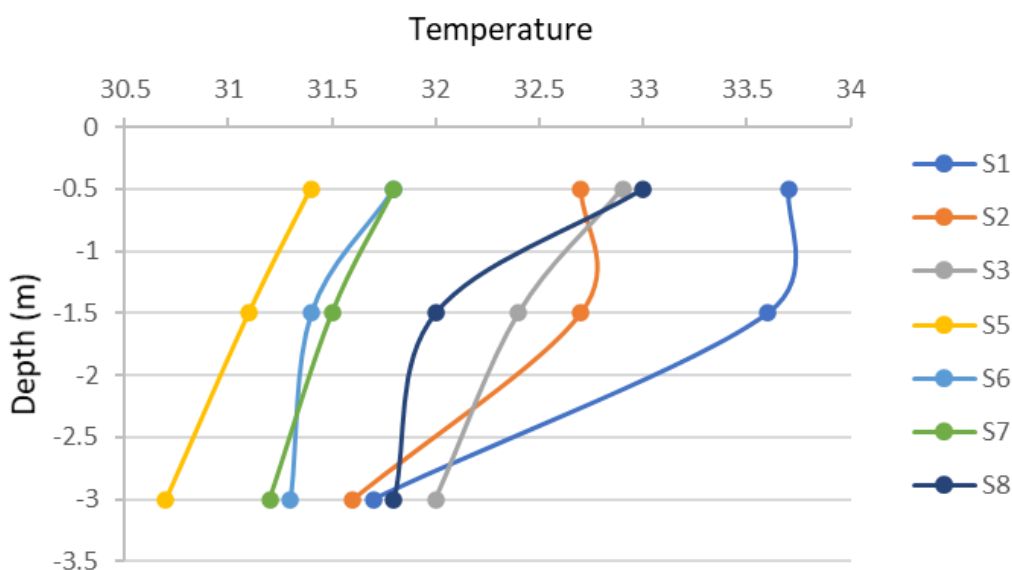


Figure 4. Temperature trends in the water column of Lake Buyo during low-water periods.

ii. Evolution of lake pH

The water of the downstream sector of Lake Buyo was alkaline, with basicity increasing from north to south. pH values ranged from 7.9 to 9.78, with an average of 8.61 ± 0.55 . The

highest pH values (9.1-9.78) were found in the area around the spillway (Figure 5). The pH values measured at the surface were more basic than those measured at the bottom (Figure 6).

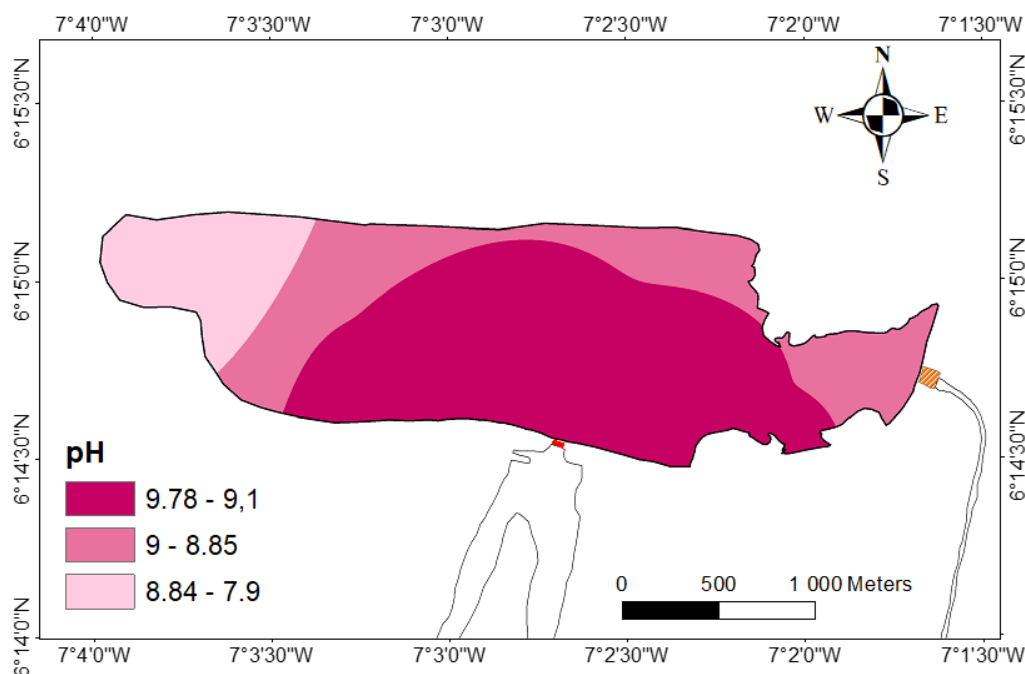


Figure 5. Spatial distribution of surface water pH during low-water periods.

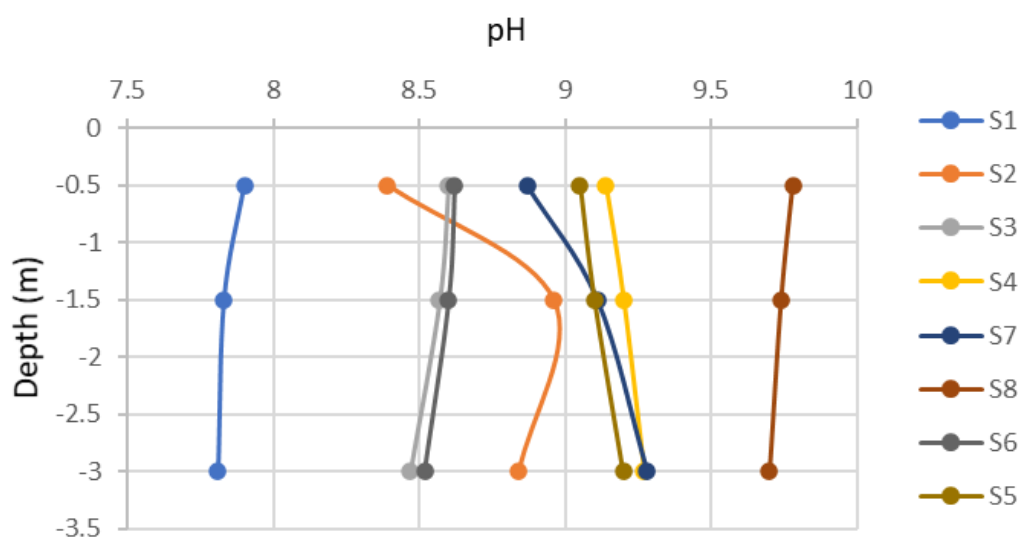


Figure 6. Evolution of pH in the water column of Lake Buyo during low-water periods.

iii. Distribution of lake water conductivity

During low-water periods, conductivity values ranged from $60 \mu\text{S}/\text{cm}$ to $80 \mu\text{S}/\text{cm}$, with an average of $67.5 \mu\text{S}/\text{cm} \pm 7.07$ (Figure 7). The highest conductivity values were recorded to

the west of the water body, and the lowest on the side of the flood spillway. Conductivity levels tended to increase with depth, averaging of $83.68 \mu\text{S}/\text{cm} \pm 10.75$ (Figure 8).

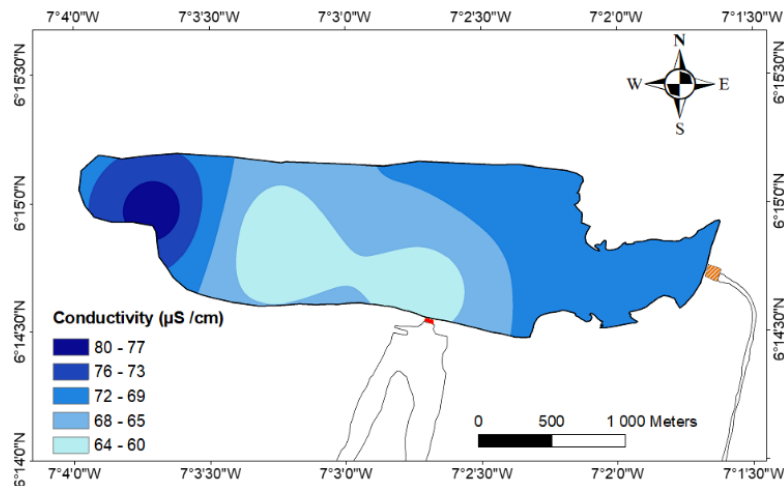


Figure 7. Spatial distribution of surface water conductivity during low-water periods.

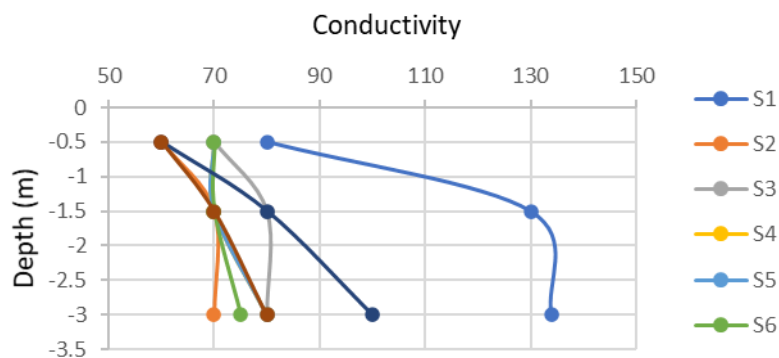


Figure 8. Evolution of conductivity in the water column of Lake Bujo during low-water periods.

iv. Distribution of dissolved oxygen content of lake waters

The spatial evolution of dissolved oxygen during low-water periods shows that the dissolved oxygen content varied between 5 and 7 mg/L, with an average of $5.5 \text{ mg/L} \pm 0.75$ (Figure 9). High levels (6 and 7 mg/L) were found to the southwest

of the lake and at the water intake. Low levels of dissolved O_2 (5-5.4 mg/L), which were more dominant, were located in the vertical axis of the spillway. Figure 10 showed an overall decrease in dissolved oxygen with depth during low-water periods, reaching its lowest value at station 3 (5 to 1 mg/L).

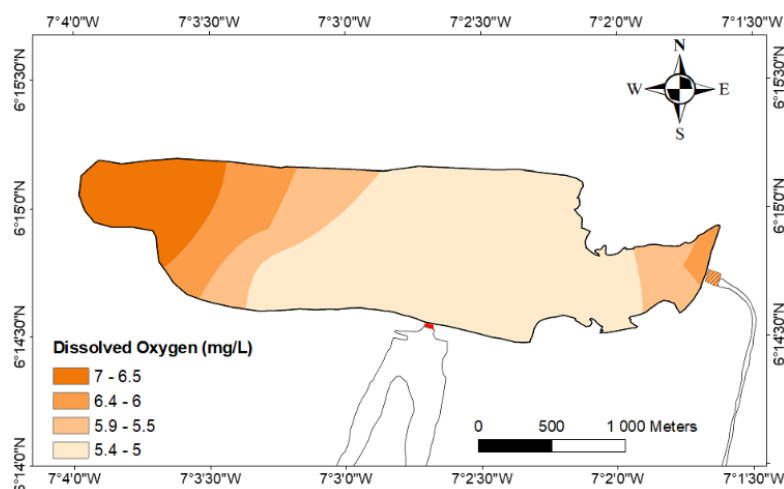


Figure 9. Spatial distribution of dissolved oxygen in surface water during low flow periods.

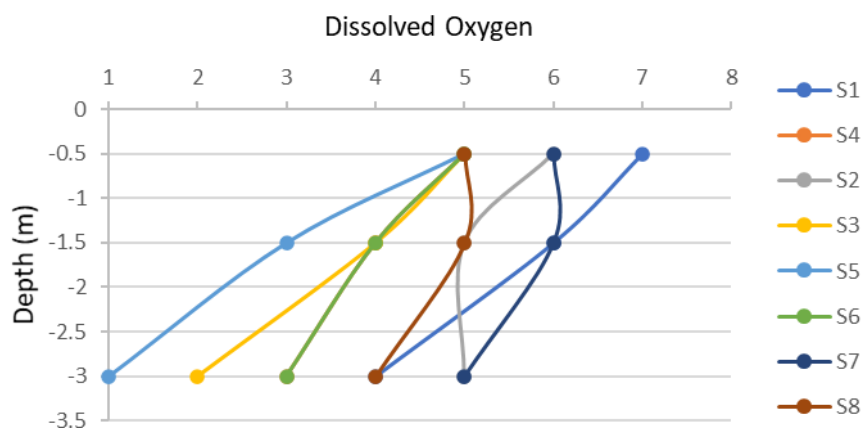


Figure 10. Variation in the dissolved oxygen content in the water column of Lake Buyo during low flow periods.

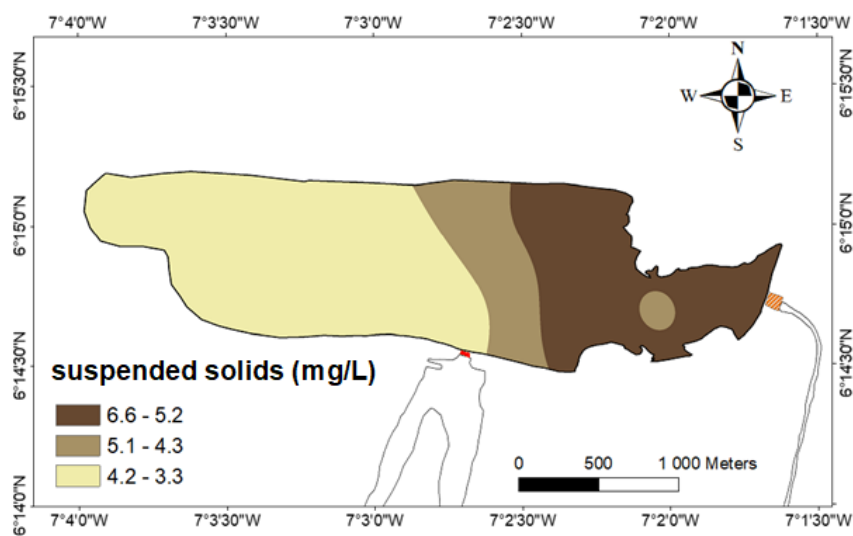


Figure 11. Spatial distribution of SS from surface waters during low-water periods.

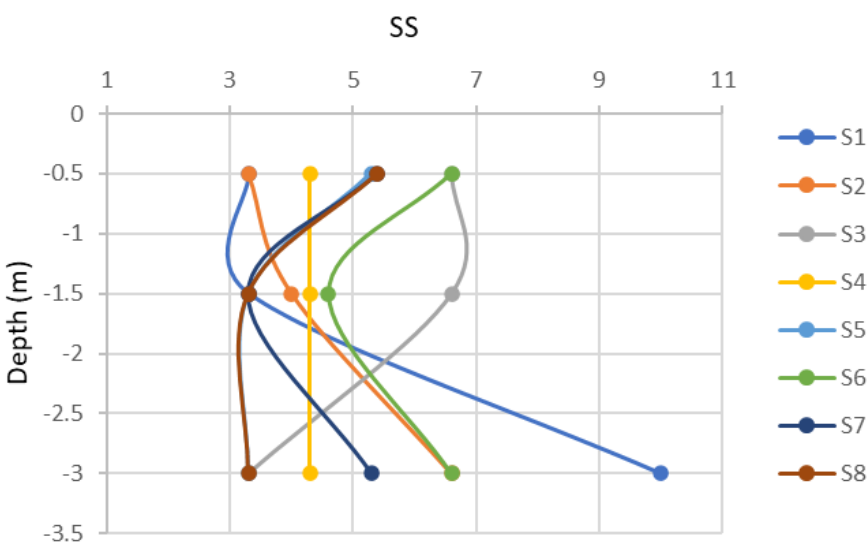


Figure 12. Variation of SS in the water column of Lake Buyo during low-water periods.

v. Distribution of suspended solids (SS) in lake water

The dry-season suspended solids distribution map showed

a heterogeneous distribution. Total suspended solids concentrations varied from 3.3 to 6.6 mg/L, with an average of 5.025 mg/L $\pm$ 1.30 (Figure 11). Transparency values ranged from 1.3 m to 1.7 m, with an average of 1.48 m. However, the SS concentration generally decreased with depth (Figure 12).

vi. *Distribution of ammoniacal nitrogen in lake waters*

Spatial variation during low-water periods highlighted the predominance of contents between 0.16 mg/L and 0.17 mg/L.

Ammonium levels ranged between 0.07 mg/L to 0.17 mg/L, with an average of 0.127 mg/L $\pm$ 0.03. Low levels (0.07-0.11 mg/L) were found to the east of the reservoir, near the water intake, while high levels were found to the west, near the flood spillway (Figure 13). Analysis of the profiles highlights a decrease in ammonium with depth. However, there was a clear increase in NH_4^+ content at stations 5 and 8 (Figure 14).

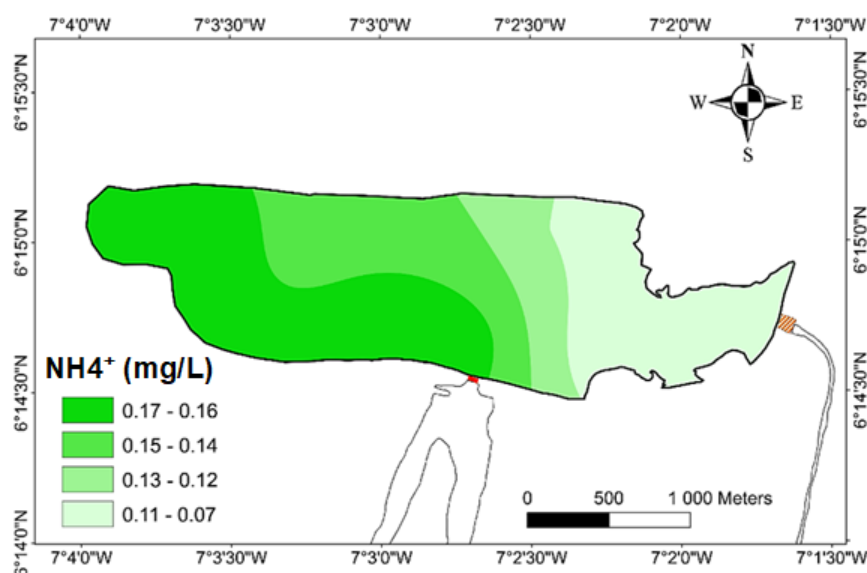


Figure 13. Spatial distribution of ammonium NH_4^+ during low-low periods.

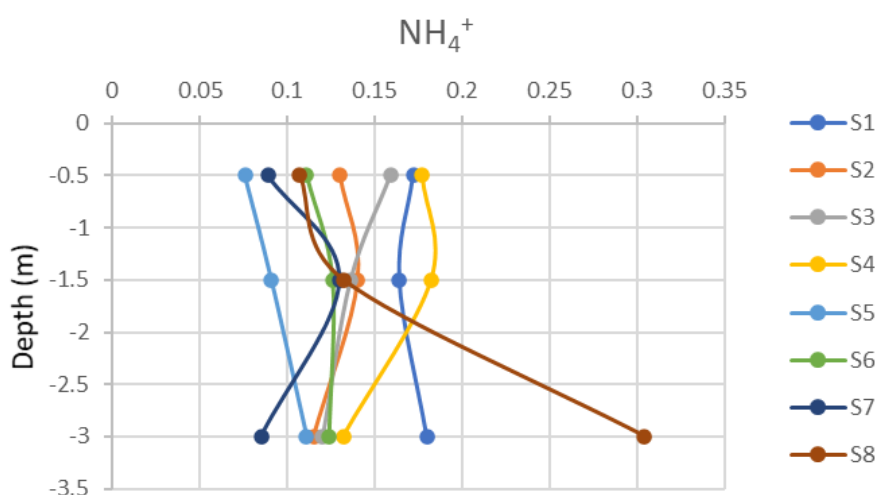


Figure 14. Variation in the ammonium content in the water column of Lake Buyo during low-water periods.

vii. *Distribution of nitrates in lake water*

At low water, NO_3^- contents oscillated between 0.401 mg/L and 1.9 mg/L, with an average of 0.975 mg/L $\pm$ 0.47 (Figure 15). The highest levels (1.61-1.9 mg/L) were found to the

south, on the spillway side, and to the east, at the water intake. Analysis of the profiles shows an increase in the NO_3^- content from the surface to a depth of 1.5 m, and a gradual decrease to a depth of 3 m (Figure 16).

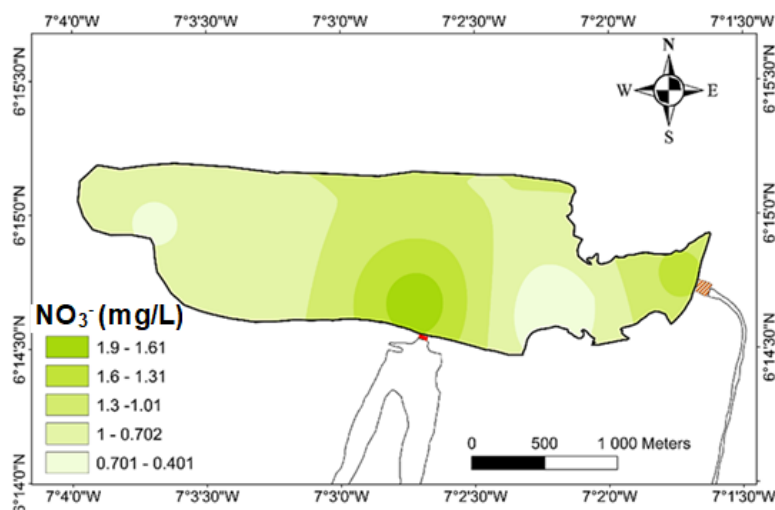


Figure 15. Spatial distribution of NO_3^- nitrates during low-water periods.

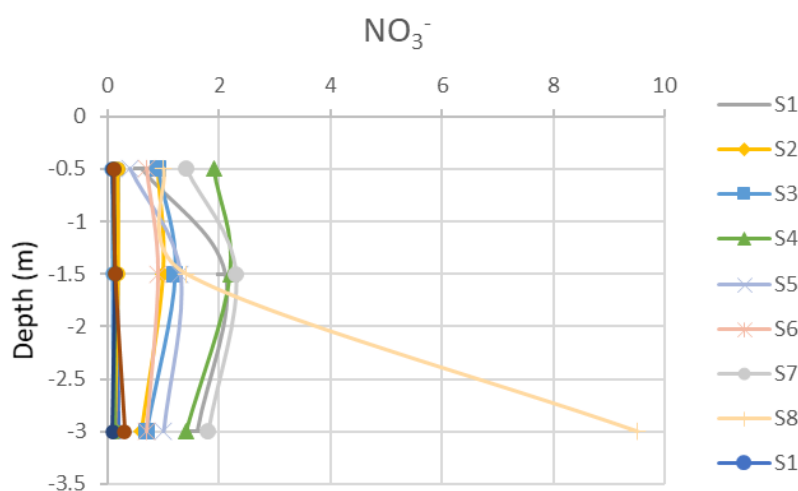


Figure 16. Variation in nitrate content in the water column of Lake Buyo during low-water periods.

3.2. Statistical Analysis of Physico-chemical Data from the Lake's Surface Waters

i. Correlation matrix

Table 2 presents the correlation matrix showing the relationships between the physicochemical variables taken two by two. On analysis, it emerges that:

A good correlation ($r = 0.74$) between temperature and ammonium;

A positive mean correlation ($r = 0.50$) between temperature

and dissolved oxygen;

A positive mean correlation ($r = 0.53$) between dissolved oxygen and conductivity;

A good negative correlation ($r = -0.71$) between pH and dissolved oxygen;

A good negative correlation ($r = -0.70$) between dissolved oxygen and SS;

A negative mean correlation ($r = -0.50$) between temperature and SS;

A negative mean correlation ($r = -0.50$) between conductivity and nitrate.

Table 2. Correlation matrix.

Matrice	T °	pH	O ₂	Cd	NH ₄	NO ₃	SS
T °	1.00						

Matrice	T°	pH	O ₂	Cd	NH ₄	NO ₃	SS
pH	-0.32	1.00					
O ₂	0.50	-0.71	1.00				
Cd	0.15	-0.23	0.53	1.00			
NH ₄	0.74	-0.42	0.26	-0.20	1.00		
NO ₃	0.02	0.35	-0.16	-0.50	0.34	1.00	
SS	-0.50	0.37	-0.70	-0.13	-0.37	-0.10	1.00

*T°: temperature, Cd: conductivity, NH₄: ammonium, NO₃: nitrates, O₂: dissolved oxygen, pH: hydrogen potential, SS: suspended solids.

ii. Principal component analysis of variables

Table 3 shows the percentage of variance expressed by each factor. Analysis of this table shows that the first two factorial axes account for 43.54% and 26.85% respectively of the variance expressed. These factors express 70.39% of the cumulative variance. Given these percentages, these factors

(Fact. 1 and Fact. 2) alone provide over 70% of the statistical information. For this reason, PCA is right take only two factors into account when analysing factorial designs. Representation using the first two factors gives a satisfactory account of the structure of the cloud of points.

Table 3. Eigen values and percentages of variances expressed by the factors.

	F1	F2	F3	F4	F5	F6	F7
Own values	3.05	1.88	0.81	0.68	0.42	0.16	0.00
%Variance expressed	43.54	26.85	11.54	9.68	6.01	2.34	0.04
%Cumulative variance	43.54	70.39	81.93	91.61	97.62	99.96	100.00

iii. Projection into variable space

The projection of the variables onto the plane formed by the first two factors (F1 and F2) during the low-water period is illustrated by Figure 17.

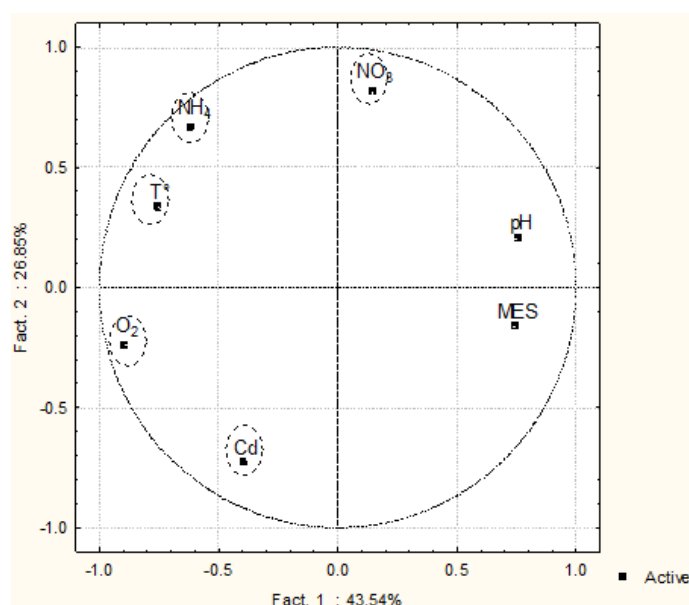


Figure 17. Community circle of the F1-F2 factorial plan for the downstream sector of Lake Buyo during low-water periods.

Temperature, dissolved O_2 and ammonium, on the other hand, are defined on the negative side of this axis. Factor 1 therefore reflects a gradient of organic matter decomposition by cyanobacteria.

The positive part of the Factor 2 is determined by NO_3^- and NH_4^+ , while the negative part is determined by conductivity. Factor 2 reflects an increasing gradient water nitrification.

Figure 18 distinguishes three (3) families of stations: GI,

GII and GIII. Group I is represented by station 1, located to the southwest of the reservoir. It is characterized by a fairly low pH, high dissolved oxygen levels and strong mineralization. Group II comprises stations 2, 3 and 4. These waters are low in suspended matter and conductivity. Group III, comprising stations 5, 6, 7 and 8, is characterized by waters with a high suspended solids content and moderate mineralization.

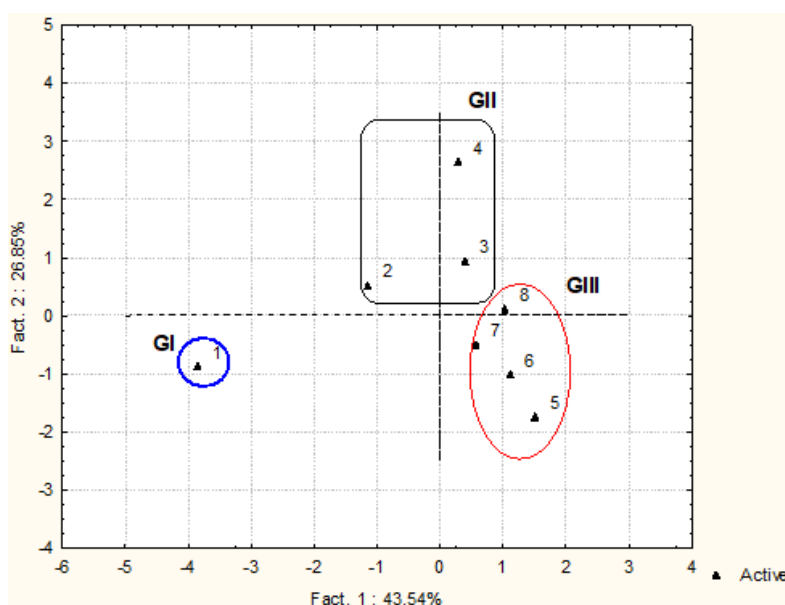


Figure 18. Representation of the stations in the F1-F2 factorial plan of the waters of the downstream sector of Lake Buyo during low-water periods.

3.3. Environmental Quality of Lake Water

Quality of “drinking water”

Ammonium (NH_4^+) and nitrate (NO_3^-) contents of the waters in the downstream sector of Lake Buyo were used to assess the water quality. Average values during low-water periods were $1.56 \text{ mg/L} \pm 0.59$ for NO_3^- and $0.13 \text{ mg/L} \pm 0.009$ for NH_4^+ in Lake Buyo. Considering the results, these waters are of good quality for consumption during low-water periods.

The value of mineral nitrogen (ammonium and nitrates) in the surface waters of Lake Buyo during low-water periods is 1.10 mg/L . The lake's water quality is therefore mediocre during low-water periods.

4. Discussion

Analysis of surface hydrogen potential showed that pH values vary in the downstream sector of Lake Buyo from 7.81 to 9.78, with an average of 8.67 during low- water periods. The pH values obtained are more or less close to those measured on Lake Bacon which varies from 6.5 to 9.5 [4]. Taking into

account the observation period, the average dissolved oxygen content of the surface waters of Lake Buyo is 5.5 mg/L . This result is consistent with those obtained by [1] on Lake Buyo (5.7 mg/L). DO concentrations in Lake Buyo show that the surface waters are more oxygenated than bottom waters. The high oxygen contents, recorded in the superficial zones, are due to photosynthetic activities which generally occur with greater intensity in these zones due to the high light penetration. In deeper zones, on the other hand, the oxidation of organic matter leads to deoxygenation of the water. These same observations were made by [9, 2], in Taabo and Buyo lakes respectively. The temperature values observed indicate that the waters are warmer during low- water periods (32.47°C). Temperatures of Lake Buyo vary little and are substantially identical to those obtained (27.48°C to 32.45°C) by [10] on Lake M'bakré and those of [1] (26°C to 32°C) on Lake Buyo. Furthermore, temperature changes with depth reveal thermal stratification. This occurs when depth permits and has repercussions on dissolved oxygen concentrations and pH values.

The average conductivity of surface water in the downstream sector of Lake Buyo during low-water periods is $67.5 \mu\text{S/cm}$. Lake Buyo therefore has very low electrical conductivity (EC less than $100 \mu\text{S/cm}$). Conductivity values during

this dry season are in line with those obtained by [9] on Lake Taabo (83 $\mu\text{S}/\text{cm}$). This is explained by the drop in input flows due to runoff. Analysis of SS in Lake Buyo shows that the waters are very lightly loaded during low- water periods (4.81 mg/L). [11] reports that the importance and nature of the suspended solid flow are linked to the intensity of erosion by runoff water, and therefore to the amount of rainfall.

The levels of nutrient salts (ammonium and nitrates) in the downstream sector of Lake Buyo are relatively low. These results are consistent with those of [1]. According to [1], these low nutrient levels in the Buyo zone, in particular, could be the result of photosynthetic activity due to phytoplankton rather than macrophytes. Ammonium and nitrate concentrations compared to the [6] guide values show that the water is of good quality for consumption at low water levels.

5. Conclusions

The waters in the downstream sector of Lake Buyo are alkaline, weakly mineralized, relatively well oxygenated at the surface and deoxygenated at depth. SS concentrations vary with depth during the low-water period and generally show a negative vertical gradient. This variation may reflect surface current phenomena in the lake. The average value during low-water periods is $1.56 \text{ mg/L} \pm 0.59$ for NO_3^- and $0.13 \text{ mg/L} \pm 0.009$ for NH_4^+ in Lake Buyo. The ammonium and nitrate value comply with the WHO guideline for drinking water. In addition, the waters in the downstream sector of Lake Buyo are poor during the low-water period. The use of multivariate techniques (ACPN) enables us to highlight the decomposition of organic matter by cyanobacteria, nitrification and natural mineralization of the lake.

Abbreviations

WFD	Water Framework Directive
ME	Body Mass Index
DO	Dissolved Oxygen
SS	Solid Suspension
NPCA	Normal Principal Component Analysis
PCA	Principal Component Analysis
WHO	World Health Organisation
MEEDDAT	Ministry of Ecology, Energy, Sustainable Development and Territory Planning
IDW	Inverse Distance Weighted
GPS	Global Positioning System
CIE	Compagnie Ivoirienne d'Electricité

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Author Contributions

Ronald Sosthène Désiré Yapi Atto: Conceptualization, Formal Analysis, Funding acquisition, Project administration, Supervision, Writing – original draft

Kouadio Assemien François Yao: Formal Analysis, Project administration, Supervision

Guy Serges Konan: Formal Analysis, Funding acquisition, Project administration, Supervision

Sylvain Monde: Supervision

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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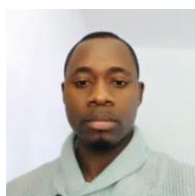
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Biography



of AFRICA.

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Guy Serges Konan is a PhD in marine geology from the Université Félix Houphouët-Boigny (2023), specialising in hydrosedimentary modelling applied to dam lakes. He obtained a master's degree in marine geology in 2018, and his work focuses on the morphobathymetric and sedimentological characterisation of lake environments. He has taken part in several major projects in Côte d'Ivoire, including the hydrosedimentary study of the Soubré dam lake and the analysis of the water bodies surrounding the Ehotilé Islands as part of their World Heritage listing. He also carried out a doctoral internship in Switzerland, working for HydroExploitation SA, on the silting up of Lake Dix (Grande Dixence dam). His current research incorporates digital tools, hydrosatial analysis and modelling for the



international Association of Sedimentologists and the Order of Geologists of Quebec. Beyond academia, he serves as a municipal councilor in Azaguié and Vice-President of the Commission for Social and Cultural Affairs. His career reflects a strong commitment to scientific excellence and sustainable development in Africa.

Sylvain Monde is a Full Professor of Geosciences at Félix Houphouët-Boigny University (UFHB), Côte d'Ivoire, where he currently serves as Head of the Department of Geosciences. He holds two Ph.D. degrees: one from UFHB and another from La Rochelle University (France), complemented by postdoctoral research in oceanography at Québec University (Canada). Professor MONDE's research spans marine geology, sedimentology, coastal dynamics, and hydrosedimentary modeling. He has authored over 130 scientific publications and supervised numerous doctoral and master's theses. His work has contributed to national and international projects, including oceanographic missions and environmental assessments. He is actively involved in scientific networks such as the International Association of Sedimentologists and the Order of Geologists of Quebec.

Research Field

Ronald Sosthène Désiré Yapi Atto: hydro-sedimentology, hydro-sedimentary modelling, water quality, environmental assessment, Oceanology, reservoir petrophysics and remote sensing.

Kouadio Assemien François Yao: Geochemistry, Water quality, Climate change, Hydrogeology Modelling, and Environmental assessment.

Guy Serges Konan: digital tools, hydrosatial analysis and modelling for the sustainable management of aquatic environments.

Sylvain Monde: marine geology, sedimentology, coastal dynamics, and hydrosedimentary modeling.