American Journal of Environmental Protection
2025, Vol. 14, No. 6, pp. 284–294
https://doi.org/10.11648/j.ajep.20251406.13

Research Article

Physicochemical Characterization of Surface Waters in the Ono Lagoon Watershed Under Multiple Anthropogenic Pressures, Bonoua (Southeastern Ivory Coast)

Privat Tohouri[1, *], Braphond Rodrigue Vincent Benjamin Anongba[1], Satti Jean Robert Kamenan[2], Miessan Germain Adja[1]

[1]Department of Sciences and Technology, Higher Normal School, Abidjan, Ivory Coast

[2]Department of Engineering Sciences and Technology, Houphouêt-Boigny National Polytechnic Institute, Yamoussoukro, Ivory Coast

Abstract

Domestic, industrial, and agricultural pressures are increasingly impacting the Ono Lagoon watershed (Bonoua, Ivory Coast). This study aimed to identify the main sources of pollution and assess the physicochemical quality of surface waters. Twenty-five (25) sites were sampled, and ten (10) parameters were analyzed: pH, temperature, electrical conductivity, nitrate, nitrite, ammonium, orthophosphate, sulfate, potassium, and sodium. Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), two multivariate statistical methods, revealed moderate mineralization (mean electrical conductivity: 34.8 µS/cm) and significant acidity (mean pH: 5.43), both below World Health Organization (WHO) standards. Orthophosphate concentrations exceeded WHO guidelines at 88% of the sites, indicating substantial agricultural pressure. PCA identified three main gradients: seasonal nitrate leaching, agro-industrial inputs (sulfate, ammonium), and domestic pollution (nitrite, orthophosphate, potassium, sodium). HCA grouped the sites into three distinct clusters, with site S25 showing particularly degraded water quality. These results highlight the complex interactions among different pollution sources and emphasize the importance of regular monitoring of surface waters. They also underscore the need for integrated and targeted management strategies to mitigate the impacts of domestic and agricultural activities on the watershed's surface waters. In summary, this study provides essential information to guide the protection and sustainable management of water resources in the Ono Lagoon watershed.

Keywords

Orthophosphates, Ono Lagoon, Principal Component Analysis, Hierarchical Cluster Analysis, Diffuse Pollution, Water Quality

1. Introduction

Since the Second World War, the main transformations of agricultural practices leading to increased productivity included mechanization, irrigation, and the practice of extensive synthetic fertilization and pesticides [1]. The country Ivory Coast has an estimated annual consumption in tons of fertilizers at 47,580 and pesticides at 6,000 for its major economic

*Corresponding author: privatohouri@gmail.com (Privat Tohouri)

Received: 25 October 2025; **Accepted:** 4 November 2025; **Published:** 11 December 2025

sector [2, 3]. The Ono Lagoon is found in the watershed within Bonoua sub-prefecture, about 80km east of Abidjan, southeastern Ivory Coast, where large agro-industrial farms (pineapple and rubber plantations) coexist with smallholder agriculture. It is typical for smallholders to apply. Chemical inputs without any regulation [4]. Other sources of pressure are untreated domestic wastewater plus urban runoff, and industrial discharges. Surface waters near agricultural zones previously tested positive for pesticides [5].

It intends to evaluate the physicochemical surface waters of the Ono Lagoon watershed under combined agricultural, industrial, and domestic pressures and further tries to identify the main sources of pollution. It hypothesizes that surface waters under strong anthropogenic influences, specifically reflecting the intensity and type of influence, would have significant variations in their physicochemical properties, with more contamination reflected in areas receiving agricultural and domestic effluents. Thus, such dynamics will inform scientifically based evidence for ecological and economic interests in this region for sustaining water resource management while ensuring aquatic ecosystem protection, together with human health protection.

2. Materials and Methods

2.1. Study Area

The Lagoon Watershed is situated in the Bonoua sub-prefecture, which is found in southeastern Ivory Coast, some 80 kilometers east of Abidjan. More specifically, it falls within the coordinates of latitudes 5°05' to 5°30' N and longitudes 3°25' to 3°45' W. It has a surface area of approximately 402 square kilometers with a perimeter of 101 kilometers. To the northwest lies Alépé, with Oghlwapo sharing a border on its western side; eastern borders are shared with Aboisso, while Assinie, together with Grand-Bassam, can be found further south (Figure 1). The region is characterized by flat relief, with elevations below 200m above sea level, typical of coastal Côte d’Ivoire. The landscape consists mainly of low plateaus (40-50m) resting on Tertiary sedimentary formations (fine sands, clays, and sandy-clay alluvium) [6]. Slopes are gentle (less than 10%), favoring surface runoff that drains into the Ono, Kodjoboué, and Hébé Lagoons as well as several streams. These water bodies receive inputs from both natural runoff and anthropogenic sources, including agriculture, settlements, and industrial areas [7]. The watershed has a subequatorial climate with an average annual rainfall of 1,176 mm [7]. While this high rainfall benefits agriculture, it also promotes leaching and the transfer of nutrients and contaminants, particularly fertilizers and pesticides, into surface waters, especially during the rainy season.

The dominant geological formations consist of Quaternary deposits (leached mud and sand) and Continental Terminal sediments composed of sand and clay [8]. Paleoproterozoic metamorphic outcrops, such as gneisses and granitoids, are found locally in the north. The majority of the soils are sandy, and their limited ability to hold onto pollutants is made worse by the fragmented vegetation cover brought on by agricultural activity. Bonoua is a major agricultural area in southeastern Ivory Coast. It hosts two large agro-industrial companies: the Banana Cultivation Research and Development Company (SCB) in Ono and the African Rubber Plantation Company (SAPH) at the Bongo Integrated Agricultural Center. These mechanized farms use large amounts of agrochemicals [4]. In addition, smallholder agriculture also relies on fertilizers and pesticides, often without regulation. The lack of sanitation infrastructure contributes to the direct discharge of untreated wastewater and solid waste, increasing pressure on water quality [5].

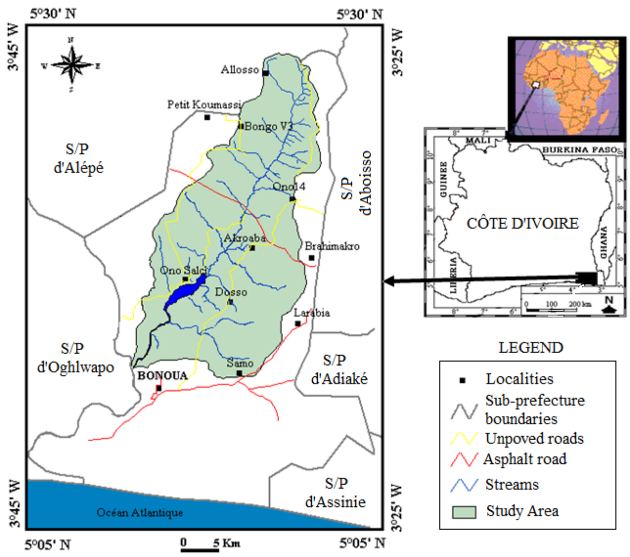


Figure 1. Geographical Location of the Study Area.

2.2. Data Collection

To capture the spatial variability of possible pollution sources within the watershed, 25 sampling sites were carefully chosen (Figure 2). The selection criteria included being close to industrial activities, settlements, and agricultural production areas (such as rubber and pineapple plantations). To justify their inclusion in the monitoring program, sites were also selected based on their accessibility and the frequency with which local communities use them for domestic purposes, such as cooking, drinking, and washing. Rivers, lagoon inlets, and outlets that were linked to the Continental Terminal aquifer were all part of the network.

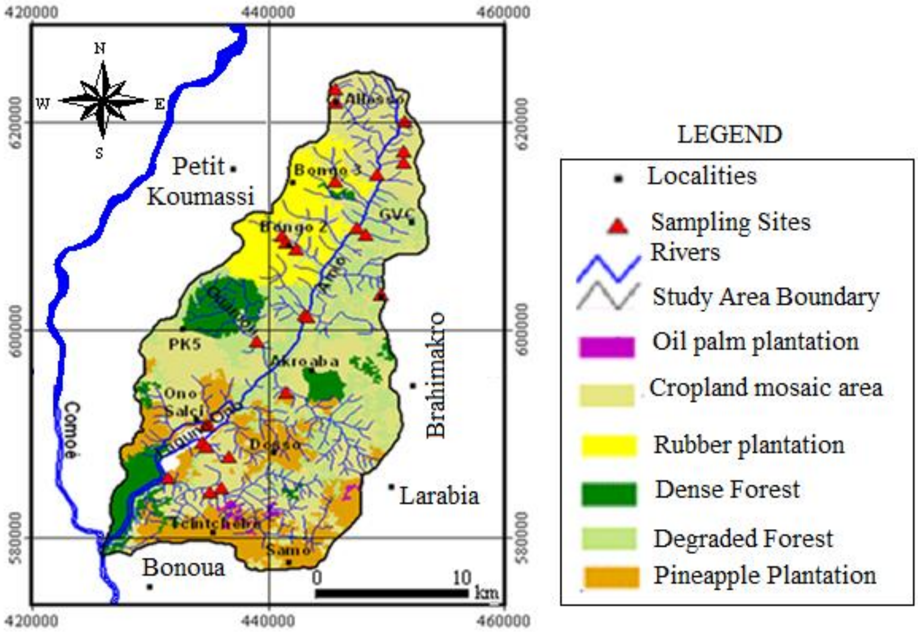


Figure 2. *Map Showing the Sampling Site.*

A clearer picture of pollutant concentrations was obtained by sampling during the start of the main dry season, when dilution by rainfall is at its lowest. The logistical difficulties that fieldwork occasionally encountered were lessened by the use of portable equipment and pre-survey reconnaissance, particularly those pertaining to accessibility in swampy areas and the presence of dense vegetation. Standard protocols were followed in the collection of water samples [9]. Before being collected, each sample was cleaned with nitric acid, rinsed with distilled water, and flushed with site water in a 1-liter polyethylene bottle. The bottles were submerged 20cm below the surface, sealed to prevent air bubbles, stored at 4°C, and delivered to the CIAPLOL (Centre Ivoirien Antipollution) laboratory for analysis in less than an hour. A Garmin Map 60 CSX GPS receiver was used to georeference each sampling site after assigning it a code (S1 to S25) (Table 1). A HACH HQ40d multiparameter probe was used to measure the temperature and pH in situ, and a HANNA HI 99301 conductivity meter was used to measure the electrical conductivity. In accordance with AFNOR guidelines, laboratory analyses concentrated on the main nutrients and ions (nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), orthophosphate (PO_4^{3-}), sulfate (SO_4^{2-}), potassium (K^+), and sodium (Na^+)) [10, 11] (Table 2).

Table 1. *Characteristics of the sampled water points: Sample.*

Sample code	GPS Coordinates		Sample code	GPS Coordinates	
	X (m)	Y (m)		X (m)	Y (m)
S1	437893	589970	S14	442500	607354
S2	438587	590293	S15	445525	611623
S3	593437	593437	S16	445532	617129
S4	437638	593163	S17	445558	618126
S5	435296	590959	S18	449846	615814
S6	439052	592413	S19	449788	613771
S7	442525	596980	S20	448109	612128
S8	443665	602369	S21	446898	608346
S9	440702	600501	S22	447417	607880

Sample code	GPS Coordinates		Sample code	GPS Coordinates	
	X (m)	Y (m)		X (m)	Y (m)
S10	437777	594636	S23	449771	612946
S11	437595	594609	S24	448392	603807
S12	442330	607872	S25	443823	602210
S13	443151	606903			

Table 2. *Analytical methods, standards, and detection limits.*

Parameters	Analytical methods	Standard references (NF T)	Detection limits (mg/L)
Nitrates (NO_3^-)	Molecular absorption spectrophotometry	NF T 90-012	0.05 - 0.1
Nitrites (NO_2^-)	Molecular absorption spectrophotometry	NF T 90-013	0.01 - 1
Ammonium (NH_4^+)	Molecular absorption spectrophotometry	NF T 90-015	0.01 - 0.02
Phosphates (PO_4^{3-})	Molecular absorption spectrophotometry	NF T 90-023	0.01 - 0.05
Potassium (K^+)	Flame atomic absorption spectrometry	NF T 90-020	0.1 - 0.2
Sodium (Na^+)	Flame atomic absorption spectrometry	NF T 90-019	0.1 - 0.2
Sulfates (SO_4^{2-})	Ion chromatography	NF T 90-040	0.1 - 0.5

2.3. Statistical Analysis

To give a general picture of the central tendency and variability of the measured water quality variables, descriptive statistical parameters such as mean, minimum, maximum, standard deviation, and coefficient of variation were first calculated. By methodically comparing these values with the World Health Organization's (WHO) recommended limit, it was possible to identify parameters that went beyond international norms and to highlight possible threats to the health of people and ecosystems [12]. Multivariate statistical analyses were used to further interpret the data and identify the primary sources of pollution [13, 14]. To determine the primary factors influencing the variability of water quality, Principal Component Analysis (PCA) was used to assess the dataset's dimensionality [15]. The method makes it possible to distinguish between anthropogenic impacts and natural geochemical processes. PCA, or Principal Component Analysis, was used. In order to guarantee comparability between variables of various scales, PCA was performed on standardized data (zero mean, unit variance) using a correlation matrix. Scree plot analysis, cumulative variance explained, and eigenvalues greater than one were used to determine how many components were kept. The sampling sites were then categorized into homogeneous groups based on their hydrochemical properties using Hierarchical Cluster Analysis (HCA). Ward's method was selected as the linkage rule to minimize within-cluster variance and maximize between-cluster differentiation, while the Euclidean distance was employed as a measure of dissimilarity [16]. Site affinities and spatial patterns of water quality were visually represented by the resulting dendrogram. This clustering technique aids in validating the PCA results and defining areas with comparable pollution pressures. The XLSTAT software (version 2025.7.1, demo edition), which incorporates reliable multivariate algorithms frequently used in hydrogeochemical and environmental investigations, was used for all statistical analyses. By facilitating pattern cross-validation and enhancing the reliability of source identification, the combined application of PCA and HCA improves the interpretation of water quality dynamics.

3. Results

3.1. Physicochemical Characteristics

Table 3 presents a summary of the surface water's physical and chemical attributes within the Ono Lagoon watershed. The attributes were measured both in the field and in the laboratory.

Table 3. Statistical variables and extreme values of physicochemical parameters.

Parameters	SI units	Min	Mean	Max	Standard deviation	Coefficient of variation (%)	WHO (2011) Guidelines
Electrical conductivity (CE)	µS/cm	21	34.78	184.30	31.50	91	≤ 500
Temperature (T)	°C	24.90	26.61	30.20	1.51	6	≤ 25
pH	-	4.20	5.44	6.70	0.69	13	6.5 – 8.5
Nitrate (NO_3^-)	mg/L	0.30	1.77	4.73	1.33	75	≤ 50
Nitrite (NO_2^-)	mg/L	0.00	0.03	0.33	0.06	196	≤ 0.1
Ammonium (NH_4^+)	mg/L	0.00	0.01	0.03	0.01	75	≤ 0.5
Orthophosphate (PO_4^{3-})	mg/L	0.01	0.18	0.82	0.18	99	≤ 0.05
Sulfate (SO_4^{2-})	mg/L	1.00	2.08	8.00	1.44	69	≤ 250
Potassium (K^+)	mg/L	0.15	0.83	5.78	1.08	131	≤ 12

3.1.1. Physical Characteristics

Electrical conductivity (EC) varied considerably, ranging from 21 to 184.30 µS/cm, with an average of 34.78 µS/cm. The high coefficient of variation (CV = 91%) shows considerable spatial variation. The water temperature was generally stable, averaging 26.61°C, with fluctuations between 24.90 and 30.20°C (CV = 6%). A large majority of the samples (96%) were below the World Health Organization's 30°C limit for tropical areas. The pH level changed from 4.20 to 6.70, with an average of 5.44 ± 0.69 (CV = 13%), which points to conditions that are a bit to very acidic. About 96% of our samples fell under the WHO's lowest pH limit of 6.5.

3.1.2. Chemical Characteristics

Nitrate (NO_3^-) concentrations ranged from 0.30 to 4.73 mg/L, with a mean of 1.77 ± 1.33 mg/L, and a coefficient of variation 75%. All concentrations were below the WHO guideline of 50 mg/L. Nitrite (NO_2^-) concentrations were variable with a coefficient of variation of 196%, a mean of 0.03 ± 0.06 mg/L. Ammonium concentrations ranged from 0 to 0.03 mg/L, with a mean of 0.01 ± 0.01 mg/L and a CV of 75%. Orthophosphate (PO_4^{3-}) concentrations varied from 0.18 to 0.82 mg/L, with a mean of 0.18 ± 0.18 mg/L and a CV of 96%. However, 88% of samples were above the WHO limit of 0.05 mg/L for drinking water. Sulfate (SO_4^{2-}) concentrations were very low, with a mean of 2.08 ± 1.44 mg/L and a CV of 69%. All concentrations were well below the WHO guideline of 250 mg/L. Potassium (K^+) concentrations ranged from 0.15 to 5.78 mg/L, with a mean of 0.83 ± 1.08 mg/L and a CV of 131%, which suggests high variability. Sodium (Na^+) concentrations varied from 0.34 to 5.44 mg/L, with a mean of 1.37 ± 0.99 mg/L and a CV of 72%; all concentrations were below the WHO guideline of 12 mg/L for drinking water.

3.2. Principal Components Approach

Principal component analysis, using the Kaiser criterion of eigenvalues exceeding 1, revealed three components accounting for 75.58% of the variance in the data (Table 4). This suggests a good representation of the data.

Table 4. Eigenvalues of the Principal Components and Their Explained Variance (%).

Component	Eigenvalue	Cumulative Eigenvalue	% of Variance Explained	Cumulative% of Variance
F1	4.80	4.80	47.97	47.97
F2	1.49	6.29	14.95	62.92
F3	1.27	7.56	12.66	75.58

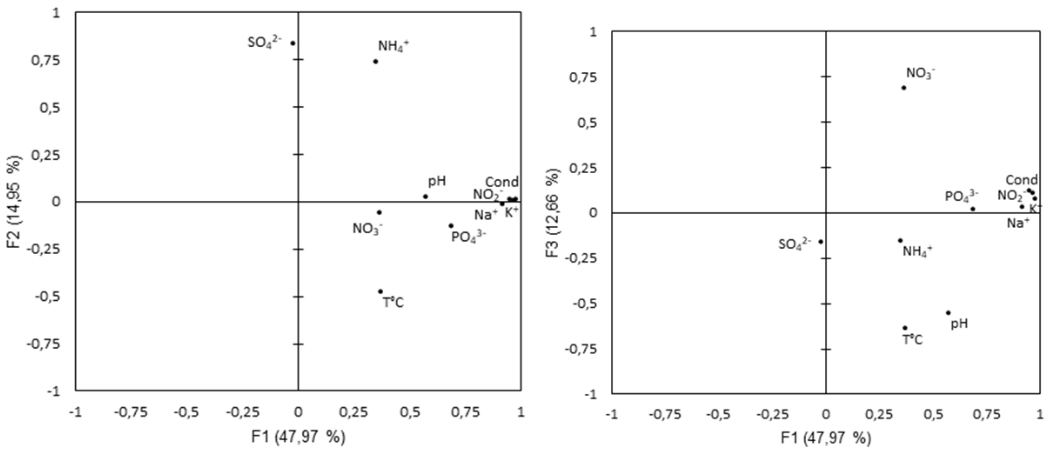
The correlation matrix (Table 5) showed several strong links. Electrical conductivity had a high correlation with potassium (r = 0.96), nitrite (r = 0.96), and sodium (r = 0.89), which suggests they are key to water mineralization. Potassium and sodium also had a high correlation (r = 0.91), likely due to a shared source, probably domestic or from the edge of urban areas. Phosphate had a moderate correlation with nitrite (r = 0.58), potassium (r = 0.61), and sodium (r = 0.61), suggesting a mix of agricultural and domestic sources. Sulfate showed slight or inverse relationships, indicating that mainly climatic factors are at play.

Table 5. Matrix of linear correlation coefficients between physicochemical parameters.

Variables	Cond	T °C	pH	NO_3^-	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	K^+	Na^+
Cond	1,00									
T° C	0,29	1,00								
pH	0,44	0,45	1,00							
NO_3^-	0,39	-0,10	0,04	1,00						
NO_2^-	0,96	0,26	0,45	0,38	1,00					
NH_4^+	0,34	-0,05	0,08	-0,13	0,35	1,00				
PO_4^{3-}	0,57	0,13	0,45	0,19	0,58	0,03	1,00			
SO_4^{2-}	-0,05	-0,24	0,25	0,04	-0,08	0,39	-0,05	1,00		
K^+	0,96	0,31	0,48	0,38	0,92	0,35	0,61	-0,04	1,00	
Na^+	0,89	0,29	0,37	0,22	0,84	0,36	0,57	-0,12	0,91	1,00

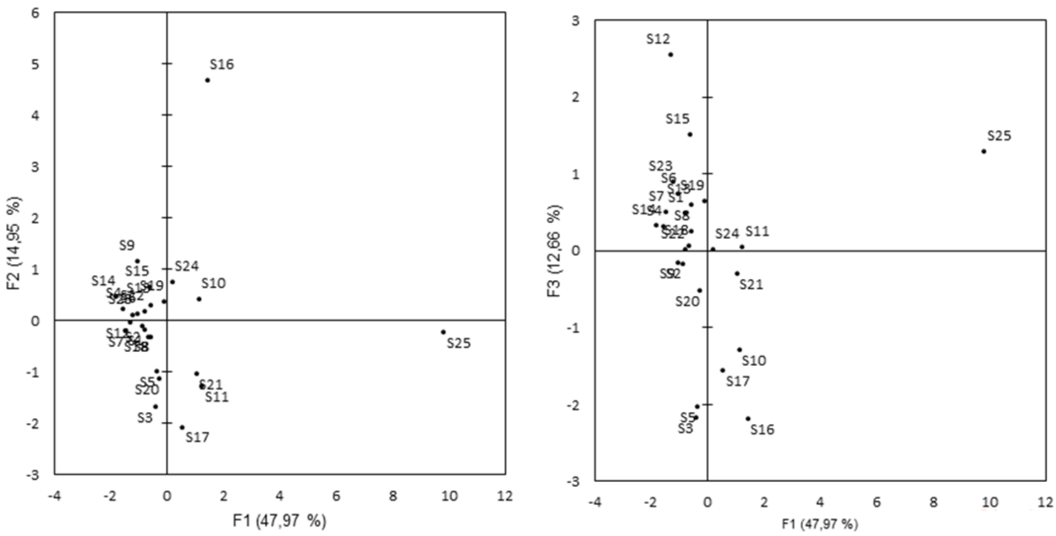
The variables' projections (Figure 3) on the factorial planes showed three main trends. The first axis (F1, 49.97% of variance) linked EC, NO_2^-, PO_4^{3-}, K^+, Na^+, and pH, sggesting domestic pollution. The second axis (F2, 14.95%) is mainly tied to NH_4^+ and SO_4^{2-}, pointing to local agricultural and industrial pollution. The third axis (F3, 12.66%) opposed NO_3^- and temperature, which implied seasonal changes related to rainfall leaching.

Looking at site projections (Figure 4) confirms these trends. Data from site S25, similar to F1, showed elevated levels of Na^+ (5.44 Mg/L), K^+ (5.78 mg/L), NO_2^- (0.33 mg/L), and EC (184.30 µS/cm), suggesting notable household pollution. Sites S9 and S16, similar to F2, presented increases in NH_4^+ (0.025 mg/L) and SO_4^{2-} (5 mg/L), probably related to agro-industry. Sites S12 and S15, linked to F3, had higher NO_3^- concentrations (up to 4.28 mg/L), probably because of agricultural runoff.



a. Variable Space on the F1-F2 Factorial Plane b. Variable Space on F1-F3 Factorial Plane

Figure 3. Projection of surface water variables from the watershed on the F1-F2 and F1-F3 factorial planes (PCA).



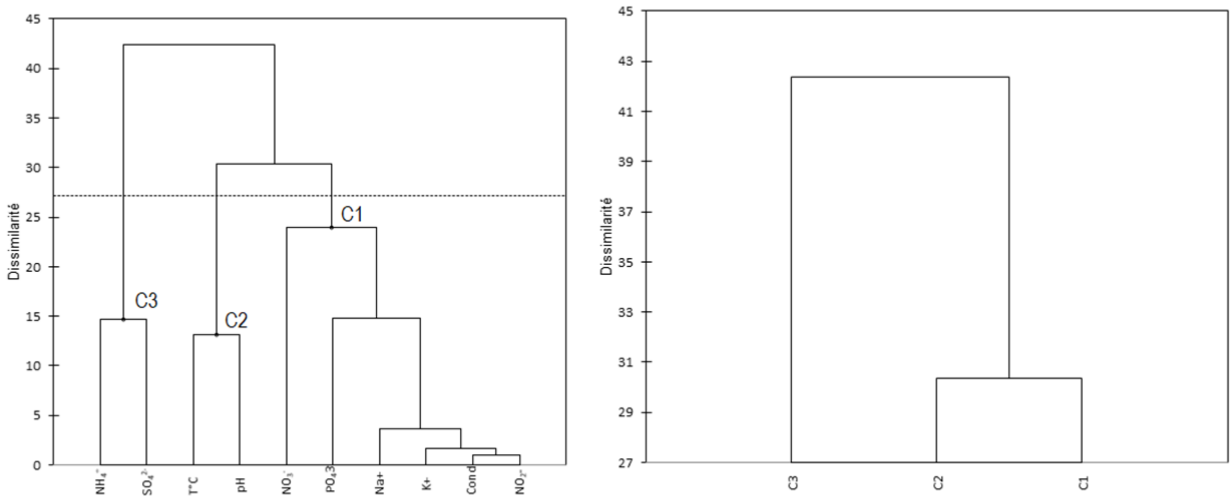
a. Individual Space on the F1-F3 Factorial Plane b. Individual Space on the F1-F3 Factorial Plane

Figure 4. *Projection of the surface water sampling sites from the watershed on the F1-F2 and F1-F3 factorial planes (PCA).*

3.3. Analysis of Hierarchical Clusters

3.3.1. Classification of the Variables

We grouped variables by statistical similarity with hierarchical clustering. Table 6 and Figure 5a show three main groups. The first groupe (C1) includes conductivity, NO_3^-, NO_2^-, PO_4^{3-}, K^+ and Na^+. This group has a moderate intra-class variance (9.001) and a mean distance to the centroid of 2.501, showing good internal consistency. The variables in this group mostly represent pollution from homes and farms, especially from fertilizer and wastewater. The second group (C2) has temperature and pH. This group has a higher intra-class variance (13.103) and likely shows natural conditions or Things only slightly affected by humans. These variables usually change with the seasons and climate. The third group (C3) has NH_4^+ and SO_4^{2-}. Even though it has few variables, this group has the highest intra-class variance (14.667) and centroid distance (2.708), which points to a specific pollution source, probably organic waste or factory discharge. The dendrogram (Figure 5b) supports this grouping. Group C3 is different from groups C1 and C2, suggesting a local pollution source. Groups C1 and C2 look closer, meaning they have some shared environmental influence.



a. Dendrogram of Variables b. Dendrogram of Classes

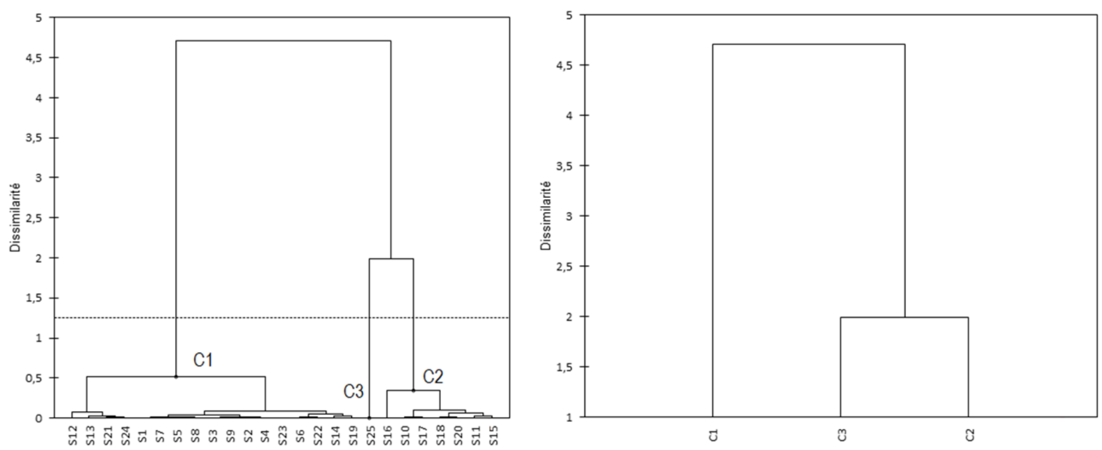
Figure 5. *Dendrograms of variables and corresponding clusters.*

Table 6. Characteristics of variable classes based on Hierarchical Ascending Classification.

Classes	C1	C2	C3
Number of variables per class	6	2	2
Sum of weights	6	2	2
Within-class variance	9.001	13.103	14.667
Minimum distance to centroid	1.480	2.560	2.708
Mean distance to centroid	2.501	2.560	2.708
Maximum distance to centroid	4.468	2.560	2.708
Variables	Cond, NO_3^-, NO_2^-, PO_4^{3-}, K^+, Na^+	T°C, pH	NH_4^+, SO_4^{2-}

3.3.2. Classification of Sampling Sites

Table 7 shows the characteristics of the sampling site clusters. Based on Table 7 and Figure 6a, we identified three groups. Cluster C1 has 17 sites with low variance (0.056) and short distances to the center (0.210), meaning they are alike. These sites have low mineralization (mean EC = 24.10 µS/cm) and seem to be affected by widespread home and farm pollution, as seen in Cluster C1. Cluster C2 has seven sites (S10, S11, S15, S16, S17, S18, and S20) with a bit more variance (0.091) and spread out a bit more (maximum distance = 0.547). These sites have average mineralization (mean EC = 39.36 µS/cm) and are affected by both natural factors like pH and temperature, and certain polluants like NH_4^+ and SO_4^{2-}. Lastly, Cluster C3 has just one site (S25), which is different because it has much higher EC (184.30 µS/cm) and more Na^+, K^+, NO_2^-, and PO_4^{3-}. This points to strong, local home pollution. The site dendrogram in Figure 6b supports these observations, showing that Cluster C1 is tightly grouped, while Clusters C2 and C3 are closer to each other. This suggests that most sites share similar characteristics, although some, such as S25, experience distinct environmental conditions.



a. Dendrogram of Sampled Sites b. Dendrogram of Classes

Figure 6. Dendrograms of sampled sites and corresponding clusters.

Table 7. Characteristics of site classes based on Hierarchical Ascending Classification.

Classes	C1	C2	C3
Number of sites per class	17	7	1
Sum of weights	17	7	1

Classes	C1	C2	C3
Within-class variance	0.056	0.091	0.000
Minimum distance to centroid	0.082	0.139	0.000
Mean distance to centroid	0.210	0.248	0.000
Maximum distance to centroid	0.414	0.547	0.000
Sites	S1, S2, S3, S4, S5, S6, S7, S8, S9, S12, S13, S14, S19, S21, S22, S23, S24	S10, S11, S15, S16, S17, S18, S20	S25

4. Discussion

The use of physicochemical analyses, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA) helped to have a good grasp of what causes pollution and how surface waters in the Ono Lagoon watershed are structured environmentally. The waters usually had low mineralization (mean EC: 34.78 µS/cm), which means that human activity doesn't change the water chemistry much. Similar things were seen in Lake Buyo, Côte d'Ivoire [17], and in the Lake Bam basin, Burkina Faso [18]. Still, pH values were usually acidic (mean: 5.44), with 96% of samples under WHO guidelines. This acidity probably comes from runoff in wooded and farmed areas [19] and could also get worse because of the breakdown of organic matter and the release of domestic waste. Temperature, which matters for water life [20], went from 24.9 to 30.2°C (mean: 26.61°C), which is more than the WHO guideline of 25°C [12]. Higher temperatures might come from mixing after rain and the air getting warmer, which helps microbes grow and can make water worse [21]. These things fit with the local climate [22], and how similar they are across sites might show when the sampling was done. Other West African watersheds have had similar results [23, 24]. Most chemical parameters (NO_3^-, NH_4^+, K^+, Na^+, SO_4^{2-}) stayed within WHO limits, which means there's some pollution. On the other hand, there was always a lot of phosphate (PO_4^{3-}), with 88% of samples over the WHO guideline of 0.05 mg/L (mean: 0.18 mg/L). This is because people use a lot of fertilizer, and soil washes away during the rainy season (annual rainfall: 1,716 mm). The Haut-Bandama basin had similar stuff [25], while the Nakambé basin, Burkina Faso, had less [26]. [27] said that erosion makes phosphate move to surface waters faster. Nutrients, especially phosphates with nitrates and sulfates, are probably causing eutrophication in some places (Figure 7).

Even small concentrations (0.3 mg/L NO_3^-, 0.01 mg/L PO_4^{3-}, 0.5 mg/L SO_4^{2-}) are sufficient to trigger eutrophication [28]. This finding underscores the impact of unsustainable agricultural practices and inadequate soil management, consistent with the observations of [26]. Even though nitrate levels stayed under WHO limits, the highest (4.73 mg/L) was at Bongo, where there's a lot of farming and latex processing. This could be a sign that nitrate is building up because there's no wastewater treatment.

a. River at Bong

b. River at N'Djak

Figure 7. Illustration of surface water eutrophication in the watershed (Photograph taken during the sampling campaign).

Multivariate statistical analyses backed up the main pollution factors. PCA found three main things: (i) pollution from homes, with a lot of Na^+, K^+, NO_2^-, and PO_4^{3-}; (ii) industry influencing farming, with NH_4^+ and SO_4^{2-}; and (iii) seasonal things, with NO_3^- and temperature going against each other, which showed fertilizer washing away when it rained. These findings align with those of the Haut-Bandama basin [25]. Strong ties (r > 0.89) between EC, K^+, Na^+, and NO_2^- show how much they add to water mineralization. HCA also found three kinds of pollution. The first kind was from farming and homes in different places. The second was about natural or climate stuff, like pH and temperature. The third was about problems in certain places with NH_4^+ and SO_4^{2-}. The sites also showed these things. Most sites had some pollution from different places (category 1), while some had different things affecting them (category 2). On the other hand, site S25 had very high ion amounts, which means there's a lot of pollution from homes because the sanitation is bad. N'Zianouan has had similar water problems because of bad sanitation [29].

5. Conclusion

This study checked the physicochemical quality of surface waters in the Ono Lagoon watershed. Even though there wasn't much mineralization usually (mean EC: 34.78 µS/cm), there was a lot of phosphate in 88% of the samples, more than the WHO guideline of 0.05 mg/L, which means there's a big chance of eutrophication. Multivariate analyses found three main things that cause contamination. The first was pollution from homes, with a lot of Na^+, K^+, NO_2^-, and PO_4^{3-}, especially near where people live. The second was pollution from farming in different places, with NO_3^- and PO_4^{3-} during runoff. The third was pollution. From organic stuff or industry in certain places, with NH_4^+ and SO_4^{2-}, probably from farming or livestock releasing stuff. Where the sites were shown, most had some pollution in different places, while site S25 had really bad problems because of a lot of stuff from homes, probably because the sanitation is bad. Because of these things, some things need to happen first. Water quality should be watched more with more checking at different times and places. Farming methods that don't hurt the environment should be pushed to use less fertilizer and put it on in ways that don't hurt the environment. How homes and factories handle wastewater needs to improve with good sanitation. People in the area should be told about how to lower human effects on water life.

Abbreviations

HCA	Hierarchical Cluster Analysis
PCA	Principal Component Analysis
SCB	Banana Cultivation Research and Development Company
SAPH	African Rubber Plantation Company
WHO	World Health Organization
µS/cm	Microsiemens per Centimeter
mg/L	Milligrams per Litre
CV	Coefficient of Variation
EC	Electrical Conductivity

Acknowledgments

The authors express their gratitude to the Ivorian Anti-Pollution Centre (CIAPOL) for providing the necessary data for this research. Special thanks are extended to Mr. Sangaré Madou for his logistical support and in-depth field knowledge, which contributed greatly to the success of the sampling campaign.

Author Contributions

Privat Tohouri: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft

Braphond Rodrigue Vincent Benjamin Anongba: Conceptualization, Data curation, Formal Analysis, Investigation, Software, Validation, Writing – review & editing

Satti Jean Robert Kamenan: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing

Miessan Germain Adja: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Funding

This work is completely self-funded.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Laurent, F. Water pollution from agriculture in western France. Water, Source of Life, Source of Conflicts, 15th Forum of Le Monde Diplomatique, Carrefours de la Pensée, Rennes, France, 2006; pp. 143-150.

[2] MINAGRA. Master Plan for Agricultural Development 1992-2015. Ministry of Agriculture, Côte d'Ivoire, 1993; pp. 19-31.

[3] MLCVE. Framework Law No. 96/766 Establishing the Environmental Code. Ministry of Environment, Côte d'Ivoire, 1997.

[4] Anoh, K. Evaluation of the specific vulnerability of groundwater in the Bonoua region to agricultural inputs. Master's Thesis, University of Cocody, Abidjan, Côte d'Ivoire, 2009.

[5] MINEEF. National Implementation Plan for the Stockholm Convention on Persistent Organic Pollutants. Ministry of Environment, Côte d'Ivoire, 2006.

[6] Avenard J. M. Geomorphological Aspects of the Natural Environment of Côte d'Ivoire. Mémoire ORSTOM No. 50. Paris: ORSTOM, 1971.

[7] Nandjui, J., Kouadio, Y. R., Kouassi, K. H. Integrated Management Plan for Fauna, Flora, and Landscape of the Ono Production Site. 2007, pp. 19-40.

[8] Loroux B. F. E. Contribution to the hydrogeological study of the coastal sedimentary basin of Côte d'Ivoire. Ph.D. Thesis, University of Bordeaux I, France, 1978.

[9] Rodier, J. Water Analysis: Natural Waters, Wastewater, and Seawater. 7th ed. Paris: Dunod Technique; 1984.

[10] AFNOR. Water Quality, Vol. 1: Terminology, Sampling and Evaluation of Methods. 3rd ed. Paris: AFNOR; 1997.

[11] Rodier, J., Legube, B., Merlet, N. Water Analysis. 9th ed. Paris: Dunod; 2009; pp. 141-159.

[12] World Health Organization (WHO). Guidelines for Drinking-Water Quality. 4th ed. Geneva, 2011.

[13] Dagnelie, P. Theoretical and Applied Statistics, Vol. 2: Statistical Inference in One and Two Dimensions. Brussels: De Boeck Supérieur; 2006.

[14] Hamzaoui, A. F., Bouhlila, R., Gueddari, M. Characterization of water mineralization in the Triassic sandstone aquifer (Southeastern Tunis) by geochemical and statistical methods. Geo-Eco-Trop. 2012, 36, 49-62.

[15] Kaiser, H. F. The application of electronic computers to factor analysis. Educational and Psychological Measurement. 1960, 20(1), 141-151.

[16] Cloutier, V., Lefebvre, R., Therrien, R., Savard, M. M. Multivariate statistical analysis of geochemical data as indicative of the hydrogeochemical evolution of groundwater in a sedimentary rock aquifer system. Journal of Hydrology. 2008, 353, 294-313. https://doi.org/10.1016/j.jhydrol.2008.02.015

[17] Yapo, O. B., Mambo, V., Sanogo, T. A., Houenou, P. V. H. Analytical study of chemical characteristics of a eutrophic tropical lake: Conductivity as a trophic indicator of Buyo Lake, Côte d'Ivoire. Journal de la Société Ouest-Africaine de Chimie. 2008, 25, 87-108.

[18] Millogo, C., Bakouan, C., Sawadogo, S., Dousse, N. S. Physico-chemical contribution of surface waters and weathered rocks in the Bam Lake watershed, North-central Burkina Faso. Afrique Science. 2020, 17(5), 137-150.

[19] Tohouri, P., Adja, M. G., Ake, G. E., Soro, G., Konan, N. I., Biemi, J. Hydrochemistry of rainy season surface water in the Bonoua region, southeastern Côte d'Ivoire. Afrique Science. 2016, 12(6), 151-167.

[20] Abboudi, A., Tabyaoui, H., El-Hamichi, F. Study of physico-chemical quality and metal contamination of surface waters in the Guigou watershed, Morocco. European Scientific Journal. 2014, 10(23), 84-94.

[21] Chairi, R. Organic geochemistry of surface waters in the northern Sebkha of Moknine, eastern Tunisia. Larhyss Journal. 2005, 4, 17-30.

[22] Aboulkacem, A., Chahlaoui, A., Soulaymani, A., Rhazi-Filali, F., Benali, D. Comparative study of the bacteriological quality of Boufekrane and Ouislane rivers through the city of Meknes (Morocco). Revue de Microbiologie Industrielle et Environnementale. 2007, 1, 10-22.

[23] Ahoussi, K. E. Quantitative and qualitative assessment of water resources in southern Côte d'Ivoire: application of hydrochemistry and environmental isotopes to the study of continuous and discontinuous aquifers in the Abidjan–Agboville region. Ph.D. thesis, University of Cocody, Abidjan, Côte d'Ivoire, 2008.

[24] Talabi, A. O., Afolagboye, O. L., Tijani, M. N., Aladejana, J. A., Ogundana, A. K. Hydrogeochemical assessment of surface water in the central part of Ekiti State, southwestern Nigeria. American Journal of Water Resources. 2013, 1(4), 56–65. https://doi.org/10.12691/ajwr-1-4-1

[25] Tieligounon, A. S., Kigbafori, D. S., Zeré, M. G., Lacina, C., Gouli, G. B. Physicochemical parameters of the waters of the Haut-Bandama basin (Côte d'Ivoire). Rev. Sci. Technol., Synthèse. 2021, 27(1), 33-48.

[26] Koussao, S., Youssouf, D., Some, L., Millago, R. Agricultural water pollution in the Nakanbé Basin: The case of the Loumbila and Mogtédo reservoirs in Burkina Faso. Sud Sciences et Technologies. 2008, 16, 1-9.

[27] Ake, G. E. Impacts of climatic variability and anthropogenic pressures on water resources in the Bonoua region (Southeast Côte d'Ivoire). Ph.D. dissertation, University of Cocody, Abidjan, Côte d'Ivoire, 2010.

[28] Nisbet, M., Verneaux, J. Chemical components of running water. Discussion and proposed classification system as a basis for interpreting chemical analyses. International Journal of Limnology. 1970, 6(2), 161-190. https://doi.org/10.1051/limn/1970015

[29] Ouattara, A., Meite, A., Dally, T., Ouattara, H., Kati-C. S. Study of the quality of drinking water in the locality of N'Zianouan (Tiassalé) and precarious neighborhoods of three communes in the Abidjan District (Koumassi, Treichville, Attécoubé). Journal of Applied Biosciences. 2016, 102, 9708-9715.