

Research Article

Polymetallic Contamination Assessment of Lake San-Pedro: Characterization by ICP-MS and Heavy Metal Pollution Index (HPI)

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Abstract

Heavy metal contamination of aquatic ecosystems is a major environmental and public health issue, particularly in rapidly urbanizing regions of developing countries. This study assessed the polymetallic pollution of Lake San-Pedro (Côte d'Ivoire) during the rainy season, focusing on the spatial distribution and severity of contamination. A total of 12 surface water samples—three point samples per station—were collected from four stations selected based on their exposure to industrial, domestic, and urban discharges. Samples were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) to determine the concentrations of nine heavy metals. Key physicochemical parameters were also measured, and the Heavy Metal Pollution Index (HPI) was applied to quantify the overall contamination level. The results revealed elevated concentrations of iron (1.10-1.93 mg/L), aluminum (0.36-1.33 mg/L), and nickel (0.03-0.38 mg/L), all significantly exceeding World Health Organization (WHO) guidelines. HPI values at all stations were well above the critical threshold of 100, indicating severe heavy metal pollution. High turbidity and elevated organic loads were observed across several sites, suggesting substantial degradation of water quality. Statistical analysis (one-way ANOVA) confirmed significant spatial differences ($p < 0.05$) in the concentrations of Al, Fe, Ni, Pb, and Cr, with stations 1 and 2—located near major anthropogenic activities—showing the highest contamination levels. These findings highlight the urgent need for integrated watershed management measures, including wastewater treatment, pollution source control, and routine monitoring of water quality. This study provides key data to support the protection and sustainable use of Lake San-Pedro's aquatic resources.

Keywords

Heavy Metals, Water Pollution, ICP-MS, HPI Index, Lake San-Pedro

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1. Introduction

The pollution of aquatic ecosystems by heavy metals is among the most pressing environmental challenges of the 21st century due to the high toxicity, non-biodegradable nature, and bioaccumulative potential of these elements throughout the trophic chain [1, 2]. Even at trace levels, heavy metals can induce long-term ecotoxicological effects, threatening aquatic biodiversity, human health, and the socio-economic uses of water resources [3].

Lakes located in areas under strong anthropogenic pressure are particularly vulnerable as they serve as sinks for pollutants from industrial, domestic, and agricultural effluents or diffuse erosion processes. Lake San-Pedro, an urban water body in the Bas-Sassandra district of Côte d'Ivoire, plays a key role in supplying water for domestic, industrial, agricultural, and recreational purposes. However, uncontrolled urban expansion, lack of wastewater treatment, and failures in water management systems have led to its progressive and alarming degradation [4, 5].

Identifying and quantifying metal contaminants is therefore essential to inform protection, remediation, and governance efforts for this resource. Among reference analytical techniques, inductively coupled plasma mass spectrometry (ICP-MS) has emerged as a state-of-the-art method for ultra-trace multi-elemental detection in complex environmental matrices [6, 7]. Coupled with the Heavy Metal Pollution Index (HPI), a composite indicator based on water quality guideline thresholds, this approach allows for a comprehensive evaluation of metal pollution levels and mapping of environmental risk [8].

This study aims to assess the polymetallic contamination of Lake San-Pedro during the rainy season through ICP-MS analysis of heavy metal concentrations and calculation of the HPI. It also includes a physicochemical characterization of the water to identify potential pollution sources and understand the spatial-environmental dynamics. The results will provide scientific data to support sustainable management and restoration strategies for this fragile aquatic ecosystem.

2. Materials and Methods

2.1. Study Area

The study was conducted in San-Pedro, a major coastal city in southwestern Côte d'Ivoire (4.7485°N, 6.6363°W), with an estimated population of approximately 330,000 inhabitants (National Census, 2021). As the country's second-largest seaport, San-Pedro is undergoing rapid urbanization and hosts a variety of industrial activities, including agro-industry, oil processing, and chemical manufacturing.

Lake San-Pedro, located centrally between the S é w é k é Lac, industrial, and port districts, is a strategic freshwater resource used for domestic, agricultural, industrial, and recreational purposes. However, its ecological integrity is increasingly threatened by untreated industrial and domestic effluents, as well as uncontrolled urban runoff, placing the lake under significant anthropogenic pressure.



Figure 1. Geographical location of Lake San-Pedro.

2.2. Selection and Description of Sampling Stations

A reconnaissance mission conducted on April 22, 2024, led to the identification of four (4) stations representative of the main pollution sources:

Station 1: Located near the CODICAO industry, influenced by both industrial and domestic discharges (S'ew & é neighborhood, industrial zone, airport area).

Station 2: Close to the AWAHUS industry and healthcare facilities (Jules Ferry and S'ew & é neighborhoods).

Station 3: Downstream of the S2K industry and informal activities (Lac and Cit é neighborhoods).

Station 4: Mainly receives domestic wastewater discharges (Cit é Porto 1 neighborhoods, and port zone).

Each station includes three sampling points to ensure spatial representativeness.

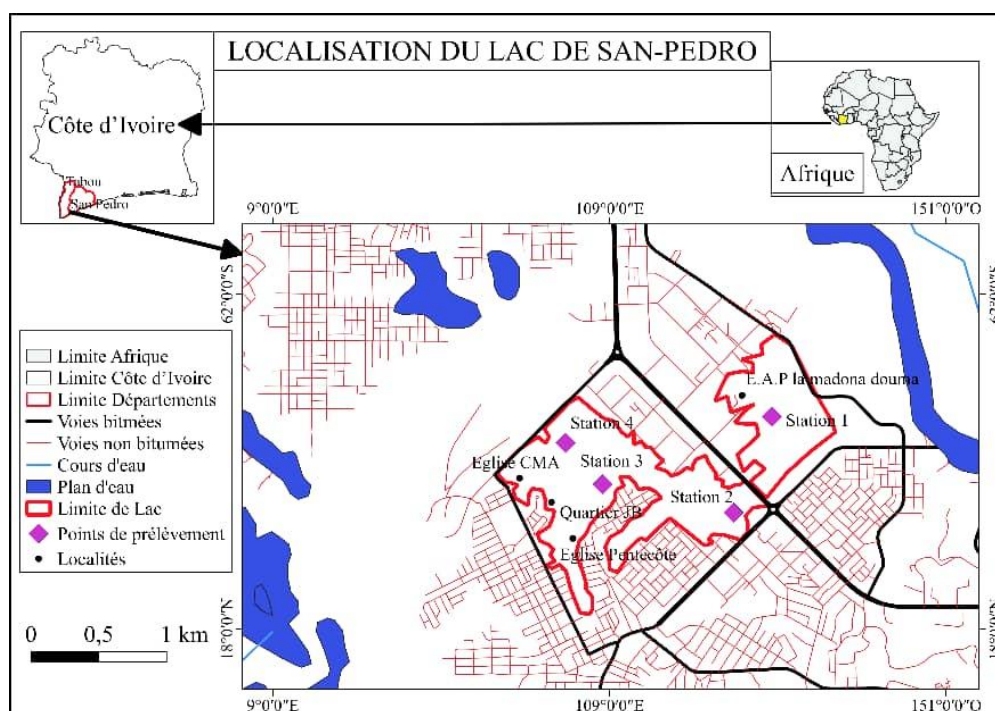


Figure 2. Sampling stations.

2.3. Water Sampling from the Lake

Sampling was conducted on May 8, 2024, during the peak of the rainy season, using a motorized canoe. Surface water was collected at a depth of 30 cm using 1-liter polyethylene bottles for physicochemical analyses and 50 mL hemolysis tubes for metal analyses. All containers were meticulously pre-treated: washed with a detergent solution, rinsed with distilled water, then decontaminated with a 10% nitric acid solution, followed by a final rinse on-site using lake water after 24 hours of rest, in accordance with AFNOR standards (2001) and Rodier's recommendations (2009) [9]. Samples were immediately stored in a cooler at 4 °C and transported the same day to the laboratory of the National Laboratory for Testing, Quality, Metrology and Analysis (LANEMA) for processing and analysis.

2.4. Analysis of Physicochemical and Organic Parameters

2.4.1. In Situ Measurements

The following parameters were measured directly on-site using a HANNA HI9829 multiparameter probe, according to standardized AFNOR methods (AFNOR, 2001): electrical conductivity, turbidity, dissolved oxygen, pH, and temperature.

2.4.2. Physicochemical and Organic Parameter Analysis

In the laboratory, additional analyses were conducted to determine the concentrations of key chemical and organic indicators, including: chlorides (Cl^-), total hardness (TH), total alkalinity (TAC), dissolved oxygen (DO), biochemical oxygen demand over 5 days (BOD_5), chemical oxygen demand (COD), phosphates (PO_4^{3-}), nitrites (NO_2^-), nitrates

(NO₃⁻), and sulfates (SO₄²⁻). All analytical procedures were carried out in accordance with AFNOR standards (2001) and the protocols described by Rodier (2009), ensuring reliability and consistency in data collection.

2.5. Heavy Metal Analysis by ICP-MS

Water samples were analyzed for heavy metal concentrations using inductively coupled plasma mass spectrometry (ICP-MS) following microwave-assisted acid digestion based on US EPA Method 3051A. Each sample was digested with a 9:1 mixture of concentrated nitric acid (HNO₃, 65%) and hydrogen peroxide (H₂O₂, 30%) to remove organic matter and ensure complete metal solubilization.

After digestion and cooling, the solutions were filtered through a 0.45 µm membrane, transferred to 10 mL volumetric flasks, and diluted to volume with ultrapure deionized water (resistivity 18.2 MΩ cm). Prior to analysis, water samples were further filtered (0.45 µm) and diluted at a ratio of 1 mL sample to 9 mL of 1% nitric acid to stabilize dissolved metals and prevent precipitation or adsorption.

Analyses were performed at the National Laboratory for Quality Testing, Metrology and Analyses (LANEMA) using an Agilent 7850 ICP-MS equipped with a quadrupole mass analyzer and helium collision cell to reduce polyatomic interferences. Ultra-high purity argon gas (99.999%) served as the plasma source. Rhodium (Rh) at 10 µg/L was used as an internal standard to correct for instrumental drift and matrix effects.

Target elements included aluminum (Al), chromium (Cr), iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), and mercury (Hg). Limits of detection ranged from 0.001 to 0.005 mg/L depending on the element. Data acquisition and processing were conducted using Agilent MassHunter software, with results expressed in micrograms per liter (µg/L) and interpreted according to World Health Organization (WHO, 2018) drinking water quality standards.

2.6. Evaluation of Metal Pollution

The Heavy Metal Pollution Index (HPI) was used to evaluate the overall level of contamination (degree of pollution). This index is a weighted measure based on the observed concentration (Vi) in relation to the WHO guideline value (Si), and is calculated using the following equations:

$$HPI = \frac{\sum_{i=1}^n Q_i \cdot W_i}{\sum_{i=1}^n W_i} \quad (1)$$

$$Q_i = \left(\frac{V_i}{S_i} \right) * 100 \quad (2)$$

$$W_i = \frac{k}{S_i} \quad (3)$$

Where k = 1

Where Vi is the measured concentration of the i-th metal (µg/L), Si is the WHO standard for the i-th metal, Qi is the sub-index of metal i, Wi is the unit weight, inversely proportional to the standard (i.e., metals with stricter standards have higher weights), and n is the number of metals analyzed.

The level of metal contamination in water is categorized into three pollution classes based on the HPI value:

HPI < 100: Low pollution

HPI = 100: Critical threshold

HPI > 100: High pollution

2.7. Data Processing

Raw data were entered and processed using Microsoft Excel. Means, standard deviations, and charts were used to provide a preliminary statistical interpretation of the results. In addition, a one-way analysis of variance (ANOVA) was applied to determine whether the variations in heavy metal concentrations between sampling stations were statistically significant (significance level set at $p < 0.05$). The test was performed using the XLSTAT software.

3. Results and Discussion

3.1. Physicochemical Characteristics of Lake San-Pedro Water

3.1.1. Physical Parameters of Water Quality

Table 1 presents the measured values of key physical parameters (temperature, pH, turbidity, and electrical conductivity) of lake San-Pedro's waters during the rainy season.

Table 1. Physical parameters of Lake San-Pedro water during the rainy season.

Station	Temperature (°C)	pH	EC (µS/cm)	Turbidity (NTU)
Station 1	30,55	7,11	1192,00	44,03
Station 2	30,87	8,05	1257,00	95,60
Station 3	30,87	7,18	915,00	118,67

Station	Temperature (°C)	pH	EC (µS/cm)	Turbidity (NTU)
Station 4	31,33	7,04	995,00	19,64
Minimum	30,55	7,04	915,00	19,64
Maximum	31,33	8,05	1257,00	118,67
Mean	30,91	7,35	1089,75	69,49
Standard Deviation	0,32	0,47	161,19	45,58
WHO Limits	20-25	6,5-8,5	< 500	< 5

EC: Electrical Conductivity; NTU: Nephelometric Turbidity Units

The recorded temperatures ranged from 30.55 °C to 31.33 °C, with an average of 30.91 ± 0.32 °C. These values far exceed the WHO recommended range (20-25 °C), reflecting the climatic influence of the rainy season and suggesting weak thermal stratification. Such elevated temperatures may enhance biochemical reactions and reduce dissolved oxygen availability, thereby affecting aquatic life [10, 11].

pH values ranged from 7.04 to 8.05, with a mean of 7.35 ± 0.47 . This range reflects slightly basic conditions, within WHO guidelines (6.5-8.5) [12]. However, the higher values, particularly near industrial zones (e.g., Station 2), may result from photosynthetic activity, alkaline industrial effluents, or agricultural inputs [13, 14].

Turbidity showed substantial variation, ranging from 19.64 to 118.67 NTU, with an average of 69.49 ± 45.58 NTU. All stations recorded values well above the WHO threshold of <5 NTU. High turbidity, especially at Station 3, indicates significant suspended solids, potentially due to runoff, erosion, or domestic and industrial waste discharge [9, 15].

Electrical conductivity (EC) ranged between 915 and 1257 µS/cm, with a mean value of 1089.75 ± 161.19 µS/cm. These elevated levels, more than double the WHO limit (<500 µS/cm), suggest high mineral content and dissolved ionic species. This mineralization likely originates from domestic, industrial, or agricultural sources [16], impairing the water's suitability for drinking and irrigation purposes [17].

Collectively, these physicochemical parameters reflect a significant degradation of Lake San-Pedro's water quality,

mainly driven by anthropogenic pressures. Notably, Stations 1 and 2 exhibited the highest temperatures, sometimes exceeding 40 °C—above the Ivorian regulatory threshold for wastewater discharge [18]. This thermal pollution likely results from industrial effluent discharge and local climate effects [12, 19].

A comparative analysis of the sampling stations enables a clear ranking of physicochemical pollution across Lake San-Pedro: Station 4 < Station 3 < Station 1 < Station 2. Station 4, situated upstream, exhibits the lowest contamination levels and thus serves as a relative reference point for baseline water quality. In contrast, Station 2, located downstream and directly exposed to industrial and urban effluents, emerges as the most degraded site. Station 1, affected by agri-food discharges, and Station 3, influenced by agricultural runoff, fall in between. This spatial gradient underscores a progressive accumulation of pollutants along the lake's hydrological axis, illustrating how anthropogenic pressures intensify from upstream to downstream. Such a pattern reflects the cumulative impact of land use, industrial activity, and wastewater inputs on the aquatic ecosystem's health.

3.1.2. Chemical and Organic Parameters

Table 2 presents the chemical parameters measured in the waters of Lake San-Pedro during the rainy season in May 2024.

Table 2. Chemical parameters of Lake San-Pedro water during the rainy season.

Stations	Cl ⁻	TH	TAC	DO	SO ₄ ²⁻	NO ₃ ⁻	NO ₂ ⁻	COD	BOD ₅	PO ₄ ³⁻
Station 1	261,33	17,09	19,42	6,83	5,33	19,46	0,07	125,33	13,33	1,62
Station 2	287,41	17,43	23,11	7,03	7,20	22,85	0,10	144,00	21,67	1,24
Station 3	198,61	16,21	13,71	7,01	8,97	29,24	0,08	116,67	28,33	1,27
Station 4	149,04	24,26	23,07	7,48	0,98	20,17	0,02	22,67	2,50	1,14
Minimum	149,04	16,21	13,71	6,83	0,98	19,46	0,02	22,67	2,50	1,14

Stations	Cl ⁻	TH	TAC	DO	SO ₄ ²⁻	NO ₃ ⁻	NO ₂ ⁻	COD	BOD ₅	PO ₄ ³⁻
Maximum	287,41	24,26	23,11	7,48	8,97	29,24	0,10	144,00	28,33	1,62
Mean	224,10	18,75	19,83	7,09	5,62	22,93	0,07	102,17	16,46	1,32
Standard deviation	62,39	3,71	4,43	0,28	3,43	4,45	0,03	54,21	11,15	0,21
Normes	< 250	-	1,6-16,4	> 7	<500	< 50	<0,2	-	-	<0,05

Cl⁻: Chlorides; TH: Total Hardness; TAC: Total Alkalinity Capacity; DO: Dissolved Oxygen; COD: Chemical Oxygen Demand; BOD₅: Biochemical Oxygen Demand over 5 Day

The physicochemical assessment of Lake San-Pedro revealed a heterogeneous pattern of chemical and organic contamination, primarily driven by anthropogenic pressures. Chloride concentrations ranged from 149.04 to 287.41 mg/L, with an average of 224.10 ± 62.39 mg/L. While this mean value slightly exceeds the WHO guideline (<250 mg/L), the notably elevated level at Station 2 points to potential saline intrusion or substantial domestic and industrial discharges [12].

Total hardness (TH) varied between 16.21 and 24.26 °F (mean: 18.75 ± 3.71 °F), classifying the water as very hard (>14.8 °F). This suggests elevated levels of divalent cations—mainly calcium (Ca²⁺) and magnesium (Mg²⁺)—particularly at Stations 2 and 4, possibly stemming from geological weathering or industrial effluents [12].

Similarly, total alkalinity (TAC) values ranged from 13.71 to 23.11 °F (mean: 19.83 ± 4.43 °F), reflecting a buffered system that resists sudden pH fluctuations, with the most pronounced buffering capacity at Stations 1, 2, and 4. This buffer effect is likely due to high concentrations of bicarbonates and carbonates, often resulting from agricultural runoff or treated effluents [12].

Dissolved oxygen (DO) levels ranged from 6.83 to 7.48 mg/L (mean: 7.09 ± 0.28 mg/L), indicating favorable conditions for aquatic life. These levels exceed the minimum ecological threshold for most freshwater species (5 mg/L) [20], although they may mask underlying organic stress if oxygen is continuously replenished by photosynthetic activity or surface aeration.

Sulfate (SO₄²⁻) concentrations remained low (0.98 to 8.97 mg/L), well below the WHO guideline (<500 mg/L), indicating no major sulfur contamination and suggesting limited input from industrial sulfur sources or mining activities [12].

In contrast, nitrate (NO₃⁻) concentrations ranged from 19.46 to 29.24 mg/L (mean: 22.93 ± 4.45 mg/L), remaining below the WHO limit (<50 mg/L) but still reflective of significant nutrient input, likely due to agricultural runoff, leaching from fertilizers, or domestic wastewater [21]. Nitrite (NO₂⁻) concentrations (0.02 to 0.10 mg/L) remained well within the WHO safe limit (<0.2 mg/L), suggesting effective nitrification and low microbial contamination at the time of

sampling [12].

Phosphate (PO₄³⁻) levels were markedly high across all sites (1.14 to 1.62 mg/L; mean: 1.32 ± 0.21 mg/L), dramatically exceeding the WHO guideline of 0.05 mg/L. These elevated concentrations indicate a strong eutrophication risk driven by detergents, fertilizers, and sewage discharge [22, 23]. Sustained phosphate enrichment may result in algal blooms, followed by oxygen depletion during organic matter decay.

The Chemical Oxygen Demand (COD) showed a wide range from 22.67 to 144.00 mgO₂/L (mean: 102.17 ± 54.21 mg/L). Stations 1 to 3 displayed very high COD values, reflecting the presence of organic pollutants from industrial discharges, including oils, fats, phenols, surfactants, and solvents [16, 24]. According to international standards, including the World Bank guideline (COD <150 mgO₂/L for industrial discharges into surface waters), ISO 6060 (125 mgO₂/L as a threshold for significant organic pollution), and the French Arrêt éminist ériel of 2 February 1998 (125 mgO₂/L for effluent discharges), values observed—especially at Station 2—either approach or exceed these environmental norms [22, 23]. These high COD levels likely indicate persistent organic pollutants not easily biodegradable, signaling insufficient wastewater treatment or overloaded systems [25].

Such elevated COD promotes oxygen depletion, reduces the self-purification capacity of aquatic ecosystems, and may trigger hypoxic or anoxic conditions. These conditions undermine biodiversity and disrupt ecosystem stability while encouraging the growth of anaerobic and potentially pathogenic microorganisms [26, 27].

The Biochemical Oxygen Demand over five days (BOD₅) followed a similar trend, ranging from 2.50 to 28.33 mg/L (mean: 16.46 ± 11.15 mg/L). The high BOD₅ at Stations 1-3 indicates substantial biodegradable organic matter, often linked to untreated sewage, slaughterhouse runoff, or food industry waste [28]. In contrast, Station 4, with a BOD₅ of 2.50 mg/L, appears relatively preserved. According to WHO and EU benchmarks, BOD₅ values above 6 mg/L are indicative of strong organic pollution, which aligns well with the COD findings and confirms anthropogenic pressures on the lake.

Turbidity values exceeding 100 NTU at Stations 2 and 3

reinforce the evidence of suspended solids, which may transport both pathogens and heavy metals [29]. High turbidity also reduces light penetration, disrupting photosynthetic processes and exacerbating oxygen imbalances in the water column [30].

Synthesizing all these parameters reveals a spatial gradient of contamination, with a ranking based on both organic and chemical pollution as follows: Station 2 > Station 1 > Station 3 > Station 4.

Station 2 is the most heavily impacted, receiving untreated industrial and urban effluents. Station 1 is affected by agri-food discharges and high COD/BOD₅ levels. Station 3 suffers from agricultural runoff and nutrient inputs. Station 4, while less polluted, still experiences diffuse contamination from surface runoff and atmospheric deposition.

This downstream accumulation of contaminants aligns with intensified human activities and increased wastewater discharge. Notably, even upstream zones are not exempt from environmental stressors, emphasizing the need for comprehensive watershed management.

3.2. Metal Pollution in the Waters of Lake San Pedro

The analysis of nine heavy metals (Al, Cr, Fe, Ni, Cu, Zn, Cd, Pb, Hg) in Lake San-Pedro reveals a complex pattern of polymetallic contamination, with several elements exceeding WHO (2018) drinking water standards, notably aluminum, iron, and nickel (Table 3, Figure 3).

Table 3. Heavy metal concentrations in Lake San-Pedro waters.

Stations	Al	Cr	Fe	Ni	Cu	Zn	Cd	Pb	Hg
Station 1	0,767	0,034	1,312	0,127	0,026	0,111	0,001	0,010	0,000
Station 2	0,548	0,034	1,103	0,381	0,022	0,122	0,001	0,010	0,000
Station 3	1,328	0,008	1,823	0,030	0,020	0,107	0,001	0,010	0,000
Station 4	0,359	0,008	1,934	0,054	0,019	0,129	0,001	0,008	0,000
Minimum	0,359	0,008	1,103	0,030	0,019	0,107	0,001	0,008	0,000
Maximum	1,328	0,034	1,934	0,381	0,026	0,129	0,001	0,010	0,000
Mean	0,751	0,021	1,543	0,148	0,022	0,117	0,001	0,010	0,000
Standard deviation	0,419	0,015	0,399	0,161	0,003	0,010	0,000	0,001	0,000
Normes	0,200	0,050	0,300	0,020	2,000	3,000	0,003	0,010	0,006

All metal concentrations are expressed in mg/L.

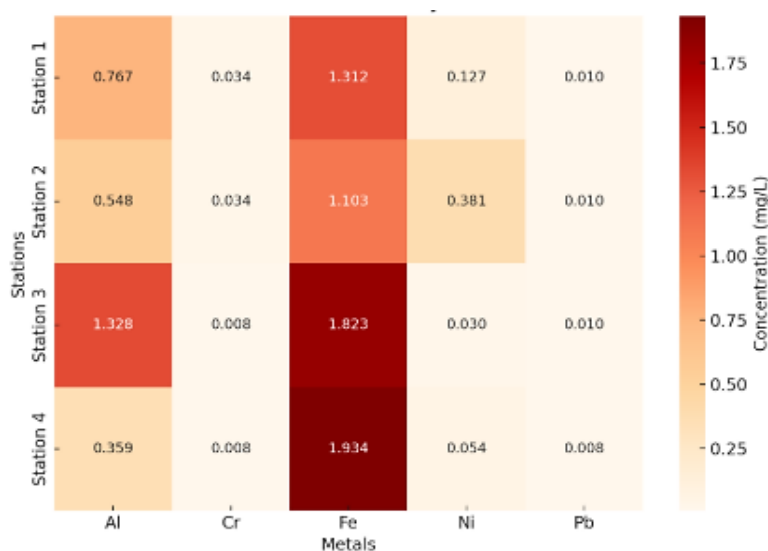


Figure 3. Spatial variation in heavy metal concentrations across the sampling stations in Lake San-Pedro.

Aluminum (Al) concentrations ranged from 0.359 to 1.328 mg/L (mean: 0.751 ± 0.419 mg/L), nearly four times above the recommended limit of 0.2 mg/L, with the highest value observed at Station 3, likely linked to industrial coagulant discharge or increased soil erosion within the watershed. Similarly, iron (Fe) levels, ranging from 1.103 to 1.934 mg/L (mean: 1.543 ± 0.399 mg/L), significantly exceeded the 0.3 mg/L threshold at all stations, indicating widespread ferric pollution due to domestic wastewater discharge, leaching of lateritic soils, or corrosion from anthropogenic metal infrastructure.

Nickel (Ni) presents a particularly concerning case: with a mean concentration of 0.148 mg/L and a peak of 0.381 mg/L at Station 2, it exceeds the guideline value (0.02 mg/L) nearly twentyfold. This likely reflects inputs from electronic waste leaching, electroplating activities, and the petroleum industry [25]. Although lead (Pb) levels were close to the WHO limit of 0.01 mg/L, they remain ecotoxicologically significant due to Pb's high bioaccumulation potential. Cadmium (Cd) was consistently detected at 0.001 mg/L—below the 0.003 mg/L threshold—while mercury (Hg) remained below detection limits, though its extreme toxicity, even at trace levels, makes it a critical contaminant [26].

The simultaneous presence of these metals, sometimes at sub-lethal concentrations, raises concern due to their chronic toxicity, environmental persistence, and strong tendency to bioaccumulate. Cadmium is known for its nephrotoxicity and carcinogenicity; it accumulates mainly in the liver and kidneys, with a biological half-life exceeding 10 years, leading to kidney damage, osteomalacia, and hypertension with long-term exposure [27].

Lead, a powerful neurotoxin, is especially dangerous for children, impairing cognitive function and neurological development. It is also associated with hematological, cardiovascular, and reproductive disorders [28, 31]. Mercury, especially in its organic form methylmercury, can cross the blood-brain barrier and the placenta, causing sensory and motor impairments, immune suppression, and neurodevelopmental disorders [32].

In aquatic fauna, Cd, Pb, and Hg accumulate in the gills, liver, and muscles of fish, causing oxidative stress, enzyme inhibition, and histopathological lesions [33]. Mercury impairs fish behavior, reduces fertility, and causes DNA damage [34], while lead interferes with calcium metabolism, negatively affecting bone development and survival [35].

In aquatic plants, heavy metals disrupt photosynthesis, reduce chlorophyll content, and impair nutrient uptake. Cd and Hg, in particular, inhibit root elongation and cell division, thereby limiting primary productivity [36]. Although cyanobacteria are relatively metal-tolerant, exposure to Cd and Pb reduces nitrogen fixation and pigment synthesis, compromising their ecological role in oxygen production and nitrogen cycling [37].

Additionally, chronic metal exposure alters microbial

communities, favoring metal-resistant—yet often pathogenic—bacteria, which reduces ecological resilience and natural self-purification capacities [38]. These structural disruptions negatively affect food webs, reduce biodiversity, and undermine critical ecosystem services such as water purification, nutrient cycling, and fishery productivity [39]. Over the long term, metals accumulated in sediments can be remobilized under anoxic or low-pH conditions, creating persistent pollution loops [40].

Spatially, Station 2 emerged as the most contaminated, showing the highest concentrations of Al, Fe, Ni, Cu, and Cd—likely due to direct industrial discharges or illegal dumping. Station 1, though slightly less affected, displayed elevated Pb and Cu levels, indicative of urban runoff and infrastructure degradation. Station 3 showed moderate pollution, particularly in Cr and Zn, suggesting diffuse sources such as atmospheric deposition or agricultural inputs. Finally, Station 4, although the least impacted, revealed trace levels of Hg and Cd, indicating background contamination that warrants continuous monitoring.

Thus, even when concentrations remain below regulatory limits, the ecotoxicological risks associated with Cd, Pb, and Ni are significant due to their persistence, bioaccumulative nature, and potential for synergistic toxicity. Combined exposure to these metals can amplify their harmful effects on aquatic organisms and human health [41]. It is therefore essential to adopt a precautionary approach by incorporating not only regulatory thresholds but also toxicological indicators—such as the Hazard Quotient (HQ), Hazard Index (HI), and biomarkers in local species—to more accurately assess chronic exposure and overall ecosystem health.

3.3. Chemical Water Quality: Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) is a synthetic tool used to assess the overall impact of heavy metals in aquatic ecosystems. It combines the concentrations of various metals, weighted according to their importance to health and the environment, to produce a single value that facilitates the interpretation of complex water quality data. In the literature, HPI has proven essential for environmental monitoring, offering a simplified yet comprehensive assessment of heavy metal contamination, particularly in surface waters [25, 26]

Table 4. HPI values and risk interpretation.

Station	HPI	Pollution risk
Station 1	77 138,1	High pollution
Station 2	180 642,9	High pollution
Station 3	45 210,9	High pollution

Station	HPI	Pollution risk
Station 4	49 483,5	High pollution
Mean	88 118,8	High heavy metal pollution

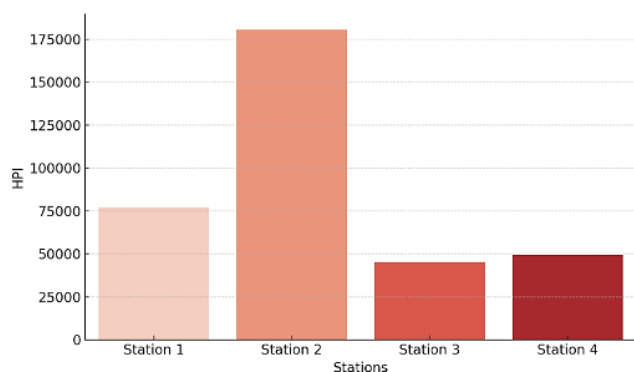


Figure 4. Variation of the Heavy Metal Pollution Index (HPI) across Lake San-Pedro sampling stations.

In this study, HPI values were calculated for four sampling stations within Lake San-Pedro, Côte d'Ivoire. As detailed in Table 4 and illustrated in Figure 4, all stations exhibited HPI values that exceeded the critical threshold of 100, indicating a high degree of contamination. The classification typically used defines $HPI < 100$ as low pollution, $HPI = 100$ as the critical limit, and $HPI > 100$ as indicative of high pollution risk [29]. These results highlight an alarming level of heavy metal pollution throughout the lake, which is consistent with the concentrations measured for individual metals.

Among the sampling sites, Station 2 recorded the highest HPI value, which aligns with its elevated concentrations of aluminum (Al), iron (Fe), nickel (Ni), copper (Cu), and cadmium (Cd). This station, therefore, represents a significant contamination hotspot. Station 1 was also highly polluted, with critical levels of lead (Pb), copper, and zinc (Zn), suggesting localized sources of contamination. Station 3, while less polluted than Stations 1 and 2, still showed intermediate HPI values likely resulting from diffuse inputs such as runoff. Even Station 4, located in an upstream position, surpassed the critical threshold, which may point to persistent background contamination or upstream anthropogenic influences.

The relevance of HPI extends beyond pollution classification; it also serves as a vital indicator of water's suitability for human consumption. According to World Health Organization (WHO) guidelines, heavy metals such as

Pb ($> 10 \mu\text{g/L}$), Cd ($> 3 \mu\text{g/L}$), and Ni ($> 70 \mu\text{g/L}$) are toxic even at low concentrations [12]. When HPI exceeds 100, water is generally considered unfit for potable use without advanced treatment. Therefore, the high HPI values obtained from Lake San-Pedro suggest that the water, in its untreated state, poses substantial risks to public health and cannot be considered safe for drinking purposes [28].

Several studies worldwide have confirmed the usefulness of the HPI in assessing water quality, showing that sites with HPI values above 100 are unsuitable for drinking and irrigation [31, 32]. This confirms the applicability of HPI across various hydrological and industrial contexts. The consistently elevated HPI values observed in Lake San-Pedro underline severe ecological stress and the urgent need for targeted environmental management interventions. Potential sources of the contamination likely include a combination of point sources—such as industrial effluents, artisanal and small-scale mining activities, and domestic wastewater discharges—and non-point sources, notably agricultural runoff and urban stormwater [27]. Over time, chronic exposure to metals like Cd, Pb, and Ni leads to bioaccumulation in aquatic organisms, disturbs trophic interactions, and threatens biodiversity, ultimately compromising aquatic ecosystem health and food safety [33].

In conclusion, the application of the Heavy Metal Pollution Index in this study provides a clear, quantitative perspective on the extent of contamination in Lake San-Pedro. The findings emphasize the value of integrating HPI into national water quality monitoring frameworks as part of a proactive approach to pollution management. This integration would not only enhance early warning capabilities but also support evidence-based policy decisions aimed at protecting both environmental integrity and public health.

3.4. Anova Test Results Statistical Analysis of Metal Contamination and Spatial Variability

The application of one-way analysis of variance (ANOVA) to the concentrations of heavy metals across the four sampling stations of Lake San-Pedro offers critical insights into the spatial distribution and variability of metal pollution within the aquatic system. Statistically significant differences ($p < 0.05$) were observed for aluminum (Al), iron (Fe), nickel (Ni), lead (Pb), and chromium (Cr), indicating substantial spatial heterogeneity (Table 5). In contrast, copper (Cu), zinc (Zn), cadmium (Cd), and mercury (Hg) did not exhibit significant spatial variation, suggesting a more uniform distribution across the lake.

Table 5. One-way ANOVA test for heavy metal concentrations across sampling stations in Lake San-Pedro.

Metal	F-value	p-value	Significant difference ($p < 0.05$)
Aluminium (Al)	9.24	0.0031	Yes
Iron (Fe)	7.88	0.0049	Yes
Nickel (Ni)	12.65	0.0014	Yes
Chromium (Cr)	6.57	0.0093	Yes
Copper (Cu)	2.13	0.1398	No
Zinc (Zn)	1.74	0.2021	No
Lead (Pb)	5.17	0.0215	Yes
Cadmium (Cd)	1.12	0.3622	No (constant values)
Mercury (Hg)	-	ND	No (not detected)

The significant spatial differences in Al, Fe, Ni, Pb, and Cr concentrations point toward the influence of localized anthropogenic sources. These may include industrial effluents, untreated urban runoff, shipping and port-related activities, and possibly leachates from waste disposal sites, all of which tend to discharge high concentrations of pollutants at specific points [36, 37]. The particularly high metal levels recorded at Stations 1 and 2 support this interpretation, identifying these areas as potential pollution hotspots and priorities for environmental monitoring and remediation. This observation is consistent with findings in the literature, which report that freshwater systems located near industrial or urban areas often exhibit sharp spatial gradients in heavy metal concentrations due to point-source discharges [38].

In contrast, the absence of statistically significant spatial variability for Cu, Zn, Cd, and Hg implies either a uniform dispersal of these metals or concentrations too low to differentiate across sites. This could be attributed to diffuse pollution sources such as atmospheric deposition, low-intensity agricultural runoff, or natural background levels, which tend to affect the lake more homogeneously [39]. For instance, cadmium, often associated with phosphate fertilizers and long-range atmospheric transport, may persist at consistently low concentrations due to legacy pollution rather than active discharge [40]. The non-detection of mercury in all water samples suggests either its absence in the catchment or effective dilution and dispersion, though this does not preclude future risk. Given mercury's extreme toxicity, persistence, and bioaccumulative nature, ongoing surveillance remains essential, especially in sediment and biota matrices [41].

Employing ANOVA in this context proves instrumental in identifying metals with spatially heterogeneous distributions—those most likely tied to human activity and requiring targeted mitigation. These results support a spatially nuanced approach to pollution management, enabling

environmental authorities to focus monitoring and remediation resources on critical zones of ecological risk [42]. Furthermore, the spatial resolution provided by ANOVA can inform risk assessments, pollution source tracking, and the implementation of buffer zones or waste management interventions.

However, water-based analyses alone may not fully capture the extent and dynamics of contamination. Sediments in particular act as both sinks and secondary sources for heavy metals, influencing water quality over time through resuspension and diffusion processes [43]. Therefore, integrated monitoring—including sediments and aquatic organisms—is essential for a comprehensive understanding of the fate, transport, and bioavailability of these metals. For example, studies have shown that Ni and Pb exhibit high bioaccumulation potential in aquatic fauna, making biota analysis an indispensable tool in ecological risk evaluation [44].

In summary, the ANOVA findings underscore the complex and metal-specific spatial variability of contamination in Lake San-Pedro. While some metals show pronounced localized enrichment—reflecting anthropogenic point sources—others appear more uniformly distributed, likely due to diffuse background inputs. This distinction is pivotal for effective, evidence-based management strategies aimed at protecting lake ecosystems, prioritizing intervention zones, and promoting the sustainable use of aquatic resources.

4. Conclusion

This study evaluated heavy metal pollution in Lake San-Pedro (Côte d'Ivoire) during the rainy season using inductively coupled plasma mass spectrometry (ICP-MS) and the Heavy Metal Pollution Index (HPI). The results revealed significant contamination by heavy metals, particularly iron (Fe), aluminum (Al), nickel (Ni), and lead (Pb), with mean

concentrations reaching 1.54 mg/L for Fe (exceeding the WHO guideline of 0.3 mg/L by over fivefold), 0.75 mg/L for Al (WHO limit: 0.2 mg/L), 0.15 mg/L for Ni (WHO limit: 0.02 mg/L), and 0.01 mg/L for Pb (at the WHO limit of 0.01 mg/L). Other metals such as cadmium (Cd), copper (Cu), and zinc (Zn) were detected at lower concentrations, generally below WHO thresholds, while mercury (Hg) was undetectable.

Physicochemical parameters confirmed a marked deterioration of water quality, with high turbidity (>100 NTU at some stations), elevated mineralization (chlorides averaging 224 mg/L), and substantial organic pollution indicated by Chemical Oxygen Demand (COD) values averaging 102 mgO₂/L, far exceeding environmental standards. The Heavy Metal Pollution Index (HPI) corroborated the severity of metallic contamination, with all stations presenting values above the critical threshold of 100 — notably Station 2, with an HPI exceeding 180, identifying it as a pollution hotspot.

Statistical analysis via ANOVA revealed significant spatial variability for Al, Fe, Ni, Pb, and chromium (Cr), confirming heterogeneous distribution likely driven by localized sources such as untreated industrial effluents and urban runoff, particularly at Stations 1 and 2. In contrast, metals such as Cu, Zn, Cd, and Hg exhibited no significant spatial differences, suggesting more diffuse sources or background contamination.

This chronic polymetallic pollution, driven by anthropogenic activities including industrial discharge, domestic wastewater, and agricultural runoff, poses severe risks to aquatic biodiversity, ecosystem functioning, and human health. The bioaccumulation potential of metals like Ni, Pb, and Cd raises concerns for fish and other aquatic organisms, and through the food chain, for local populations relying on the lake for drinking water, fishing, and irrigation.

These findings highlight the urgent need for integrated lake management strategies incorporating industrial effluent treatment, creation of protective buffer zones, and enhanced environmental monitoring with regular sampling of water, sediments, and biota. Additionally, ecotoxicological assessments focusing on bioaccumulation and biomagnification are essential to better evaluate the long-term ecological and health risks posed by metal contaminants in Lake San-Pedro.

Abbreviations

ANOVA	A One-way Analysis of Variance
HPI	Heavy Metal Pollution Index
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
WHO	World Health Organization

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Conflicts of Interest

The authors declare no conflicts of interest.

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