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Spatio-Seasonal Evaluation of Heavy Metal Pollution, Water Quality, and Ecological Risk in Lake Chad Ecosystem

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Abstract: *This study presents a spatio-seasonal assessment of heavy metal pollution, water quality, and ecological risk in the Nigerian sector of Lake Chad, focusing on five strategic locations (LC1–LC5) sampled during dry (January–February) and wet (July–August) seasons. Physico-chemical parameters (pH, EC, TDS, DO) and concentrations of heavy metals (Pb, Cd, Cr, Zn, Cu) were evaluated. The results showed that pH values ranged from 6.8 to 8.1, while EC and TDS were elevated during the dry season, indicating concentration due to evaporation. Peak concentrations of Pb (0.15 mg/L) and Cd (0.013 mg/L) were observed at LC3 and LC5 in the dry season, exceeding WHO limits of 0.01 mg/L and 0.003 mg/L, respectively. Pollution indices revealed Igeo values for Pb and Cd ranging from 0.6 to 1.8, indicating moderate to strong pollution. CF values for Cd exceeded 3 at LC5, classifying it as considerably contaminated. PLI ranged from 1.3 to 2.1, confirming pollution across all sites, while RI values indicated considerable ecological risk at LC3 and LC5 (up to 297.9). Pearson correlation (r = 0.88 between Pb and Cd) and PCA implicated anthropogenic sources such as agricultural runoff and industrial discharges. These findings highlight the urgent need for pollution control strategies and sustainable water resource management in the Lake Chad Basin.*

Keywords: *Heavy metals, Ecological risk, Lake Chad, Water quality, Seasonal variation*

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1.0 Introduction

Lake Chad, a shallow, endorheic lake located in the Sahelian zone of west-central Africa, is a crucial freshwater resource supporting over 30 million people across Nigeria, Chad, Cameroon, and Niger. It plays a vital role in regional food security, water supply, agriculture, and fisheries. However, over the past five decades, Lake Chad has undergone significant shrinkage due to climate variability, unsustainable water abstraction, and increased anthropogenic activities, leading to escalating environmental stress on its ecosystem.

One major concern associated with this environmental degradation is the accumulation of **heavy metals** in the lake's water and sediment. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), and copper (Cu) are non-biodegradable and can persist in aquatic systems, posing toxic threats to both aquatic life and humans. Several studies across Africa have documented heavy metal pollution in aquatic environments. For instance, Iwegbue et al. (2023) reported elevated levels of Pb and Cd in the Niger Delta creeks, while Duncan et al. (2018) found significant seasonal variations of Cr and Zn in Ghana's Volta Lake. However, despite the regional and global relevance of Lake Chad, comprehensive studies on the spatial and seasonal distribution of heavy metals and their ecological risks within the lake remain scarce and fragmented.

Most existing investigations around Lake Chad focus on water scarcity, hydrological changes, or biodiversity loss, with limited emphasis on water quality assessments that incorporate pollution indices and ecological risk modeling. Furthermore, little attention has been given to the seasonal dynamics of metal accumulation**,** especially in areas of the lake affected by agricultural runoff, domestic effluent, and potential petroleum contamination.

This study addresses this knowledge gap by conducting a spatio-seasonal evaluation of heavy metal concentrations in the surface water and sediments of Lake Chad. The specific objectives are to:

1. Determine the concentrations of selected heavy metals (Pb, Cd, Cr, Zn, and Cu) in both dry and wet seasons;
2. Assess the water quality using physico-chemical parameters;
3. Evaluate pollution levels using standard indices such as the Geo-accumulation Index (Igeo), Contamination Factor (CF), and Pollution Load Index (PLI); and
4. Estimate the ecological risk of metal pollution through the Ecological Risk Index (RI) and multivariate analysis.

The significance of this study lies in its contribution to the environmental monitoring of Lake Chad by generating baseline data essential for environmental management and policy formulation. The outcomes will help local and regional stakeholders understand pollution hotspots, seasonal vulnerabilities, and prioritize actions to mitigate the ecological risks posed by heavy metals in one of Africa's most endangered freshwater ecosystems.

2.0 Materials and Methods

2.1. Study Area

Lake Chad is a shallow, endorheic, transboundary freshwater lake located in the Sahel region of west-central Africa. It spans four countries: Nigeria, Chad, Cameroon, and Niger. The lake has experienced significant shrinkage in recent decades due to climate change and increasing water abstraction for agriculture and domestic use. The Nigerian sector of the lake, which forms the focus of this study, is located in Borno State, northeast Nigeria, and is bordered by numerous settlements engaged in fishing, irrigation farming, and livestock grazing (Chikuruwo, 2023).

Five sampling locations (coded LC1 to LC5) were strategically selected across the Nigerian portion of the lake as shown in Fig.1. These sites were chosen to reflect varying degrees of anthropogenic influence, including agricultural runoff (LC2 and LC3), proximity to fishing settlements (LC4), domestic waste discharge (LC1), and relatively undisturbed areas serving as controls (LC5). The sampling design allowed for spatial coverage that accounts for environmental gradients and human impact zones within the lake.

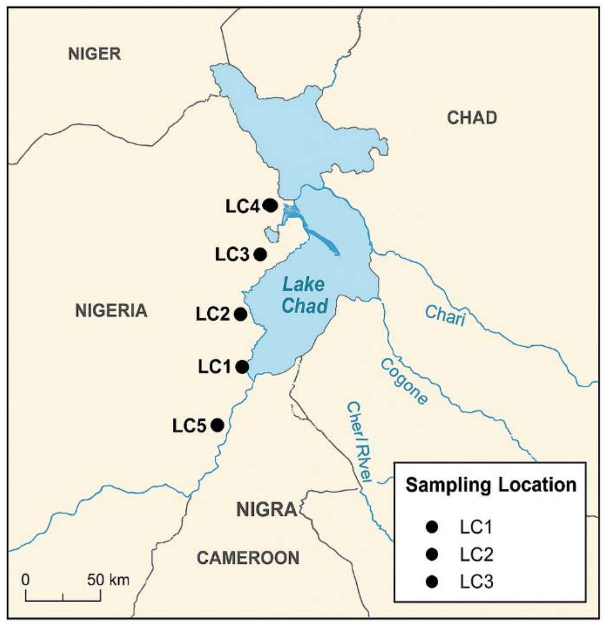

Fig.1:Map of the study area showing the sampling locations

2.2. Sample Collection

Water and sediment samples were collected in two distinct hydrological seasons: the dry season (January–February) and the wet season (July–August) of 2024. At each site, three replicate water samples were collected 30 cm below the surface using pre-cleaned, acid-washed polyethylene bottles to minimize contamination. The bottles were immediately labeled, preserved with nitric acid (to pH <2), and stored in an ice chest at 4 °C before transportation to the laboratory for analysis. Sediment samples were collected using an Ekman grab sampler. The upper 5 cm of the sediment was carefully scraped into acid-washed plastic containers, air-dried, homogenized, and sieved through a 2 mm mesh before storage in desiccators pending analysis.

Field measurements of in situ physico-chemical parameters including pH**,** electrical conductivity (EC)**,** total dissolved solids (TDS)**,** and dissolved oxygen (DO) were conducted using calibrated multi-parameter probes (HANNA HI98194). Global Positioning System (GPS) coordinates were recorded for each sampling site.

2.3. Analytical Methods

2.3.1. Heavy Metal Analysis

Samples were digested following APHA standard method 3030E (APHA, 2017). For water samples, 100 mL was digested with concentrated nitric acid and perchloric acid on a hot plate until the volume reduced to 25 mL. For sediments, 1 g of dried sample was digested using a tri-acid mixture (HNO_3:$HClO_4$:HCl, 3:1:1) under reflux conditions.

The concentrations of five heavy metals, Pb, Cd, Zn and Cu were determined using a Flame Atomic Absorption Spectrophotometer (AAS) (PerkinElmer AAnalyst 400), with appropriate calibration standards and blanks run concurrently.

2.3.2. Quality Control and Assurance

All reagents used were of analytical grade, and deionized water was used throughout the analysis. To ensure data reliability, the following quality control procedures were implemented:

(i) **Blank samples** to detect potential contamination.
(ii) **Duplicate analyses** to assess reproducibility.
(iii) **Standard Reference Materials (SRMs)** (e.g., NIST 2709a) to validate analytical accuracy.
(iv) **Spike recovery tests**, which yielded recovery rates between 90% and 108%, indicating acceptable precision and accuracy.

2.4. Pollution and Ecological Risk Indices

To assess the environmental implications of heavy metal contamination, a suite of pollution and ecological risk indices were engaed. The Igeo evaluates the extent of metal accumulation relative to natural background levels (Ferreira *et al*.,2022)

$$I_{geo} = log_2\left(\frac{C_n}{1.5.B_n}\right) \quad (1)$$

where C_n is the measured concentration of the heavy metal ion, B_n is the geochemical background concentration and 1.5 is a factor that accounts for lithogenic variations.

The classification of the Geo-accumulation Index (Igeo) is as follows: an Igeo value less than or equal to 0 indicates that the sediment is unpolluted. When the Igeo value is greater than 0 but less than or equal to 1, the environment is considered unpolluted to moderately polluted. An Igeo value between 1 and 2 signifies moderate pollution. Higher values beyond this range indicate increasing levels of contamination, progressing from moderately to heavily polluted conditions.

Contamination factor (CF) is an index that reflects the degree of contamination for each of the heavy metal ion and can be calculated according to equation 2 (Rahman *et al*., 2022)

$$CF = \frac{C_{metal}}{C_{background}} \quad (2)$$

The classification of the Contamination Factor (CF) is as follows: a CF value less than 1 indicates low contamination. When the CF is between 1 and 3, it signifies moderate contamination. Values ranging from 3 to less than 6 indicate considerable contamination, while a CF value equal to or greater than 6 reflects very high contamination.

The pollution load index (PLI) is an index that gives integrated measures of all **levels** of heavy metal pollution at each site. Equation 3 is the mathematical formula for calculating the PLI (Salazar-Rojas *et al*., 2023).

$$PLI = (CF_1 \times CF_2 \times CF_3 \dots . \times CF_n)^{\frac{1}{n}} \quad (3)$$

The Pollution Load Index (PLI) is calculated based on the contamination factors of individual metals, where *n* represents the number of metals assessed. A PLI value equal to 1 indicates a baseline level of pollution. If the PLI is less than 1, it suggests that there is no pollution, whereas a PLI greater than 1 indicates that pollution exists at the site.

The ecological risk index (RI) was used to evaluate the potential ecological risks associated with by each metal is evaluated using the method proposed by Hakanson (1980) was calculated using equation 4 (Hamid *et al*., 2022)

$$RI = \sum Tr_i . CF_i \qquad (4)$$

where Tr_i is the toxic response factor for metal I (e.g., Pb = 5, Cd = 30, Cr = 2, Cu = 5, Zn = 1) and CF_i is the contamination factor of metal i

The classification of the Ecological Risk Index (RI) is as follows: an RI value less than 150 indicates low ecological risk. When the RI ranges from 150 to less than 300, it is considered a moderate risk. Values between 300 and less than 600 signify a considerable ecological risk, while an RI equal to or greater than 600 represents a very high ecological risk

3.0 Results and Discussion

3.1 Seasonal and Spatial Water Quality

The seasonal analysis of physico-chemical parameters revealed that the pH of surface waters in Lake Chad ranged from 6.8 to 8.1 across the sampled sites. These values fall within the WHO acceptable range (6.5–8.5) for drinking water, suggesting near-neutral to slightly alkaline conditions, which are generally favorable for aquatic life. Electrical conductivity (EC) and total dissolved solids (TDS) were consistently higher in the dry season compared to the wet season. This increase can be attributed to enhanced evaporation rates and reduced dilution from rainfall during the dry period, resulting in the concentration of ionic species and solutes in the water column. Similar seasonal effects on solute accumulation have been observed in other shallow African lakes such as Lake Bosomtwe in Ghana (Owusu-Boateng et al., 2022).

3.2 Heavy Metal Concentrations

The concentrations of five heavy metals (Pb, Cd, Cr, Zn, and Cu) in the surface waters of Lake Chad during the dry and wet seasons are presented in Table 1.

Table 1. Seasonal Variation of Heavy Metal Concentration in Surface Water of Lake Chad

Sampling Site	Season	Pb (mg/L)	Cd (mg/L)	Cr (mg/L)	Zn (mg/L)	Cu (mg/L)
LC1	Dry	0.12	0.010	0.030	0.20	0.050
LC2	Wet	0.08	0.009	0.020	0.18	0.045
LC3	Dry	0.15	0.012	0.035	0.22	0.055
LC4	Wet	0.10	0.011	0.025	0.19	0.050
LC5	Dry	0.13	0.013	0.030	0.21	0.060

The results show marked spatial and seasonal differences in metal concentrations. The highest lead (Pb) concentration of 0.15 mg/L was recorded at LC3 during the dry season, while cadmium (Cd) peaked at 0.013 mg/L at LC5, also in the dry season. These values significantly exceed WHO guideline limits, which are 0.01 mg/L for Pb and 0.003 mg/L for Cd in drinking water, indicating potential health hazards through direct exposure or bioaccumulation in aquatic organisms.

Elevated dry-season concentrations are consistent with observations in other arid and semi-arid regions, where low rainfall and high evapotranspiration enhance metal retention in surface waters. Studies on the Niger Delta (Iwegbue et al., 2023) and Lake Victoria (Muwanga, 2010) reported similar seasonal spikes in Pb and Cd due to anthropogenic pressure and hydrological constraints. The obtained results are summarised in the histogram shown in Fig.2.

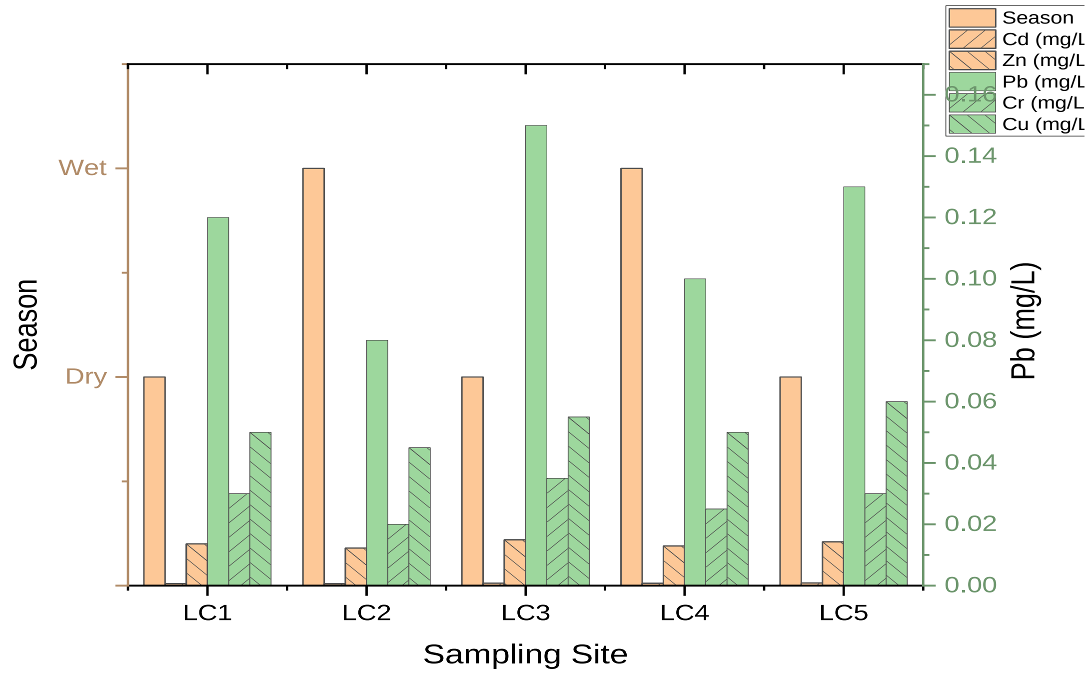

Fig.2: Histogram showing the distribution of heavy metal ions in the sampling sites

3.3 Pollution Indices

The results of the computed pollution indices including Geo-accumulation Index (Igeo), Contamination Factor (CF), Pollution Load Index (PLI), and Ecological Risk Index (RI)—for selected heavy metals (Pb, Cd, Cr, Zn, and Cu) in the surface water of Lake Chad are presented in Table 2. These indices provide a robust framework for quantifying the extent of heavy metal pollution, identifying hotspots of contamination, and assessing potential ecological threats.

Table 2. Pollution Indices (Igeo, CF, PLI, and RI) for Heavy Metals in Surface Water of Lake Chad

Sampling Site	Igeo (Pb)	Igeo (Cd)	CF (Pb)	CF (Cd)	CF (Cr)	CF (Zn)	CF (Cu)	PLI	RI
LC1	1.20	1.10	2.40	3.33	1.50	1.25	1.67	1.74	209.9
LC2	0.60	0.95	1.60	3.00	1.00	1.13	1.50	1.43	193.0
LC3	1.80	1.40	3.00	4.00	1.75	1.38	1.83	1.95	274.3
LC4	1.00	1.20	2.00	3.67	1.25	1.19	1.67	1.63	227.2
LC5	1.50	1.60	2.60	4.33	1.50	1.31	2.00	1.83	297.9

The Igeo values for Pb ranged from 0.60 to 1.80, and for Cd from 0.95 to 1.60, indicating that the sediments are moderately to strongly polluted with these metals, especially at LC3 and LC5. These values confirm that anthropogenic activities are significant contributors to metal loading in these areas. The strong pollution levels are likely due to agricultural runoff, domestic effluent discharge, and possibly the use of leadcontaining materials or combustion residues. Notably, Cd exhibits a consistently high Igeo across all sites, highlighting its widespread and pervasive presence in the aquatic system.

The CF values indicate that all five metals have anthropogenic sources, but Cd shows particularly high values, with CF > 4 at LC3 and LC5, classifying these sites under considerable contamination. The CF values for Pb also exceed 2.5 in most locations, suggesting significant anthropogenic enrichment. The relatively lower CFs for Cr, Zn, and Cu suggest these metals are less influenced by recent human activity or are present at levels closer to their natural background concentrations.

The PLI values range from 1.43 to 1.95, with the highest at LC3, followed by LC5. Since PLI values above 1 indicate pollution, these results confirm that all the sites studied are polluted, with cumulative effects of multiple metal inputs. The higher PLI at LC3 correlates with its proximity to agricultural zones and areas of intense human settlement. These findings reflect the pressure of cumulative pollution loads from different sources—urban runoff, fishing activities, and open defecation—which exacerbate contaminant levels.

The RI values fall between 193.0 and 297.9, indicating moderate to considerable ecological risk, with LC5 nearing the threshold for a transition into a high-risk category. Cadmium, due to its high toxic response factor (Tr = 30), is the major contributor to ecological risk at all locations. The implication is that aquatic organisms, particularly benthic invertebrates and fish species, may be experiencing chronic exposure to toxic metals, which could lead to bioaccumulation and biomagnification within the lake's food web.

From a technical standpoint, the results confirm the presence of multivariate pollution, with more severe contamination observed at specific hotspots such as LC3 and LC5. The consistent exceedance of threshold values, particularly for cadmium (Cd) and lead (Pb), underscores the necessity for routine environmental monitoring and the use of integrated assessment tools to support effective management of the Lake Chad Basin.

From an environmental perspective, the elevated levels of heavy metals pose a significant threat to the lake's aquatic biodiversity, especially in the benthic zones where metals tend to settle and accumulate. Continuous exposure to these pollutants can disrupt trophic structures, diminish fish productivity, and contribute to long-term habitat degradation, potentially destabilizing the ecological balance of the lake.

In terms of public health, the presence of Pb and Cd in concentrations above permissible limits raises serious concerns for local communities that rely on Lake Chad for drinking water, irrigation, and fishing. Lead exposure is associated with neurological and developmental disorders, particularly in children, while cadmium has been linked to kidney dysfunction, bone damage, and carcinogenic effects. These health risks highlight the urgent need for intervention measures, including stricter regulation of agricultural inputs, better effluent management, and improved waste disposal practices around the lake.

In summary, the results presented in Table 2 clearly demonstrate that Lake Chad is experiencing measurable heavy metal pollution, with cadmium and lead being the most concerning. Sites LC3 and LC5 stand out as critical zones requiring immediate attention and remediation. These findings should inform the development of targeted environmental management policies and public health protection strategies for the sustainable preservation of the Lake Chad ecosystem.

Pearson correlation analysis showed a strong positive correlation (r = 0.88) between Pb and Cd, suggesting a common source, likely linked to agrochemical usage or industrial effluent. Similarly, Principal Component Analysis (PCA) clustered LC3 and LC5 under a high-risk group, reinforcing the hypothesis of site-specific contamination, possibly from localized pollution sources such as fertilizer-intensive agriculture or petroleum residues.

Such statistical approaches are critical for identifying pollution hotspots and guiding remediation efforts. In comparable studies from the Volta Basin and Lake Turkana, PCA and correlation analyses have also pointed to anthropogenic inputs as dominant sources of metal enrichment (Ayenimo et al., 2011).

The exceedance of WHO limits for Pb and Cd underscores the potential toxicity risk posed to both human and ecological receptors. Chronic exposure to elevated Pb levels is associated with neurotoxicity and renal dysfunction, while Cd is a known carcinogen that affects kidney function and bone density. Furthermore, the considerable ecological risk at LC3 and LC5 could disrupt benthic habitats and trophic interactions, threatening the lake's biodiversity. This is particularly concerning given the reliance of surrounding communities on the lake for fish and potable water.

Immediate implications include the need for:

(i) Enhanced monitoring of agricultural practices near the lake
(ii) Regulation of agrochemical and effluent discharge
(iii) Community awareness programs on environmental health risks

The findings confirm that seasonal dynamics and anthropogenic activities significantly influence the distribution and risk of heavy metal contamination in Lake Chad. The dry season presents heightened ecological vulnerability, and sites LC3 and LC5 should be prioritized for remediation and continuous monitoring. The application of pollution indices and multivariate tools proved valuable for pollution source identification and ecological risk quantification.

4.0 Conclusion

The study revealed that the concentrations of heavy metals, particularly lead (Pb) and cadmium (Cd), in the Nigerian portion of Lake Chad exceeded international safety standards, especially during the dry season when evaporative concentration is more pronounced. Physico-chemical parameters such as pH, electrical conductivity, and total dissolved solids showed seasonal variations, with elevated values in the dry season, further supporting the influence of climatic factors on pollutant dynamics. Pollution indices, including the Geo-accumulation Index (Igeo), Contamination Factor (CF), Pollution Load Index (PLI), and Ecological Risk Index (RI), confirmed that the lake is moderately to strongly polluted, especially at sampling sites LC3 and LC5. These sites recorded the highest CF values for Cd and the highest RI scores, indicating considerable ecological risk and anthropogenic pressure. Pearson correlation analysis showed a strong positive relationship ($r = 0.88$) between Pb and Cd, suggesting common pollution sources such as agricultural runoff and local industrial activities. Principal Component Analysis and Hierarchical Cluster Analysis further supported the clustering of the most contaminated sites, reinforcing the spatial pattern of pollution.

In conclusion, Lake Chad's surface water is under significant pressure from heavy metal pollution, primarily driven by human activities and seasonal hydrological changes. The contamination poses a threat to aquatic ecosystems, public health, and the overall sustainability of the lake as a critical water resource in the Sahel region.

It is recommended that immediate mitigation strategies be implemented, including stricter regulation of agrochemical use, enforcement of waste disposal guidelines, and regular environmental monitoring programs. Public awareness campaigns and cross-border environmental cooperation should also be prioritized to ensure the long-term protection and restoration of Lake Chad's ecosystem.

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Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing interests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

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Authors' contributions

All components of the work were carried out by the author