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Spatial and Seasonal Variability of Heavy Metal Concentrations in Water from Dadinkowa Reservoir, Northeastern Nigeria: Implications for Aquatic Ecosystem Health

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ABSTRACT

Heavy metal contamination in freshwater reservoirs is a growing environmental concern, especially in rapidly developing regions of sub-Saharan Africa. This study investigated the spatial and seasonal variability of five heavy metals — Cadmium (Cd), Lead (Pb), Arsenic (As), Nickel (Ni), and Iron (Fe) — in water from Dadinkowa Dam, Gombe State, northeastern Nigeria. Water samples were collected monthly from three strategically selected stations (Station A, B, and C) over a six-month period spanning the wet season (May–October). Samples were filtered through 0.45 μm membranes and analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Results showed significant spatial ($p < 0.05$) and temporal ($p < 0.05$) variations in all five metals. Concentrations were highest in July and October, coinciding with peak runoff and increased anthropogenic inputs, while August and September recorded lower concentrations attributed to dilution during peak rainfall. Station B consistently showed the highest concentrations of Cd, Pb, Ni, and Fe, suggesting localized anthropogenic influence, while Station C recorded the highest Arsenic levels. All metals exceeded WHO and USEPA permissible limits in at least one station or month, raising concerns for aquatic ecosystem integrity. The findings underscore the need for regular environmental monitoring, pollution source identification, and enforcement of water quality standards to protect the aquatic ecosystem and dependent communities.

Keywords: Heavy metals; Dadinkowa Dam; Water quality; Seasonal variation; Spatial distribution; ICP-MS; Gombe State

1. INTRODUCTION

Access to safe and uncontaminated freshwater resources is fundamental to the health of aquatic ecosystems and human populations. Freshwater bodies worldwide face growing quality degradation due to the release of toxic substances from anthropogenic sources, and heavy metals are among the most persistent and hazardous of these pollutants. Unlike organic contaminants, heavy metals are non-biodegradable and accumulate in aquatic environments over extended periods, posing profound risks to aquatic biodiversity and public health (Aziz *et al.*, 2023; Saravanan *et al.*, 2024).

Heavy metal contamination in freshwater ecosystems is primarily driven by industrialization, mining operations, agricultural runoff, and disposal of untreated municipal and industrial effluents. Major toxic elements of concern include Cadmium (Cd), Lead (Pb), Arsenic (As), Nickel (Ni), and Iron (Fe) in excess concentrations. These metals enter aquatic systems through diffuse and point-source pathways, interact with

sediment particles, dissolve in the water column, and become bioavailable to aquatic organisms (Peter, 2024; Mishra and De, 2024).

The spatial distribution of heavy metals in freshwater reservoirs is influenced by proximity to pollution sources, hydrodynamic characteristics, sediment composition, and catchment land-use patterns. Similarly, seasonal variations — particularly the alternation between wet and dry periods in tropical and semi-arid regions — significantly affect metal concentrations in surface waters. During rainfall, increased runoff mobilizes metals from agricultural land and disturbed soils; conversely, dilution effects during peak rainfall can temporarily reduce measured concentrations (Thirumala *et al.*, 2024).

Dadinkowa Dam, located in Yamaltu Deba Local Government Area of Gombe State, northeastern Nigeria, is a vital freshwater resource supporting fishing, domestic water supply, irrigation, and recreational activities. Previous studies reported elevated concentrations of heavy metals including Iron, Manganese, and Cadmium in waters associated with the dam, with hazard quotients surpassing safe limits (Maigari *et al.*, 2016). Additionally, pesticide residues and polycyclic aromatic hydrocarbons have been detected in the dam's ecosystem, compounding contamination concerns (Santuraki *et al.*, 2022; Chellube *et al.*, 2018).

Despite these documented concerns, there remains a significant gap in systematic and comprehensive monitoring of heavy metal distribution in the water column, particularly regarding spatial variability among different zones and temporal dynamics across seasonal cycles. This study therefore investigated the concentrations of Cd, Pb, As, Ni, and Fe in water from Dadinkowa Dam over six months, characterising spatial and seasonal patterns, assessing compliance with international water quality standards, and generating baseline data to support ongoing environmental governance.

2. MATERIALS AND METHODS

2.1 Study Area

Dadinkowa Dam is located in Yamaltu Deba Local Government Area of Gombe State, northeastern Nigeria (approximately 10°29'N, 11°16'E). The reservoir was constructed primarily for irrigation, water supply, and hydroelectric power generation. It lies within the Guinea Savanna zone, characterised by a tropical climate with a distinct wet season (May–October) and dry season (November–April). Surrounding land use is predominantly agricultural, with farmers applying both organic and inorganic fertilizers and pesticides that may contribute to nutrient loading and potential contamination of the reservoir (Essien *et al.*, 2019).

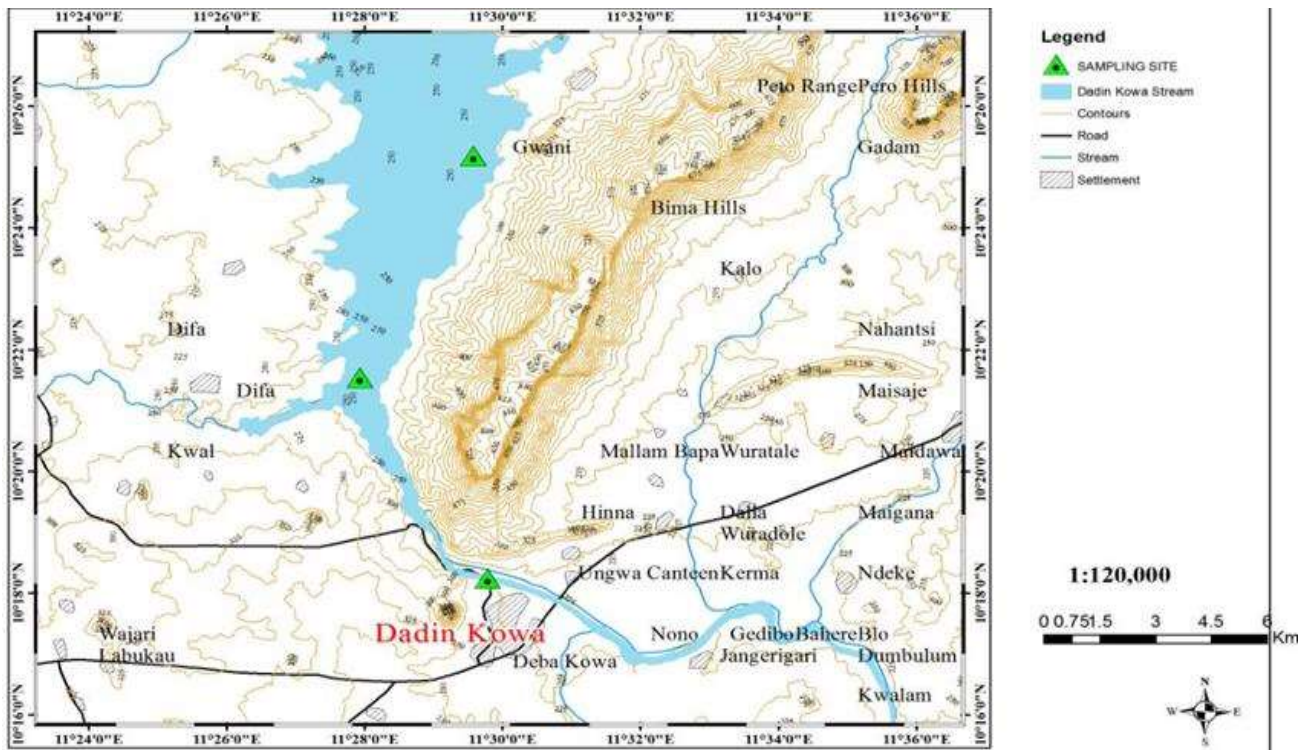


Fig. 1: Map of Dadinkowa Dam, Gombe State Nigeria. Showing the sampling stations.

2.2 Sampling Design and Water Collection

Three sampling stations were strategically selected across the dam to capture spatial variability: Station A (reference site, relatively undisturbed), Station B (near human activity zones including fishing camps and domestic use areas), and Station C (near agricultural inflow points). Water samples were collected monthly from May to October 2024, yielding a total of 18 sampling events (3 stations × 6 months). At each station, samples were collected in pre-cleaned 1-litre polyethylene bottles at a depth of approximately 30 cm below the surface to avoid surface contaminants. Samples were immediately preserved by acidification to pH < 2 using concentrated ultrapure nitric acid, transported in cool boxes, and stored at 4°C pending analysis (EPA, 1994).

2.3 Laboratory Analysis

Water samples were filtered through 0.45 µm membrane filters to remove particulate matter. The filtrates were analysed for concentrations of Cd, Pb, As, Ni, and Fe using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), a technique recognised for its high sensitivity and precision in detecting trace metal concentrations in environmental water samples (Han *et al.*, 2021). Instrument calibration was performed using certified reference standards, and procedural blanks and spiked samples were included in each analytical batch to ensure quality control and assurance.

2.4 Data Analysis

Data were expressed as mean ± standard deviation. One-way Analysis of Variance (ANOVA) was used to assess significant differences in metal concentrations across sampling stations and months using SPSS version 26. Means were separated using Tukey's post-hoc test at a 5% significance level. Measured metal concentrations were compared with permissible limits established by WHO (2017) and USEPA guidelines for drinking water and freshwater quality.

3. RESULTS

3.1 Temporal Variation in Heavy Metal Concentrations

Significant monthly variation ($p < 0.05$) was recorded in the concentrations of all five heavy metals in water from Dadinkowa Dam over the six-month sampling period (Table 1). Cadmium (Cd) concentrations ranged from 0.0931 mg/L in September to 0.3505 mg/L in October. Lead (Pb) showed relatively low concentrations throughout the sampling period, peaking in June (0.1021 mg/L) and reaching its lowest level in August (0.0328 mg/L). Arsenic (As) ranged from 0.0325 mg/L in August to 0.2002 mg/L in October. Nickel (Ni) concentrations were highest in October (0.4608 mg/L) and lowest in August (0.0517 mg/L). Iron (Fe) followed a similar pattern, with maximum concentrations in October (0.4276 mg/L) and minimum values in August (0.1685 mg/L).

The generally higher metal concentrations observed in July and October may be attributed to increased surface runoff, sediment resuspension, and heightened anthropogenic inputs during and following the rainy season. The lower concentrations recorded in August and September likely reflect dilution effects associated with peak rainfall volumes, which increase the water volume in the reservoir and temporarily reduce the concentration of dissolved metals (Table 1).

Table 1. Monthly heavy metal concentrations (mg/L) in water from Dadinkowa Dam (mean ± SD). Different superscript letters indicate significant differences across months ($p < 0.05$).

Metal	May	June	July	August	September	October
Cd	0.2199±0.008 ^d	0.2322±0.009 ^c	0.3123±0.009 ^b	0.1087±0.003 ^e	0.0931±0.004 ^f	0.3505±0.011 ^a
Pb	0.0967±0.135 ^b	0.1021±0.014 ^a	0.0717±0.002 ^d	0.0328±0.001 ^f	0.0673±0.009 ^e	0.0748±0.021 ^c
As	0.1172±0.003 ^d	0.1237±0.003 ^c	0.1816±0.010 ^b	0.0325±0.002 ^f	0.0437±0.001 ^e	0.2002±0.011 ^a
Ni	0.3732±0.019 ^d	0.3943±0.020 ^c	0.4002±0.013 ^b	0.0517±0.002 ^e	0.0790±0.004 ^f	0.4608±0.015 ^a
Fe	0.3232±0.009 ^d	0.3413±0.009 ^c	0.4132±0.010 ^b	0.1685±0.004 ^f	0.1890±0.005 ^e	0.4276±0.010 ^a

3.2 Spatial Variation in Heavy Metal Concentrations

Significant spatial differences ($p < 0.05$) were observed in heavy metal concentrations among the three sampling stations (Table 2). Station B recorded the highest concentrations of Cd (0.2593 mg/L), Pb (0.1043 mg/L), Ni (0.3228 mg/L), and Fe (0.3406 mg/L). Arsenic concentrations were highest at Station C (0.1385 mg/L), while Station A generally exhibited the lowest concentrations for most metals. The elevated metal concentrations at Station B suggest a higher degree of anthropogenic influence, possibly from human activities including fishing, domestic use, and runoff from surrounding land. The spatial variability observed demonstrates that metal contamination in the dam is site-specific rather than uniform.

Table 2. Spatial distribution of heavy metal concentrations (mg/L) across three stations in Dadinkowa Dam (mean \pm SD). Different superscript letters indicate significant differences ($p < 0.05$).

Metal	Station A	Station B	Station C
Cd	0.2032 \pm 0.014 ^b	0.2593 \pm 0.019 ^a	0.1958 \pm 0.016 ^c
Pb	0.0458 \pm 0.003 ^c	0.1043 \pm 0.010 ^a	0.0725 \pm 0.003 ^b
As	0.0937 \pm 0.007 ^c	0.1173 \pm 0.012 ^b	0.1385 \pm 0.013 ^a
Ni	0.3118 \pm 0.030 ^b	0.3228 \pm 0.032 ^a	0.2450 \pm 0.024 ^c
Fe	0.3110 \pm 0.019 ^b	0.3406 \pm 0.018 ^a	0.2798 \pm 0.015 ^c

4. DISCUSSION

The significant temporal variation in heavy metal concentrations observed in water from Dadinkowa Dam reflects the dynamic interplay between seasonal rainfall patterns, hydrological processes, and anthropogenic activities — a phenomenon widely reported in freshwater ecosystems across sub-Saharan Africa (Peter, 2024; Saravanan *et al.*, 2024). The higher metal concentrations recorded in July and October are consistent with elevated surface runoff during the active wet season, which mobilizes metals from agricultural land, eroded soils, and waste disposal sites into the reservoir. A similar pattern was reported in reservoirs in northern Nigeria, where wet season peaks in metal concentrations were attributed to intensified agricultural and domestic inputs (Maigari *et al.*, 2016).

The reduction in metal concentrations during August and September is consistent with the dilution effect commonly associated with peak rainfall volumes. As the reservoir receives large volumes of rainfall-derived water, dissolved metal concentrations are temporarily reduced despite continued input from catchment runoff. This phenomenon has been reported widely in tropical freshwater systems where seasonal hydrology exerts a dominant control over contaminant dynamics (Mishra and De, 2024; Thirumala *et al.*, 2024). However, it is important to note that lower dissolved concentrations during these months do not necessarily indicate reduced contamination, as metals may partition into sediments and re-enter the water column during subsequent dry periods.

The spatial pattern of metal distribution, with Station B consistently recording the highest concentrations for most metals, suggests the influence of localized anthropogenic activities in the vicinity of this station. Station B, positioned near areas of active domestic use and fishing activity, is likely to receive higher inputs of metals from human waste, discarded materials, and boat fuel residues. The elevated Arsenic concentrations at Station C, located near agricultural inflow points, reflect the well-documented role of pesticide and fertilizer application in elevating As concentrations in receiving water bodies (Singh *et al.*, 2024). Spatial heterogeneity in heavy metal distributions has been reported in comparable reservoir studies, where proximity to pollution sources significantly influenced metal concentrations (Habib *et al.*, 2024).

The concentrations of several metals — notably Cd, As, and Ni — exceeded WHO and USEPA permissible limits for freshwater at multiple stations and time points. Cadmium concentrations, in particular, surpassed the WHO guideline value of 0.003 mg/L for drinking water at all stations and months, indicating a persistent contamination concern. These findings are consistent with the study by Maigari *et al.* (2016), who also reported elevated Cd and Fe concentrations in water associated with Dadinkowa Dam. The exceedance of

regulatory limits underscores the potential risk to aquatic organisms and human health, particularly for communities that rely directly on the dam's water for domestic purposes without adequate treatment.

Iron concentrations, while reflecting a naturally occurring element, exceeded recommended limits throughout the study period. Elevated Fe in freshwater can exert indirect toxic effects on aquatic organisms through the formation of iron hydroxide flocs that damage gill tissue and reduce dissolved oxygen availability (Banaee, 2024). Additionally, elevated Fe may indicate redox cycling in the sediment-water interface, potentially mobilizing other co-associated heavy metals during anaerobic conditions in deeper zones of the reservoir.

5. CONCLUSION

This study demonstrated significant spatial and seasonal variability in heavy metal concentrations in water from Dadinkowa Dam, Gombe State, Nigeria. Concentrations of Cd, Pb, As, Ni, and Fe varied significantly among months and across sampling stations, reflecting the combined influence of seasonal rainfall dynamics, localized anthropogenic activities, and catchment land-use patterns. Peak concentrations were recorded in July and October, while Station B emerged as a consistent contamination hotspot. Metal concentrations for several elements exceeded WHO and USEPA permissible limits, indicating a persistent water quality concern that poses risks to aquatic ecosystem health and communities dependent on this resource. Regular water quality monitoring, pollution source identification, catchment management interventions, and public awareness campaigns are urgently recommended to safeguard the ecological integrity and public health value of Dadinkowa Dam.

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