Water quality, heavy metal contamination, and ecological risk assessment in Asejire reservoir, Nigeria

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RESEARCH ARTICLE

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Water quality, heavy metal contamination, and ecological risk assessment in Asejire reservoir, Nigeria

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ABSTRACT

Monitoring water and sediment quality in freshwater ecosystems is essential for sustainable management and ecological protection. This study assessed heavy metal contamination in water and sediments from five sampling stations in Asejire Reservoir, Oyo State, Nigeria. A range of pollution indices was employed to quantify contamination levels. Principal Component Analysis (PCA) and Cluster Analysis (CA) were used to identify potential sources of pollution, while the Water Quality Index (WQI) provided an overall evaluation of water quality. The WQI score of 74.23 indicated generally good water quality, although localized contamination was observed. PCA results suggested that most heavy metals originated from anthropogenic activities, and CA grouped pollution sources into two main clusters. The geo-accumulation index showed low cadmium (Cd) levels at most stations, with slight to moderate pollution recorded at Station 5. Chromium (Cr), copper (Cu), and lead (Pb) exhibited moderate to strong pollution levels. Ecological risk assessment indicated no significant risk from Cr, low risk from Cu and Pb, and a very high ecological risk from Cd. The Heavy Metal Pollution Index (HPI), ranging from 290.35 to 294.75, further confirmed substantial human-related input. These findings highlight the need for routine monitoring and targeted remediation to prevent further degradation, safeguard aquatic ecosystems, and protect public health.

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Introduction

Water quality is vital for human health, ecosystem stability, and socio-economic development. In many developing regions, rapid urbanization, agriculture, aquaculture, industrialization, and climate change have intensified water pollution, often outpacing regulatory enforcement (Hasimuna et al. 2021; Maulu et al. 2021; Luvhimbi et al. 2022; Phiri et al. 2024, 2025; Shaheen et al. 2024). Heavy metals are among the most toxic and persistent pollutants due to their bioaccumulation and long-term ecological and health impacts (Fernández-Luqueño et al. 2013; Basim and Khoshnood 2016; Hasimuna et al. 2023, 2024). Metals such as lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg) accumulate in aquatic systems, threatening both biodiversity and human health. Despite global efforts, including the United Nations Sustainable Development Goal (SDG) 6 on clean water and sanitation, heavy metal contamination remains a serious problem, especially in industrial and mining regions.

In Nigeria, just like in other countries, freshwater resources are increasingly under threat from industrial waste, agricultural runoff, and poor waste management (Ouma et al. 2022; Jolaosho et al. 2023, 2024). Studies have documented significant heavy metal contamination in major water bodies such as Lagos Lagoon and Elelenwo River (Oladipo et al. 2014; Utete and Fregene 2020). Similar patterns have been observed around the world, with studies like Aktar et al. (2025) reporting differences in heavy metal levels in Bangladesh's Shyamasundari Canal, and Tokatlı et al. (2025) analyzing the spread of inorganic pollutants in Türkiye's Felent Stream Basin near silver mines. Despite these documented risks, Asejire Reservoir, an important water source for surrounding communities, has not been studied enough, even though growing urbanization and industrial activities make it more vulnerable to pollution. Since sediments act both as sinks and secondary sources of heavy metals, understanding their contamination patterns is crucial for evaluating their long-term effects on water quality and the health of the aquatic ecosystems (Salomons and Stigliani 1995; Bing et al. 2019; Hasimuna et al. 2021; Jolaosho et al. 2024).

Traditional water quality assessments primarily compare metal concentrations to regulatory standards. However, to better understand contamination levels and ecological risks, pollution indices like the Heavy Metal Pollution Index (HPI), geo-accumulation index (Igeo), and ecological risk index (RI) offer a more comprehensive evaluation (Hakanson 1980; Mohan et al. 1996; Jolaosho et al. 2023). Additionally, multivariate statistical techniques such as Principal Component Analysis (PCA) and Cluster Analysis (CA) help identify pollution sources and spatial distribution patterns (Abdul-Wahab et al. 2005; Leventeli & Yalcin, 2021; Bhanbhro et al. 2024). Yüksel et al. (2025) combined chemometric methods and Monte Carlo simulation to assess contamination sources and health risks in fish from Türkiye's Miliç Wetland, highlighting the role of agriculture and urban waste in pollutant exposure. These methods have been effectively used in other waterbodies to trace pollution sources and guide mitigation efforts (Edori et al. 2019; Hasimuna et al. 2021; Sojka et al. 2022; Yüksel et al. 2025).

The current study uses a new approach that combines ecotoxicological and multivariate statistical methods to thoroughly assess the contamination status of Asejire Reservoir. Specifically, we: (1) measure heavy metal (Pb, Cd, Cr, Cu, Ni)

concentrations in both water and sediment, (2) use advanced pollution indices (HPI, Igeo, RI) and bioconcentration factors to evaluate ecological risks, and (3) apply. Additionally, PCA and CA to identify contamination sources and spatial patterns. Our approach marks a significant step forward in water quality studies in Nigeria by including sediment analysis to understand long-term contamination trends and using multivariate statistics to distinguish between anthropogenic and natural pollution sources.

We hypothesize that industrial and agricultural activities create uneven contamination patterns in the reservoir, sediments act as significant secondary sources of pollution despite surface water quality indicators and combining statistical and ecotoxicological analysis will highlight distinct contamination hotspots that require focused intervention. The results of this study will offer valuable insights into the extent of heavy metal pollution in Asejire Reservoir and contribute to sustainable water resource management in Nigeria.

Materials and methods

Study area

Asejire Reservoir (Figure 1) is a man-made lake created in November 1970 by the impoundment of River Osun and officially opened in 1972. It was primarily created to supply domestic and industrial water, although some ancillary benefits such as fishing activities have also emerged. The reservoir receives the bulk of its water

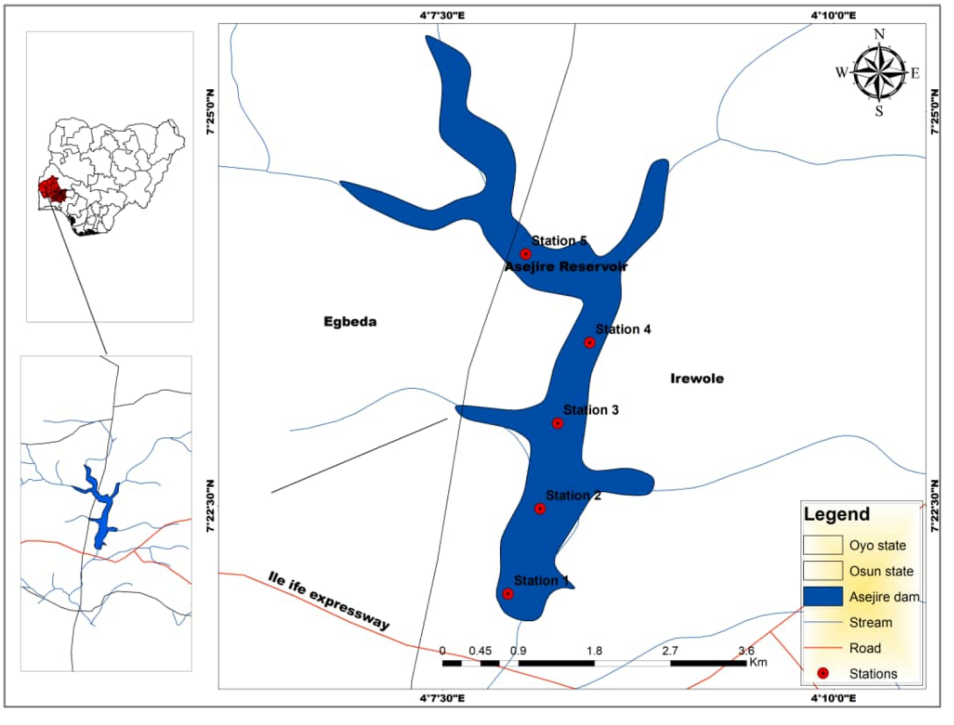

Figure 1. Map showing sampling stations at Asejire reservoir.

input from two rivers, Rivers Osun, and its main tributary River Oba. According to data provided by the Oyo State Water Corporation of Nigeria, the catchment area of the dam spans 7800 km^2, while the impounded area measures 23.42 km^2 (equivalent to 2342 hectares). The dam has a normal pool elevation (water level) of 150 m and maximum flood elevation of 152.4 m. The surface area of the reservoir is about 24 km^2. Its gross storage capacity is approximately 7403.4 million litres per day while its discharge capacity is 136.26 million litres per day with maximum water capacity of about 675 m^3.

Sampling technique

Water and sediment samples were collected weekly from five stations designated as station/sampling sites 1, 2, 3, 4 and 5 at Asejire reservoir (Figure 1). The coordinate of each location was recorded (Table 1). The samples were collected in January, April, September, October, November, and December 2022. These sampling months were chosen to cover the rainy season which occurs from April to October, and early November to January, representing the dry season where there are anticipated low dilution rates and high metal concentrations in the reservoir.

Collection of water samples and analysis

At each site, three replicate water samples were collected using a 5-liter Ruttner sampler at a maximum depth of 1 m to ensure consistency. These samples were then combined into one and stored in 500 ml sterilized polyethylene bottles, which were placed in iced cooler boxes for further laboratory analysis. In-situ measurements of pH, conductivity, turbidity, temperature, and dissolved oxygen (DO) were taken at each site using a pH meter (Hanna HI 98100), a Secchi disk for turbidity, a conductivity meter (Hanna HI 98311), and a DO meter (HACH, LDO, Germany). Water samples for Biological Oxygen Demand (BOD_5) testing were collected in 300 ml amber glass bottles with glass stoppers, following APHA (1998) preservation guidelines. The BOD_5 test was performed by measuring the dissolved oxygen (DO) levels in the samples before and after a five-day incubation in complete darkness at 20 °C. The initial DO (DO_0) was measured immediately after collection, while the final DO (DO_5) was measured after incubation. The BOD_5 value (mg/L) was calculated as the difference between the initial and final DO concentrations ($BOD_5 = DO_0 - DO_5$).

Nitrate, nitrite, and phosphate levels were measured following the procedure described by Fadiran et al. (2008). Water samples were filtered through 0.45 µm membrane filters to remove particulate matter. The filtrate was then analyzed for nitrate-nitrogen

Table 1. Coordinates of sampling stations at Asejire reservoir.

Locations	Latitude	Longitude
1	7 °21′25″N	4°32′53″E
2	7 °20′53″N	4°11′27″E
3	7 °22′9″N	4°10′8″E
4	7 °21′29″N	4°8′13″E
5	7 °23′13″N	4°12′34″E

(NO_3^--N), nitrite-nitrogen (NO_2^--N), and phosphate (PO_4^{3-}) concentrations using colorimetric methods with a HACH DR890 portable colorimeter. Phosphate was measured using the ascorbic acid method with Phosver 3 reagent powder pillows, with a detection limit of 0.07 mg/L. Nitrate was analyzed using the 8171-cadmium reduction method, and nitrite was measured using the 8507-diazotization method, with detection limits of 0.2 mg/L and 0.005 mg/L, respectively. Analytical accuracy was confirmed using 10 mg/L standard solutions provided by Hach Company, USA, for all parameters.

Collection of sediment samples

Samples of bottom sediments were collected at the same locations as the water samples using a 1-meter-long polypropylene coring device with an internal diameter of 0.1 meters. Multiple 10 cm cores were taken at each site and thoroughly mixed to form a single integrated sample, which was stored in sterilized polyethylene bags. The sediment samples were stored at 4 °C in a laboratory refrigerator for a maximum period of 24 h in preparation for heavy metal analysis.

Samples preparation and heavy metal extraction

The extraction and analysis of metals in water and sediments were carried out following the methods described by Greenberg et al. (1980) for water and APHA et al. (1998) for sediments. The sequence of activities from sampling to analysis (Figure 2) followed the description of Imran et al. (2019).

Water samples

Water samples were filtered through 0.45 µm Whatman GF/F filters to remove suspended particles and collected in sterilized 100 mL polyethylene bottles. For total

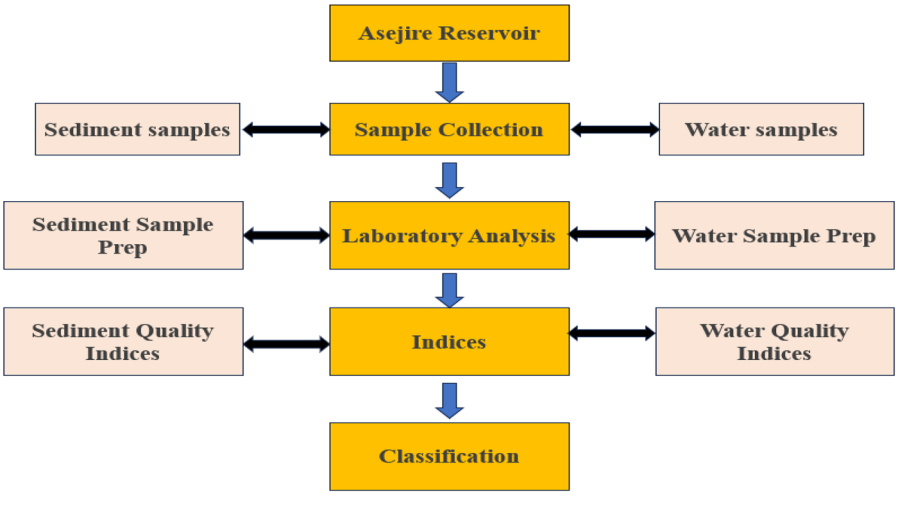

Figure 2. Flow diagram showing the sequence of activities from sampling to analysis at Asejire reservoir.

metal analysis, 100 mL of the filtered sample was acidified with 5 mL of concentrated nitric acid (HNO_3, 70%) and digested on a hotplate at 95 °C until the volume was reduced to about 20 mL. The digestate was then cooled, diluted to 100 mL with deionized water, and filtered again.

Sediment samples

Sediment samples were air-dried at room temperature in a contamination-free environment, then homogenized using porcelain mortar and pestle. They were sieved through a 2 mm nylon mesh to remove coarse debris. A 0.5 g portion of the sieved sediment was weighed into a Teflon digestion tube, mixed with 10 mL of concentrated HNO_3 (70%), and digested at 170 °C for 2 h using a hot block digester. The digested samples were cooled, diluted to 50 mL with deionized water, and filtered through Whatman No. 42 filter paper before analysis.

Heavy metal analysis by atomic absorption spectrophotometry

Metal concentrations in both water and sediment extracts were determined using a PerkinElmer 3100 Flame Atomic Absorption Spectrophotometer (FAAS). The instrument was calibrated with matrix-matched multi-element standards prepared in the same acid concentration as the samples. An air-acetylene flame was used to determine cadmium (Cd), copper (Cu), and lead (Pb), while chromium (Cr) analysis required a nitrous oxide-acetylene flame for better sensitivity. Background correction was applied for Pb and Cd to minimize spectral interferences.

Quality assurance and quality control procedures

Quality assurance measures were implemented throughout the study to ensure reliable data. All field instruments were calibrated daily using certified standards before measurements. The Hanna HI 98107 pH meter was calibrated with NIST-traceable buffer solutions (pH 4.0, 7.0, and 10.0), while dissolved oxygen measurements were taken using a HACH LDO meter (Germany), calibrated with air-saturated water and zero-oxygen solution methods. Conductivity was measured with a Hanna HI 98311 m, calibrated using a 1413 µS/cm standard solution.

For heavy metal analysis, method validation was performed using Certified Reference Materials (CRMs). Water samples were verified against NIST SRM 1640a (Trace Elements in Natural Water) and ERM-CA011b (Hard Drinking Water), while sediment samples were cross-checked with NIST SRM 2709a (San Joaquin Soil) and BCR-701 (Lake Sediment). Recovery rates for spiked samples showed accuracy, ranging from 88 to 112% for Cr, 91-105% for Cd, 85-110% for Cu, and 90–108% for Pb, all within the 85-115% range recommended by USEPA (2018). Method detection limits (MDLs) were established through seven replicate analyses of low-concentration samples. For water analysis, MDLs were 0.005 mg/L for Cr, 0.001 mg/L for Cd, 0.002 mg/L for Cu, and 0.003 mg/L for Pb. For sediment, MDLs were 0.5 mg/kg for Cr, 0.1 mg/kg for Cd, 0.2 mg/kg for Cu, and 0.3 mg/kg for Pb. Values below these limits were reported as '<MDL'.

Quality control measures included analysis of field blanks (trip blanks) and laboratory method blanks to monitor potential contamination during sampling and processing. Triplicate analyses of 10% randomly selected samples showed relative standard deviations below 10%, ensuring measurement precision. Atomic absorption spectrometry (AAS) was calibrated using multi-element standards (AccuStandard Custom Grade 3), and all results were verified against established guidelines from WHO (2011), NESREA (2011), and SON (2015). Statistical validation included principal component analysis (PCA) to identify potential outliers and paired t-tests ($p > 0.05$) to confirm consistency between duplicate runs, with results showing no significant differences.

Water quality index (WQI)

Water Quality Index (WQI) was calculated for each sampling station. The parameters used include Dissolved Oxygen, pH, temperature, biological oxygen demand, nitrate, nitrite, phosphate, and electrical conductivity.

The quality rating scale for each parameter qi was calculated using:

$$q_i = C_i / S_i \times 100$$

where C_i is the concentration of each parameter in water sample, S_i is the standard value of each parameter.

Unit weight (Wi) was calculated using:

$$W_i = 1 / S_i$$

The overall WQI was calculated using the formula:

$$WQI = \sum_{I=1}^{i=n} w_i * q_i$$

$$WQI = \sum q_i * w_i / \sum w_i$$

Ramakrishna classified water quality index as follows: <50 for excellent, 50–100 for good, 100–200 for poor, 200–300 for very poor, and >300 for unsuitable.

Index of geo-accumulation

The geo-accumulation index (Igeo) is defined by the following equation according to Müller (1969):

$$\text{Igeo} = \log\left(\frac{cn}{1.5} \times Bn\right)$$

Where: Cn is concentration of metal sample and Bn is background concentration of the metal (n) usually adopted from sediment quality guidelines.

Bioaccumulation factor

Bioconcentration factor (BCF) is the ratio of metal concentrations in sediment phase to that in the water phase, the equation used according to Van Der Kooij et al. (1991) was:

$$BCF = \frac{metals\ conentrtation\ in\ sediment}{metals\ conetration\ in\ water}$$

If BCF is greater than 1000, it was considered to be high and those under 250 were considered to be low. BCF between 250 – 1000 was considered to be moderately high.

Potential ecological risk index

This risk index (RI) was used to evaluate the ecological risk of metal contamination in sediments by considering metals toxicity and the response to the environment. The following equation was used as given by Hakanson (1980):

$$RI = \sum E_i$$

$$E_i = T_i * f_i$$

$$f_i = C_i / B_i$$

where E_i is the potential ecological risk factor, f_i is the pollution factor for metals, C_i is the concentration of metals in sediment, B_i is the natural background value of metals and T_i is metal toxic factor. As given by Hakanson (1980); the value of T_i Cr = 2, Cd = 30 and Cu and Pb =5.

The following categories of RI used in this study are RI < 1 for no potential ecological risk, $1 \leq RI < 40$ for low potential ecological risk, $40 \leq RI < 80$ for moderate potential ecological risk, $80 \leq RI < 160$ for considerate potential ecological risk, $160 \leq RI < 320$ for high potential ecological, RI > 320 for very high potential ecological risk.

Heavy metal pollution Index

The contamination status of water samples was determined using the Heavy Metal Pollution Index (HPI) to assess the suitability for human consumption. The HPI integrates multiple metal concentrations into a single value, with HPI > 100 indicating unsafe water according to Mohan et al. (1996). Higher values reflect increasing contamination severity, where values between 100 and 200 represent medium pollution, 200-300 high pollution, and >300 very high pollution (Balakrishnan and Ramu 2016). The HPI represents the total quality of water with respect to heavy metals, and it is calculated by assigning a weightage (W_i) for individual parameters which is a value between 0 and 1 reflecting the relative importance of the individual quality consideration. This study used the World Health Organization (WHO) standards permissible values for drinking

water. The HPI was calculated using the following equation (Rizwan et al. 2011; Balakrishnan and Ramu 2016):

$$HPI = \frac{\sum_{I=1}^{i=n}\left(Q_i * W_i\right)}{\sum_{i=1}^{i=n} W_i}$$

where Q_i is the sub-index of the ith parameter, W_i is the unit weight of the ith parameter and n is the number of parameters considered; the sub-index (Q_i) of the parameter is:

$$Q_i = \frac{V_i}{S_i} \times 100$$

where v_i is the monitored value of metal of ith parameter and s_i the standard value.

Statistical analysis

The results of the chemical analysis were analyzed by several multivariate statistical methods (correlation analysis, principal component analysis and cluster analysis) to determine the concentration of metals in water and sediment. The principal component analysis (PCA) is a dimensional reduction technique that represents variability in a dataset by a reduced set of new variables formed as linear combinations of the input data. Prior to PCA, the Kaiser–Meyer–Olkin test was performed to assess the adequacy of the data on metals for factor analysis, such as PCA. Bartlett's test of sphericity was also used to assess the structure of variability among the data and suitability for PCA. Principal components with eigenvalues >1 were retained for interpretation. Hierarchical cluster analysis was performed to evaluate which sampling locations have similar metals content. Euclidean distance and the average of between groups connection criteria were used in cluster analysis. The Statistical Package for Social Sciences (SPSS) 21 and Paleontological Statistics (PAST 3) Software package were used to perform these multivariate statistical analyses.

Results

Water quality parameters and water quality index

The Dissolved Oxygen (DO) levels recorded during this study were within the recommended values provided by Nigerian Standard for Drinking Quality Water (NSDQW) and World Health Organisation (WHO) (Table 2). The water Temperature, Biological Oxygen Demand, Electrical conductivity, pH, Nitrate and Phosphate values were within acceptable local and international limits except nitrite which was only higher at station 1. No significant variation was observed across the five stations for all tested water quality parameters. The computed overall WQI was 74.23, categorizing the water as 'good' (Table 3).

Table 2. Water quality parameters from asejire reservoir.

Parameters	Stations/sampling site 1	2	3	4	5	NSDQW (2007)	WHO (2011)
Temperature (°C)	28.75 ± 1.48	28.67 ± 1.50	28.58 ± 1.38	28.58 ± 1.56	28.42 ± 1.56	28 – 30	25.3
DO (mg/l)	5.07 ± 0.70	5.36 ± 0.95	5.03 ± 0.67	5.09 ± 0.64	5.29 ± 0.65	5	5
BOD (mg/l)	0.93 ± 0.22	0.94 ± 0.22	0.86 ± 0.30	0.89 ± 0.24	0.79 ± 0.25	–	2
pH	7.06 ± 0.26	7.18 ± 0.18	7.05 ± 0.26	7.07 ± 0.19	7.18 ± 0.27	6.5 – 8.5	6.5 – 8.5
EC (µs)	922.13 ± 95.21	931.81 ± 88.71	921.44 ± 96.17	928.31 ± 92.88	925.13 ± 97.45	1000	1000
Nitrate (mg/l)	0.55 ± 0.47	0.33 ± 0.41	0.55 ± 0.51	0.39 ± 0.47	0.36 ± 0.33	50	50
Nitrite (mg/l)	0.26 ± 0.26	0.16 ± 0.25	0.20 ± 0.21	0.17 ± 0.28	0.13 ± 0.17	0.2	0.2
Phosphate (mg/l)	0.14 ± 0.12	0.21 ± 0.24	0.15 ± 0.13	0.15 ± 0.13	0.15 ± 0.13	–	0.3

*No significant difference among the stations at $p > 0.05$ BOD: biological oxygen demand, dissolved oxygen.

Table 3. Water quality index across the sampling stations at Asejire reservoir.

Parameters	Observed value	Standard values	Unit weight (Wi)	Quality rating scale (qi)	Water Quality Index (WQI)
Temperature	28.58	28-30	0.033	95.3	3.18
DO	5.07	5 – 6.59	0.200	101.4	20.28
BOD	0.88	2	0.500	44.0	22.00
pH	7.11	6.5-8.5	0.133	83.6	11.13
EC	925.76	1000	0.001	92.6	0.09
Nitrate	0.44	50	0.020	0.9	0.02
Nitrite	0.18	0.2	5.000	90.0	450.00
Phosphate	0.16	0.3	3.333	53.3	177.78
			$\sum w_i = 9.22$		$\sum w_i * q_i = 684.47$

Overall WQI $= \sum q_i * w_i / \sum w_i$ (74.23).

Heavy metal concentration in water and sediments

The concentration of Cr and Cu in water was high at station 1 and 2 when compared to other sampling stations. Similar concentration values were recorded for Cd and Pb across the sampling stations (Table 4). The average Pb value (0.02 mg/L) in water was lower than NSDQW and WHO limits (1 mg/L). Cu level (0.03 mg/L) exceeded NSDQW and WHO limits (0.01 mg/L). Cr concentrations (0.05 mg/L) were within the recommended value of NSDQW and WHO (0.05 mg/L). However, Cd values (0.01 mg/L) were higher than NSDQW and WHO limits (0.003 mg/L). There were no significant variations in the concentration of all metals in water sampled in all the sampling sites.

The concentration of Cr recorded in sediments was highest (42.08 ± 9.31 mg/kg) at Station 1 and was below the acceptable international (USEPA) limits (Table 5). High Cd concentrations were detected in sediments in the reservoir at Station 2 (3.24 ± 1.47 mg/kg) with no significant difference in all the stations. The highest concentrations of Cu and Pb were recorded in sediments at Station 1 but did not exceed the acceptable limits. No significant variation in the metals across the stations was observed. Significant differences ($p < 0.05$) were observed between heavy metal concentrations in water and sediments at each station (Table 6).

Table 4. Heavy metal composition in water samples from Asejire reservoir.

Stations/sampling sites	Heavy metals (mg/l)			
	Cr	Cd	Cu	Pb
1	0.07 ± 0.02	0.01 ± 0.00	0.04 ± 0.01	0.02 ± 0.01
2	0.07 ± 0.05	0.01 ± 0.00	0.04 ± 0.04	0.02 ± 0.01
3	0.04 ± 0.01	0.01 ± 0.00	0.03 ± 0.00	0.02 ± 0.01
4	0.03 ± 0.01	0.01 ± 0.00	0.03 ± 0.01	0.02 ± 0.01
5	0.02 ± 0.01	0.01 ± 0.00	0.03 ± 0.01	0.02 ± 0.01
Mean	0.05 ± 0.02	0.01 ± 0.00	0.03 ± 0.01	0.02 ± 0.01
NSDQW/WHO	0.05	0.003	0.01	1.00

*No significant difference among the stations at $p > 0.05$.

Table 5. Heavy metal composition in sediment samples from asejire reservoir.

Stations/sampling sites	Heavy metals (mg/kg)			
	Cr	Cd	Cu	Pb
1	42.08 ± 9.31	3.24 ± 1.47	18.63 ± 7.98	8.41 ± 7.97
2	41.99 ± 9.53	2.48 ± 1.06	16.74 ± 9.03	7.93 ± 7.02
3	41.57 ± 12.54	2.06 ± 0.77	15.64 ± 7.90	7.18 ± 5.78
4	37.14 ± 11.45	1.77 ± 0.65	14.71 ± 5.15	5.16 ± 4.11
5	35.91 ± 5.18	2.09 ± 0.82	14.46 ± 4.82	6.38 ± 4.87
Mean	39.74 ± 9.60	2.33 ± 0.95	16.03 ± 6.98	7.01 ± 5.95
USEPA	43.4	0.99	31.6	35.8

*No significant difference among the stations at $p > 0.05$.

Table 6. Comparison of heavy metal concentration in water and sediment from Asejire reservoir.

Stations/ sampling sites	Heavy metals (mg/l) in water				Heavy metals (mg/kg) in sediment			
	Cr	Cd	Cu	Pb	Cr	Cd	Cu	Pb
1	0.07 ± 0.02^a	0.01 ± 0.00^a	0.04 ± 0.01^a	0.02 ± 0.01^a	42.08 ± 9.31^b	3.24 ± 1.47^b	18.63 ± 7.98^b	8.41 ± 7.97^b
2	0.07 ± 0.05^a	0.01 ± 0.00^a	0.04 ± 0.04^a	0.02 ± 0.01^a	41.99 ± 9.53^b	2.48 ± 1.06^b	16.74 ± 9.03^b	7.93 ± 7.02^b
3	0.04 ± 0.01^a	0.01 ± 0.00^a	0.03 ± 0.00^a	0.02 ± 0.01^a	41.57 ± 12.54^b	2.06 ± 0.77^b	15.64 ± 7.90^b	7.18 ± 5.78^b
4	0.03 ± 0.01^a	0.01 ± 0.00^a	0.03 ± 0.01^a	0.02 ± 0.01^a	37.14 ± 11.45^b	1.77 ± 0.65^b	14.71 ± 5.15^b	5.16 ± 4.11^b
5	0.02 ± 0.01^a	0.01 ± 0.00^a	0.03 ± 0.01^a	0.02 ± 0.01^a	35.91 ± 5.18^b	2.09 ± 0.82^b	14.46 ± 4.82^b	6.38 ± 4.87^b

*Mean with the same superscript along the row is not significantly different among the same element at $p > 0.05$.

Bioconcentration factor, potential ecological risk and geo-accumulation index

Bioconcentration factors for Cr were moderately high at stations 2 and 5 and were high at stations 1, 3 and 4. Bioconcentration factors for Cd at station 1, 2, 4 and 5 were low (< 250) across the Asejire reservoir but moderately high at station 2. Bioconcentration factors for Cu and Pb were moderately high in all the stations. The calculated average results of *Igeo* indicated that Cd is low except in station 5 which is slightly to moderately higher. Furthermore, the results indicate that Cr, Cu, and Pb show strong, moderate to strong, and moderate pollution levels, respectively, at all stations. Regarding potential ecological risk, chromium (Cr) poses no significant potential ecological risks, while Cu and Pb show low potential ecological risks. In contrast, Cd presents higher potential ecological risks (Table 7).

Heavy metal pollution index (HPI) in water

The Heavy Metal Pollution Index (HPI) was calculated using the mean concentrations of heavy metals measured at the five sampling stations within Asejire Reservoir.

Table 7. Pollution indices of metals at Asejire reservoir.

	Bioconcentration factor			
Station/sampling sites	Cr	Cd	Cu	Pb
1	2078.50	248	391	258
2	601.14	334	367.75	319
3	1238	206	482	359
4	1049.75	177	621	420.5
5	513	209	558	396.5
Mean	1096.08	234.80	483.95	350.60
Potential ecological risk				
1	0.84	372	1.69	3.36
2	0.84	486	1.52	3.17
3	0.83	309	1.42	2.87
4	0.74	265.5	1.34	2.06
5	0.72	313.5	1.31	2.55
Mean	0.79	349.2	1.46	2.80
Index of Geo-accumulation				
1	3.44	−0.88	2.76	1.63
2	3.45	−0.36	2.73	1.73
3	3.39	−0.56	2.70	1.77
4	3.46	−0.63	2.83	1.85
5	3.38	0.28	2.79	1.82
Mean	3.42	−0.43	2.76	1.76

Table 8. Heavy metal pollution index (HPI) of water sample at Asejire reservoir in comparison with WHO standard values.

	Concentration (mg/l) V_i							Sub-index, Q_i				
Metals (mg/l)	1	2	3	4	5	WHO Standard value (mg/l) S_i	Unit weightage W_i	1	2	3	4	5
Cr	0.07	0.07	0.04	0.03	0.02	0.05	20	140	140	80	60	40
Cd	0.01	0.01	0.01	0.01	0.01	0.003	333.33	333.33	333.33	333.33	333.33	333.33
Cu	0.04	0.04	0.03	0.03	0.03	1	1	4	4	3	3	3
Pb	0.02	0.02	0.02	0.02	0.02	0.01	100	200	200	200	200	200
Sum							454.33					

Table 9. Heavy metal pollution Index (HPI) of water sample at Asejire reservoir at different sampling sites.

	$Q_i \times W_i$					Mean HPI				
	1	2	3	4	5	1	2	3	4	5
	2800	2800	1600	1200	800	294.75	294.75	292.11	291.23	290.35
	111110	111110	111110	111110	111110					
	4	4	3	3	3					
	20000	20000	20000	20000	20000					
Sum	**133914**	**133914**	**132713**	**132313**	**131913**					

The computed HPI values ranged from 290.35 to 294.75 across the stations, with individual values recorded as follows: Station 1 (294.75), Station 2 (294.75), Station 3 (292.11), Station 4 (291.23), and Station 5 (290.35) (Tables 8 and 9). All stations recorded HPI values exceeding the critical threshold of 100.

Correlation linear matrix for heavy metals

The result of correlation linear matrix of heavy metals as presented in Table 10 explains the association between the elements. It was observed that there is a strong

correlation between all the elements. That is, Cr has a strong correlation with Cd, Cu and Pb; Cd has a strong correlation with Cu and Pb; Cu has a strong correlation with Pb with ($p < 0.01$).

Factor analysis

Based on the results of the Kaiser-Meyer-Olkin (KMO) test ($0.5 \leq$ KMO), the data were determined to be suitable for statistical analysis (Kaiser 1960; Lance and Vandenberg 2009) (Table 11). Since the factors with values greater than 1 were determined, three factors were identified, and 78.87% of the cumulative value was explained (Table 12). The Scree Plot graph obtained became flattened after the 3rd factor (Figure 3).

Principal component analysis (PCA) was used to reveal the differences between the samples using the variables (Table 13). In this study, PCA results revealed the change explained by the correlation matrix and varimax rotation. Three principal components were identified. Based on the component matrix, the first PCA represents Dissolved Oxygen, Temperature, Nitrate, Chromium, Cadmium, Copper, and Lead; the second PCA represents Biological Oxygen Demand, pH, Conductivity and Phosphate, the third PCA represents Nitrate and Nitrite. Four PCs were revealed with eigenvalues > 1; these PCs explained 78.87% of the total variance in the dataset (Figure 4). All the heavy metals with some water quality parameters were grouped in the first component. The component plot was also compatible with these findings and showed that the general view is concentrated in a component. The heavy metals

Table 10. Correlation coefficient matrix for the metals at sampling locations.

	Chromium	Cadmium	Copper	Lead
Chromium	1			
Cadmium	.733**	1		
	.000			
Copper	.901**	.698**	1	
	.000	.000		
Lead	.785**	.835**	.891**	1
	.000	.000	.000	

**Correlation is significant at the 0.01 level (2-tailed).

Table 11. KMO and bartlett's analysis.

KMO and Bartlett's test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.701
Bartlett's Test of Sphericity	Approx. Chi-Square	867.47
	DF	66
	Sig.	.000

Table 12. Extraction sums of squared loadings.

	Initial Eigenvalues			Extraction sums of squared loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
PC1	5.297	44.141	44.141	5.297	44.141	44.141
PC2	2.443	20.360	64.501	2.443	20.360	64.501
PC3	1.724	14.366	78.867	1.724	14.366	78.867

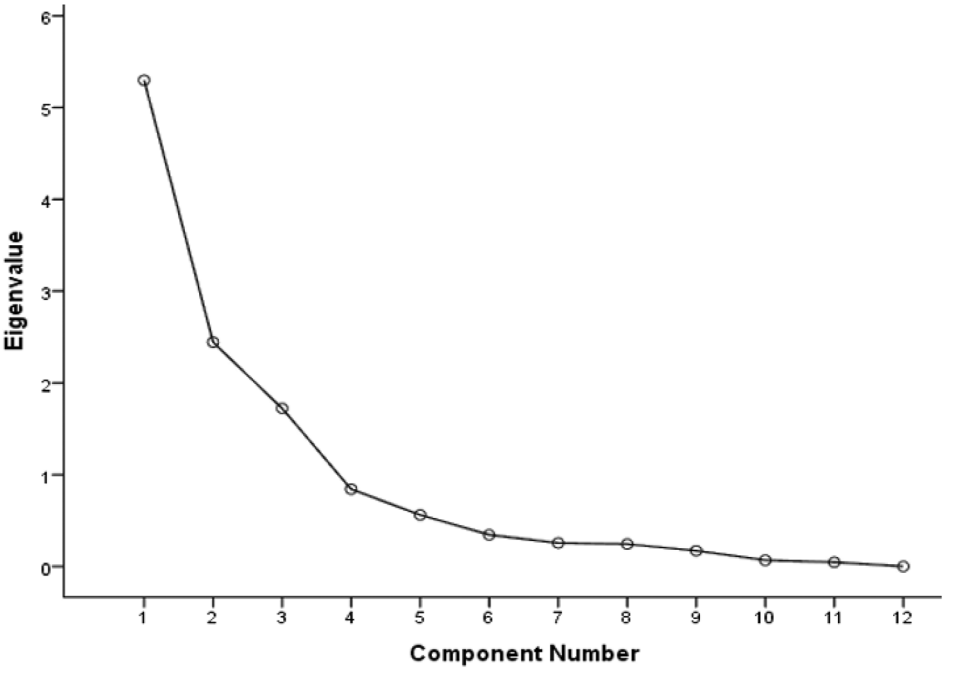

Figure 3. Scree plot of eigenvalues of components.

Table 13. Component matrix for water quality parameters and heavy metals from Asejire reservoir.

Parameters	PC1	PC2	PC3
Dissolved oxygen	.797		
Biological oxygen demand		−0.666	
Temperature	.881		
pH		.933	
Conductivity		.858	
Nitrate	−0.526		.687
Nitrite			.645
Phosphate		.533	
Chromium	.925		
Cadmium	.814		
Copper	.909		
Lead	.891		

reported in this study showed a similar origin and other sources of pollution in Asejire reservoir could come from organic matter, nutrient and dissolution of ions.

Extraction method: principal component analysis.

Cluster analysis showing similarity between sampling sites

The cluster analysis was performed using the standard method of Euclidean Distance and Ward's linkage method (Lance and Vandenberg 2009). Based on Figure 5, two groups were distinguished. The first cluster included locations of station 1, 2 and 3. The second cluster contained stations 4 and 5. This grouping showed evidence that some stations had similar sources of pollution from point

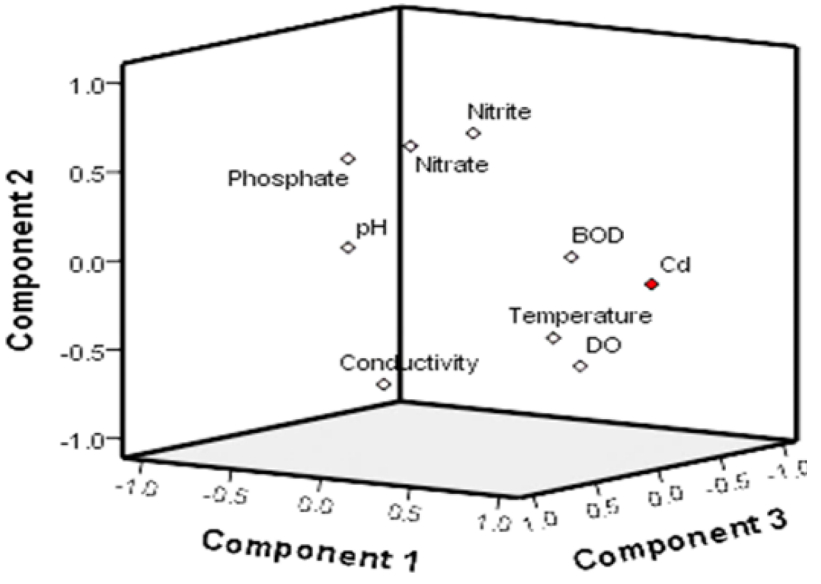

Figure 4. The view of component plot in rotated space.

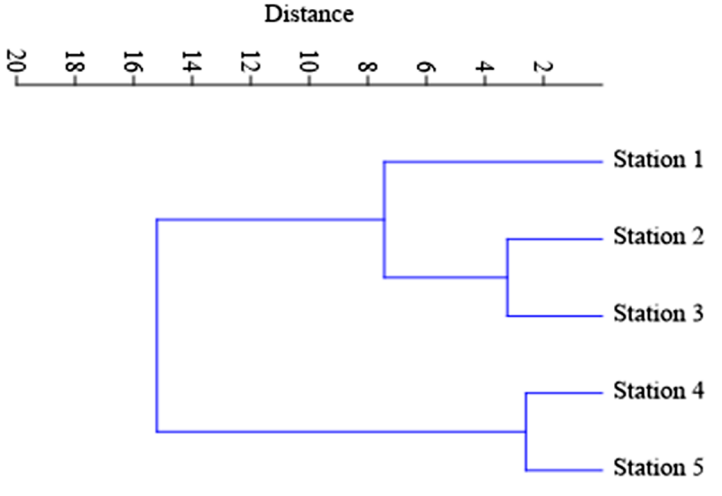

Figure 5. Dendrogram of cluster analysis of the concentration of all analyzed variables on stations.

or nonpoint sources. These sites (Station 1, 2, and 3) were polluted by industrial and agriculture activities.

Discussion

Spatial trends and pollution sources

Heavy metals tend to accumulate in reservoirs with slow flushing rates, posing significant risks to both aquatic ecosystems and human health (Salomons and

Stigliani 1995; Chiamsathit et al. 2020). In Asejire Reservoir, downstream areas exhibited the highest concentrations of metals in both water and sediments, most notably for chromium (Cr), cadmium (Cd), copper (Cu), and lead (Pb). This spatial pattern aligns with the reservoir's proximity to urban, industrial, and agricultural zones within its catchment, where runoff transports pollutants toward the lower reaches.

Sediment analysis in the present study revealed notably higher concentrations of chromium (Cr: 39.74 ± 9.60 mg/kg) compared to India's Ujani Reservoir (0.08 ± 0.03 mg/kg) as reported by Ghule et al. (2023). This substantial difference is likely due to poorly regulated effluent discharges from local textile industries operating with minimal enforcement of Nigeria's Environmental Standards and Regulations Enforcement Agency (NESREA) guidelines (Orosun et al. 2016). Likewise, lead (Pb) levels in sediments (7.01 ± 5.95 mg/kg) exceeded those recorded in Polish reservoirs (Sojka et al. 2022), potentially reflecting contamination from legacy leaded fuel use and active mining in Oyo State (Oladipo et al. 2014). When compared with Manchar Lake in Pakistan, sediment samples from this study showed higher concentrations of Cr, Pb, and copper (Cu: 16.03 ± 6.98 mg/kg), while Imran et al. (2023a, 2023b) reported considerably lower values (Cr: 17 mg/kg; Pb: 2.2 mg/kg; Cu: 1.5 mg/kg). Conversely, the levels of dissolved metals in water samples here were lower than those observed in Pakistan's major freshwater reservoirs (Imran et al. 2020, 2021).

Agricultural practices also appear to play a critical role in metal distribution. The predominance of zinc (Zn) and Cd in both water and sediments correlates with the continuous application of organopesticides and phosphate fertilizers common in Nigerian farmlands, which introduce these metals into aquatic systems *via* runoff (Fernández-Luqueño et al. 2013; Hossain et al. 2023; Imran et al. 2023a, 2023b). Furthermore, malfunctioning floodgates at Station 1 likely exacerbate contamination by prolonging the hydraulic residence time, thereby facilitating the adsorption and lateral transport of metals within the reservoir (Appiah-Opong et al. 2021).

Pollution indices and ecological risks

To evaluate contamination levels in the Asejire Reservoir, various pollution indices were applied. Heavy Metal Pollution Index (HPI) values exceeded 100 at all sampling stations, thereby classifying the reservoir as unsafe for drinking water, in accordance with the criteria outlined by Balakrishnan and Ramu (2016). Although general physicochemical parameters appeared to be within acceptable limits, the elevated HPI values revealed significant levels of heavy metals that are often undetected by standard analyses. This highlights the necessity of using metal-specific indices when assessing water quality for human consumption.

Ecological risk indices provided further insights into the potential environmental hazards posed by heavy metals. Among the metals evaluated, cadmium (Cd) exhibited the highest ecological risk, with a mean ecological risk factor (Er) of 349.2. According to Hakanson's classification (1980), this level falls within the considerable risk category, attributed to the high toxicity coefficient assigned to cadmium. Despite its low concentration in water (0.01 ± 0.00 mg/L), cadmium's acute toxicity poses

serious ecological concerns. Its presence is most likely due to agricultural runoff and domestic effluents, as supported by previous findings (Fernández-Luqueño et al. 2013; Utete and Fregene 2020). In contrast, chromium (Cr), copper (Cu), and lead (Pb) presented negligible to low ecological risks, with Er values below 150, which aligns with studies conducted in similarly affected reservoirs (Hasimuna et al. 2023; Jolaosho et al. 2023; Hasimuna et al. 2024).

The geo-accumulation index (Igeo) values, based on Müller's classification (Müller 1969), indicated moderate to heavy pollution for Cr, Cd, Cu, and Pb, with Igeo values greater than 1. This suggests that the primary sources of these metals are anthropogenic. Principal Component Analysis (PCA) corroborated this interpretation. Heavy metals showed strong loadings on the first principal component, with values as follows: Cr = 0.93, Cd = 0.81, Cu = 0.91, and Pb = 0.89. This pattern is consistent with findings from agricultural catchments where fertilizers and pesticides are major contributors to metal pollution (Yang et al. 2012). Comparable results were reported by Köse et al. (2023) in the Upper Sakarya River in Türkiye, where cadmium, nickel, and arsenic posed the greatest risks according to the Potential Ecological Risk Index, Biological Risk Index, and geo-accumulation index. In the current study, PCA accounted for over 81% of the total variance in metal concentrations, demonstrating the efficacy of multivariate statistical methods in identifying sources and patterns of contamination.

Despite sediment contamination, most of the metal concentrations in fish muscle tissues, with the exception of zinc (Zn), remained within internationally accepted limits. This suggests that under current conditions, the bioavailability of metals is relatively low. Similar findings were reported in the Darband and Samana streams in Pakistan, where molybdenum (Mo) exhibited very high contamination factors (CF = 15 to 20) and ecological risk indices ranging from 160 to 320, yet accumulation in fish was minimal (Din et al. 2023). These results reinforce the importance of evaluating sediment-bound metals, particularly because environmental changes such as pH alterations or dredging activities can remobilize these contaminants (Dragović and Mihailović, 2009; Siddiqui et al. 2024).

In contrast, Tokatlı et al. (2023) documented low ecological and health risks in Turkish ponds used for drinking and irrigation purposes, despite minor exceedances in manganese concentrations. By employing a combination of indices, including HPI, the Nemerow Pollution Index (NPI), Ecological Risk Index (ERI), and Absolute Principal Component Scores with Multiple Linear Regression (APCS-MLR), they demonstrated that metal presence could be attributed to both natural and anthropogenic sources. Their work underscores the value of integrated risk assessments, even in systems where contamination levels are relatively low.

Health and policy implications

The elevated ecological risk associated with cadmium contamination presents serious public health concerns for communities relying on Asejire Reservoir for fishing and irrigation. Chronic exposure to cadmium has been linked to renal dysfunction and bone demineralization, as observed in other Nigerian freshwater systems (Utete and Fregene 2020; Hasimuna et al. 2023). Although chromium concentrations

identified in this study do not currently pose an immediate carcinogenic risk, their values exceed global background concentrations by nearly 500-fold, raising concerns about potential long-term health effects if industrial discharges remain unregulated (Ouma et al. 2022). These findings underscore the urgency of strengthening environmental policy enforcement and implementing public health measures to mitigate exposure to toxic metals.

Limitations and future directions

The current study was limited by its single-season sampling design, which restricts insight into seasonal fluctuations in metal concentrations and bioavailability. Future studies should adopt a multi-seasonal approach to better capture temporal variability. Additionally, incorporating metal speciation analyses would enhance understanding of the bioavailable and toxic fractions of metals (Dusengemungu et al. 2022). Isotopic tracing techniques are also recommended for distinguishing between sources of lead contamination, such as mining operations and historical use of leaded fuels (Oladipo et al. 2014). Furthermore, continuous monitoring of metal accumulation in fish tissues would provide critical information regarding potential human health risks from fish consumption (Hasimuna et al. 2023). These future directions are essential for improving ecological risk assessment frameworks and guiding evidence-based management of aquatic ecosystems.

Conclusion

This study provides a detailed assessment of the physicochemical properties and heavy metal contamination in the Asejire Reservoir in southwestern Nigeria. The Water Quality Index (WQI) score of 74.23 suggests overall good water quality, with most parameters falling within national (NSDQW) and international (WHO) standards. However, elevated nitrite levels at Station 1 indicate localized contamination requiring targeted monitoring and remediation. Heavy metals including Chromium (Cr), Cadmium (Cd), Copper (Cu), and Lead (Pb) were present at varying concentrations, with bioconcentration factors indicating moderate uptake of Cr, Cu, and Pb in aquatic organisms. The geo-accumulation index revealed moderate to heavy pollution, and the ecological risk index identified Cd as the major contributor to ecological stress. Additionally, the Heavy Metal Pollution Index (HPI) values exceeded thresholds for safe drinking water, highlighting ongoing anthropogenic inputs. Multivariate analyses such as principal component analysis (PCA) and cluster analysis (CA) revealed clear patterns in contaminant distribution and helped identify potential pollution sources. These findings demonstrate spatial variability in contamination and underline the importance of continued monitoring and improved watershed management. Future research should explore heavy metal bioaccumulation in resident fish and invertebrate species to better assess ecological and human health risks. Incorporating seasonal trends and emerging pollutants will further strengthen the understanding of the reservoir's ecological health and support evidence-based strategies for conservation and sustainable water resource management.

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Ethical approval and consent to participate

Not applicable

Authors' contributions

OO, FDA and BBI: Research conceptualization; OO, FDA and BBI: Data Collection, Investigation and Analysis; All the authors participated in the writing of the original manuscript; OO: Project Administration; OJH, SM and HB: Data curation and validation; SM, HB and OJH: helped with reviewing and editing of the draft manuscript. All authors have read and approved the submission of the manuscript to the journal for publication.

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Data availability statement

The datasets and analyses generated during this study are available with the corresponding author upon reasonable request. The data is not publicly available due to privacy.

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