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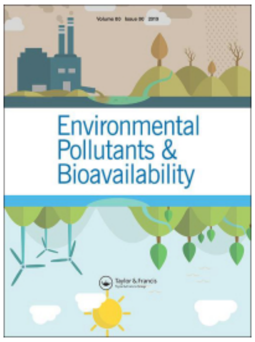

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Heavy metal contamination and ecological risk in Kabompo River, Northwestern Zambia

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ABSTRACT

Rivers are vital water sources that support aquaculture, agriculture, and domestic use, particularly in rural communities. Assessing heavy metal contamination and ecological risks is essential for sustaining these functions. This study assessed heavy metal contamination and ecological risks in the Kabompo River, Northwestern Zambia, by analysing water and sediment samples across ten sites. Water quality analysis revealed that Cadmium (Cd), Chromium (Cr), Cobalt (Co), Copper (Cu), Iron (Fe), Lead (Pb), and Zinc (Zn) concentrations were all within permissible limits set by the Zambia Bureau of Standards (ZS 190:2010), while nickel remained undetected. In sediments, the highest concentrations of zinc (23.56 ± 0.83 mg/kg), copper (31.43 ± 0.64 mg/kg), lead (4.50 ± 0.49 mg/kg), and cobalt (15.55 ± 0.58 mg/kg) occurred at the Kabompo – Lunga River confluence, while lower levels were observed at Chikalakala and Kauchimba. Enrichment factor analysis indicated severe enrichment of zinc, copper, and lead (EF > 10) at Chikalakala, Christella, and the confluence. Geoaccumulation index (I_{geo}) values were generally below zero, indicating no contamination, although copper approached moderate pollution levels at Christella and the confluence. Ecological risk indices (ERI) and contamination degrees (CD) indicated minimal ecological risk overall, though elevated metal levels at the confluence and Kalende warrant periodic monitoring. These findings suggest that the Kabompo River remains ecologically viable for aquaculture and other uses, but localised enrichment at selected sites highlights the need for routine monitoring and targeted pollution control to ensure sustainable use, particularly in regions influenced by mining activities.

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Contamination degree; ecological risk; geoaccumulation index; heavy metals; Kabompo River; water quality

Introduction

Rivers play a crucial role in sustaining biodiversity and providing ecosystem services such as fisheries, water purification, and habitat for aquatic life. They are also essential for human well-being, serving as sources of water for domestic and industrial use, aquatic food, and income. Globally, rivers supply over 60% of the world's freshwater, making them critical to both environmental integrity and socio-economic development [1,2]. Protecting river systems directly supports United Nations Sustainable Development Goals (SDGs), especially SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water), which emphasize sustainable management of aquatic resources. However, freshwater ecosystems remain highly vulnerable to anthropogenic pressures including pollution [3–7], with industrialisation, agriculture, and mining identified as major contaminant sources [8–12]. Heavy metal contamination is of particular concern due to its persistence, toxicity, and capacity for bioaccumulation in aquatic biota, posing significant ecological and human health risks [13–17].

Heavy metals such as Lead (Pb), Cadmium (Cd), Cobalt (Co), Copper (Cu), Zinc (Zn), Manganese (Mn), and Mercury (Hg) enter aquatic environments through both natural processes (e.g. weathering, volcanic activity) and anthropogenic pathways including mining effluents, wastewater discharge, and agricultural runoff [3,9–11,13,18–22]. These metals exhibit a strong affinity for sediments, creating persistent reservoirs where physical disturbances and biogeochemical changes can remobilize contaminants into biologically accessible

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forms [6,19,23,24]. This dynamic governs bioavailability, facilitating trophic transfer to fish and humans who depend on aquatic resources for nutrition and livelihoods [25–27].

In developing regions like Zambia, these risks are amplified by limited pollution control infrastructure [25,28,29] and climate-exacerbated water stress [18,21]. Zambia's Northwestern Province, endowed with extensive Cu, Co, and Au deposits, faces elevated contamination risks due to intensified mining activity [3,10,30]. The Kabompo River, a socio-ecologically vital Upper Zambezi tributary supporting fisheries, agriculture, and aquaculture broodstock, drains this mineral-rich region. Despite its importance, spatial patterns of metal contamination and associated bioavailability mechanisms remain unquantified, hindering evidence-based risk assessment and management.

This study therefore aims to:

(1) Quantify concentrations of Cd, Co, Cu, Mn, Ni, Pb, and Zn in water and sediments across the Kabompo River continuum.
(2) Evaluate spatial contamination gradients using geochemical indices (I_{geo}, EF, CD).
(3) Characterize potential bioavailability drivers through sediment-metal interactions and hydrological variables.
(4) Assess ecological and human health risks to establish bioavailability-informed management baselines.

Methodology

Study site

The Kabompo River, a principal tributary of the Upper Zambezi, traverses 440 km through Zambia's Northwestern Province, draining a catchment of approximately 14,000 km^2. This hydrosystem sustains critical socioeconomic functions including agricultural irrigation, artisanal fisheries, and domestic water supply for rural communities across Mufumbwe, Manyinga, Kabompo and Kasempa districts. Notably, it serves as a primary source of tilapia broodstock for Zambia's aquaculture sector. However, extensive artisanal mining operations (Cu, Co, and Au) along its course, coupled with agricultural runoff and settlement impacts, present tangible risks of trace metal contamination [3,31].

Ten sampling sites (Figure 1) were strategically positioned to capture environmental gradients:

- Upstream agricultural zones (Kashima and Kauchimba) exhibit shallow waters with documented grey-water runoff, particularly at Kauchimba where banana plantations dominate.
- Mid-reach sites demonstrate mixed influences: Chikalakala's subsistence farming areas feature clear vegetated shallows, while Jivundu combines fishing with low-level domestic runoff.
- High-activity fisheries nodes (Christella, Mukoka, and Ntabo) are characterized by artisanal fishing pressure, crocodile presence, and macrophyte proliferation, with Ntabo additionally influenced by rural settlement.
- Critical confluence zones include the Lunga River junction (Confluence site), where sediment loading interacts with intense hippopotamus and crocodile activity within the Game Management Area.
- Key mining and agricultural-impacted areas include Kalende, characterized by active artisanal mining alongside subsistence farming and fishing activities, where clear-to-greywater runoff converges with geothermally influenced shallows from a local hot spring; and Mubanga, exhibiting probable mining-associated sediment resuspension near human settlements.

Triplicate sediment samples (0–10 cm depth) were collected at 5 km intervals for the analysis of Cd, Co, Cu, Fe, Mn, Ni, Pb, and Zn, with concurrent water sampling at each location.

Water and surface sediment sampling

Water and surface sediment sampling was conducted once between April and August, corresponding to the dry season. Water samples were collected from ten sampling sites along the Kabompo River using acid-washed polyethylene bottles with a capacity of 500 ml. At each site, three replicate samples were combined

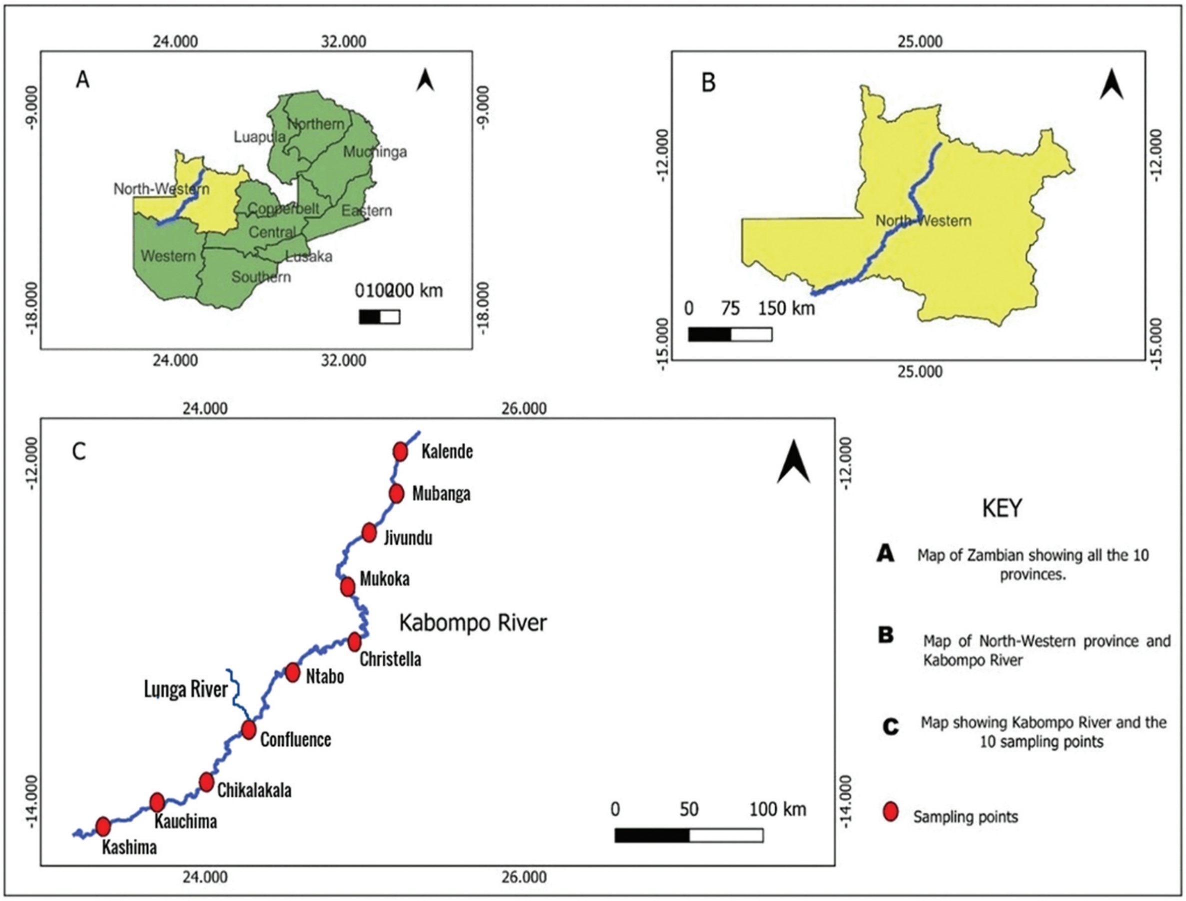

Figure 1. The map of Kabompo River (B) in Zambia (A) and ten sampling sites (C).

to form a composite sample. The collected water was stored in a cooler box and transported to the Mufumbwe Veterinary Field Laboratory within 8 hours of collection, where it was refrigerated. Later, the samples were transported to the Zambia Bureau of Standards (ZABS) for analysis. From each composite sample, a 100 ml portion was taken and filtered through a Whatman™ filter paper (No. 91, 12.5 cm). A 25 ml portion of the filtered water was transferred into a 100 ml volumetric flask, acidified with 1 ml of nitric acid (HNO_3), and topped up with distilled water. These filtered and acidified samples were analysed using a flame Atomic Absorption Spectrophotometer (AAS, Shimadzu, Model: AA-7000, Japan).

Surface sediment samples were collected simultaneously using a Van Veen sediment grab and placed in polyethylene containers. Three replicates were taken at each site, combined into a composite sample. In the laboratory, the sediment samples were spread onto trays and oven-dried at 105°C for 48 hours. Dried sediments were then ground using a mortar and pestle to create a fine texture. 2 g ground sediment was transferred into a 500 ml beaker, and 30 ml of aqua regia (2 parts HCl to 1-part HNO_3), 20 ml of hydrochloric acid (HCl), and 10 ml of HNO_3 were added. The mixture was heated on a hot plate until the volume was reduced to approximately 10 ml. After cooling, 50 ml of distilled water was added to the solution. A 25 ml aliquot of the filtered solution was transferred to a 100 ml volumetric flask, acidified with 1 ml of HNO_3, and diluted to the mark with distilled water. These prepared samples were analysed using the same AAS instrument. The recovery rates for spiked heavy metals ranged between 90% and 105%.

Contamination control and data quality control

To ensure the reliability of data and assess potential contamination, rigorous quality control and quality assurance measures were implemented. Blank samples, free of detectable metal concentrations, were systematically analysed after every five samples. The metal concentrations were measured on a dry weight basis, with each sample analysed in triplicate to enhance precision and accuracy. Internal reference, blank, and spiked samples were processed using an AAS to analyse heavy metals, including Cd, Co, Cu, Fe, Pb, Mn, Ni, and Zn, with recovery rates ranging from 90% – 95%. Quality assurance was undertaken to verify the accuracy, stability, consistency, and reliability of the analytical instruments used. To prevent contamination, all laboratory equipment, particularly glassware, underwent thorough pre-treatment, including washing with deionised water, overnight soaking in 30% HNO_3, repeated rinsing with deionised water, and heat-drying. These stringent procedures ensured the generation of contamination-free equipment and reliable analytical results.

Evaluation of potential environmental risks

The indices of enrichment factor (EF), geoaccumulation index (I_{geo}), contamination factor, contamination degree, ecological risk index (ERI), and risk index (RI) were used to estimate potential environmental risks of the analysed heavy metals from surface sediments. The potential environmental risks were analysed following the method of Li et al. [32] and Mavakala et al. [29].

Enrichment factor (EF)

This method assumes that, under natural conditions, there is a linear relationship between the conservative elements and heavy metals. Any variation in the concentration of the conservative element, caused by natural factors, is expected to result in a proportional change in the concentration of the other metals [33]. The EF was determined using the following Equation (1) [33,34]:

$$EF = \frac{\left(\frac{Concentration\ of\ metal_m}{Fe_m}\right)_{Sample}}{\left(\frac{Concentration\ of\ metal_i}{Fe_C}\right)_{Background}} \tag{1}$$

where $Concentrationofmetal_m$ is the mean concentration of the specific heavy metal from the sample; Fe_m is the mean concentration of the reference heavy metal in the analysed sample. Reference can be either Aluminum (Al), Scandium (Sc), or Iron (Fe), because they are relatively abundant, stable, and unaffected by anthropogenic activities. For this study, Fe was chosen as the reference heavy metal to calculate EF. Furthermore, $Concentrationofmetal_i$ is the background concentration of a specific metal, and Fe_C is the background concentration of Fe.

The geo-accumulation index (I_{geo})

The I_{geo} is used to assess and quantify metal contamination in sediments by comparing current concentrations with pre-industrial levels. This index has been widely employed to evaluate metal contamination resulting from both natural geological processes and anthropogenic activities [29,34–36]. The I_{geo} was calculated using Equation (2) described by Varol [34] and Mavakala et al. [29]:

$$I_{geo} = \log_2\left(\frac{Concentration_m}{1.5 * Concentration_B}\right) \tag{2}$$

where $Concentration_m$ is the mean concentration of the specific analysed metal, and $Concentration_B$ is the background concentration of specific heavy metal.

It is worth noting that different background concentrations of heavy metals were used to calculate *EF* and I_{geo} depending on whether the analysed concentrations were from sediments or soil. The background concentrations used were obtained from [15] Bradford et al. [37], Håkanson [38], Senze et al. [39], and Zhang and Liu [40].

Contamination factor (CF)

The CF indicates the ratio of the average metal concentration from the sample to the background concentration. It is used to quantify the extent of pollutant contamination in the soil or sediments [29,34]. CF was calculated as follows [34,38,41,42]:

$$CF = \frac{Concentration_m}{Concentration_B} \quad (3)$$

where $Concentration_m$ is the mean concentration of the specific metal in the sample, and $Concentration_B$ is the background concentration of the same heavy metal. $CF < 1$ indicates minimal contamination; $1 \le CF < 3$ indicates moderate contamination; $3 \le CF < 6$ indicates considerable contamination; $CF \ge 6$ indicates extreme contamination.

Contamination degree

The degree of contamination indicates the extent of pollution by multiple heavy metals at each sampling point. It helps estimate the overall poly-metallic contamination before detailed analysis [3,29]. It was calculated by adding the concentrations of various heavy metals found at each sampling location using the following formulae [38,43,44].

$$Contaminationdegree = \sum CF_i \quad (4)$$

where CF_i is the contamination factor of the analysed metals — Zn, Mn, Cu, Pb, Cd, Cr, Hg, Fe, K, Na, Ca, and Mg — determined for each site. The classification for CD is as follows: $CD < 6$: low contamination; $6 \le CD < 12$: moderate contamination; $12 \le CD < 24$: considerable contamination; $CD \ge 24$: very high contamination.

Ecological risk factor (ERI)

The ecological risk factor is an indicator used to assess the harmful effects of contaminants on the environment and human health. It reflects the toxicity and ecological sensitivity of contaminant concentrations. The ERI was calculated by taking the product of contamination factor of each heavy metal and its toxic-response factor as follows [29,36,38]:

$$Eri = Trf_i * CF_i \quad (5)$$

where Trf_i, is the toxic response factor, and CF_i is the contamination factor of heavy metals such as Zn, Mn, Cu, Pb, Cd, Cr, Hg, and Fe. The Eri of K, Na, Ca, and Mg were not calculated, as the corresponding Trf_i values are unavailable, indicating that they don't pose a toxic risk to the environment or human health. The ecological risk based on ERI is interpreted based on the classifications as follows: $Eri < 40$: a low ecological risk; $40 \le Eri < 80$: a moderate ecological risk; $80 \le Eri < 160$: a considerable ecological risk; $160 \le Eri < 320$: a high ecological risk; and $Eri \ge 320$: a very high ecological risk.

The potential ecological risk index (RI)

The RI is a comprehensive assessment tool that evaluates the combined effects of heavy metal toxicity, concentration levels, ecological sensitivity, and synergistic interactions [29]. The calculated ERI values for each heavy metal per site were summed up to estimate the potential ecological risk index using the following formulae [29,38]:

$$RI = \sum ERI_i \quad (6)$$

where ERI_i is the ecological risk factor for each metal. The potential ecological risk index is categorized as follows: $RI < 150$ indicates low ecological risk or pollution. $150 \le RI < 300$ suggests moderate ecological risk or pollution. $300 \le RI < 600$ indicates considerable ecological risk or severe pollution. $RI \ge 600$ signifies very high ecological risk or serious pollution.

Data analysis

The Shapiro-Wilk test for normality and Fligner-Killeen test for homogeneity of variance were performed to assess the distribution characteristics of the data. The results indicated that the data followed a normal distribution ($p > 0.05$) and exhibited homogeneity of variance ($p > 0.05$). Therefore, a one-way analysis of variance (ANOVA) was conducted to determine statistically significant differences in heavy metal concentrations among the sampling sites. Where significant differences were detected, the Tukey's Honestly Significant Difference (HSD) post hoc test was applied to identify pairwise differences between sampling sites. To further investigate spatial variations in heavy metal concentrations in sediment samples, Principal Component Analysis (PCA) was performed to identify patterns in the dataset. This was followed by a Permutational Multivariate Analysis of Variance (PERMANOVA) to assess the influence of sampling site on heavy metal concentrations. Additionally, descriptive statistical analyses were conducted to evaluate potential environmental risks associated with heavy metal contamination. All statistical analyses were conducted using R [45], with a significance level of $p < 0.05$.

Results

Concentrations of heavy metals in water

The analysis of heavy metal concentrations in Kabompo River water showed that all measured parameters complied with Zambia Bureau of Standards (ZS 190:2010) permissible limits for drinking water (Table 1). Cd, Cr, Co, Cu, Fe, Pb, and Zn were all detected at levels below their respective thresholds, indicating satisfactory water quality. Notably, Ni concentrations were below the detection limit (< 0.01 mg/L), but no standard exists for comparison.

Concentrations of heavy metals in surface sediments

The concentrations of heavy metals in surface sediments are presented in Table 2, with each heavy metal varying significantly across the sites. Confluence had the highest concentrations of Zn (23.56 ± 0.83), Co (15.55 ± 0.58), Pb (4.50 ± 0.49), Ni (6.23 ± 0.77), and Cu (31.43 ± 0.64), suggesting potential localized sources or environmental factors that increase metal accumulation. Furthermore, Kalende had higher concentration of Co (16.58 ± 0.60), Pb (4.52 ± 0.54) and Co (28.79 ± 1.25). In contrast, Kashima and Kauchimba had consistently lower metal concentrations, especially for Pb and Ni, indicating reduced exposure to or retention of these metals. Sites like Chikalakala and Jivundu had relatively lower levels of heavy metals in sediments among all sites sampled.

Table 1. Comparison of heavy metal concentrations in Kabompo River water with Zambia Bureau of Standards (ZS 190:2010) permissible limits for drinking water.

Parameter	ZS 190:2010 Limit (mg/L)	Measured Concentration (mg/L)	Compliance Status
Cd	0.003	<0.001	Satisfactory
Cr	0.05	<0.01	Satisfactory
Co	0.5	<0.01	Satisfactory
Cu	2.0	<0.01	Satisfactory
Fe	0.3	<0.01	Satisfactory
Ni	Not Specified	<0.01	–
Pb	0.01	<0.01	Satisfactory
Zn	3.0	<0.01	Satisfactory

Table 2. Concentration of different heavy metals in surface sediments from ten sites in Kabompo River.

Site	Zn	Co	Pb	Ni	Cu	Fe
Chikalakala	10.31±0.50^{a}	9.66±0.51^{a}	1.56±0.12^{a}	3.58±0.53^{ab}	17.49±0.91^{a}	1241.33±40.02^{a}
Christella	15.10±1.53^{a}	13.24±0.72^{ab}	3.26±0.34^{ab}	5.41±0.67^{b}	26.96±0.41^{ab}	1244.67±46.61^{a}
Confluence	23.56±0.83^{b}	15.55±0.58^{b}	4.50±0.49^{b}	6.23±0.77^{b}	31.43±0.64^{b}	1240.00±50.57^{a}
Jivundu	11.65±0.71^{a}	12.32±1.21^{ab}	2.45±0.13^{a}	4.00±0.29^{ab}	22.95±1.65^{a}	1418.00±70.09^{a}
Kalende	18.72±1.16^{ab}	16.58±0.60^{b}	4.52±0.54^{b}	4.27±0.71^{ab}	28.79±1.25^{b}	1207.00±45.12^{a}
Kashima	12.57±0.61^{a}	10.55±0.62^{a}	1.88±0.11^{a}	1.60±0.49^{a}	20.28±2.39^{a}	1243.00±26.15^{a}
Kauchimba	11.54+1.46^{a}	8.24±0.49^{a}	1.22±0.18^{a}	3.21±0.70^{a}	15.35±1.34^{a}	1250.00±38.51^{a}
Mubanga	17.55±1.42^{ab}	14.22±0.50^{ab}	3.09±1.05^{ab}	4.24±0.69^{ab}	25.90±1.55^{ab}	1223.33±8.08^{a}
Mukoka	14.94±1.43^{a}	12.21±0.88^{a}	3.52±0.17^{ab}	4.48±0.35^{ab}	21.51±0.87^{a}	1246.67±49.41^{a}
Ntabo	15.35±1.39^{a}	10.27±1.23^{a}	2.23±0.21^{a}	2.32±0.31^{a}	19.09±1.71^{a}	1219.33±35.23^{a}

Data is presented as Mean (±SD) concentrations of heavy metals in sediments across sampling sites. Superscript letters indicate significant differences between means ($p < 0.05$), determined using one-way ANOVA followed by Tukey's HSD post hoc test.

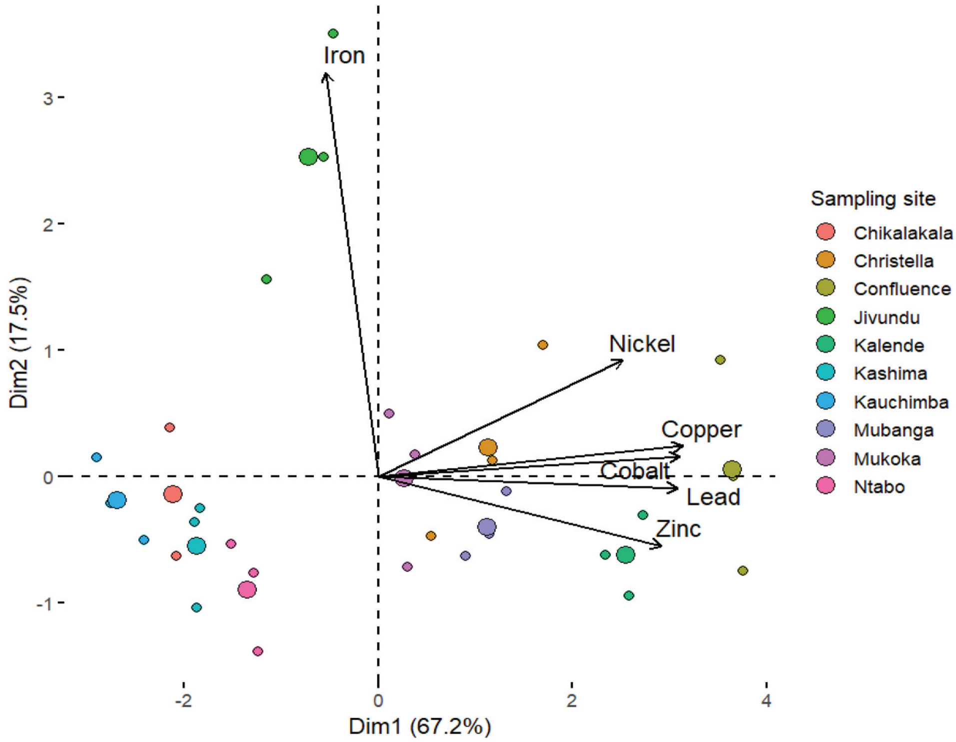

Figure 2. Principal component analysis (PCA) of heavy metal concentrations in surface sediment samples across ten sites in Kabompo River.

Principal component analysis of heavy metal distribution in sediments across sampling sites

The biplot presented in Figure 2 demonstrates a clear differentiation of samples based on concentrations of heavy metals in sediments across various sampling sites. The PCA results indicate that the confluence had higher concentration of Zn, Pb, Ni, Cu, and Co, while Jivundu had high Fe levels, and Kalende was associated with Pb and Zn. In contrast, Ntabo, Kauchimba, Kashima, and Chikalakala had lower levels of Co, Cu, Ni, Pb and Zn, and Mubanga, Mukoka, and Christella had a balanced metal concentration across the studied heavy metals. This was further supported by the results from PERMANOVA, which revealed significant differences in heavy metal concentrations among the sites (Pseudo $F = 12.15$, p-perm = 0.001). Additionally, an analysis of the similarity of dispersion for the normalized data among the sampling sites showed no significant variation (p-perm = 0.98), reinforcing the robustness of the data for the PERMANOVA analysis regarding the influence of sampling sites on heavy metal levels in sediments.

Dim.1 and Dim.2 accounted for 84.65% of the cumulative variance, indicating that the first two dimensions together capture most of the data's structure. This means Dim.1 and Dim.2 are the most critical for representing the data, with a cumulative explained variance of 84.65%, allowing the data to be effectively represented in a two-dimensional space.

Enrichment factors and spatial distribution of heavy metals

The heat map (Figure 3) provides a visual representation of the EFs of heavy metals across ten sampling sites in the study area. EFs for Zn, Co, Pb, Ni, and Cu are presented, with shading corresponding to the severity of enrichment based on a defined scale. The site-specific EF varied significantly across the heavy metals studied. Zn showed severe enrichment ($EF \geq 10$) at Chikalakala, Christella, Confluence, Kalende, and Mubanga, with moderate to minor enrichment observed at the remaining sites. Co predominantly exhibited minor enrichment ($1 \leq EF < 3$) across most sites, with moderate enrichment observed at Kalende. Pb displayed severe enrichment at Kalende, Confluence, and Christella, while Mukoka exhibited moderate enrichment, and the rest of the sites fell within minor

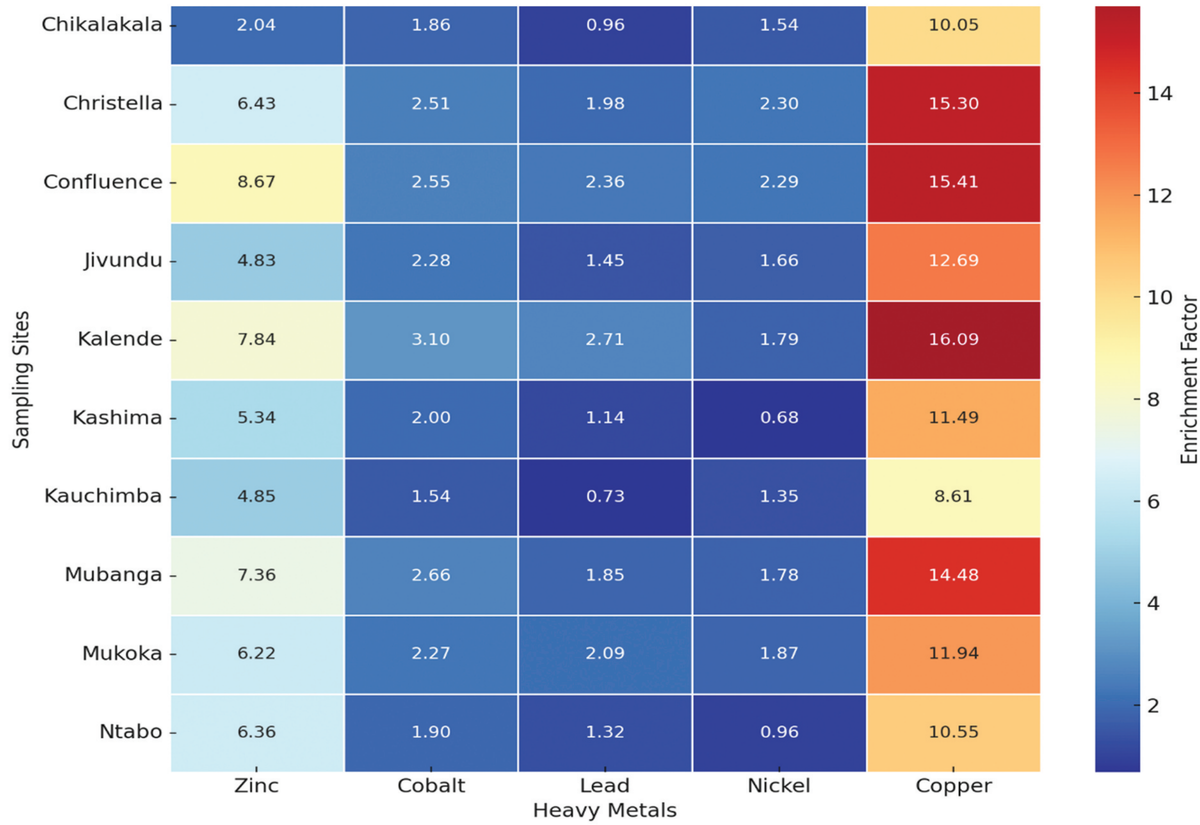

Figure 3. Heat map of enrichment factors (EF) for heavy metals (Zn, Co, Pb, Ni, and Cu) across ten sites in Kabompo River. The colour gradient indicates the level of enrichment severity, with red shades representing severe enrichment, orange denoting moderate enrichment, yellow indicating minor enrichment, and pale yellow or white showing no enrichment following the description. Key for Enrichment Factor (EF): EF < 1: No enrichment; 1 ≤ EF < 3: Minor enrichment; 3 ≤ EF < 5: Moderate enrichment; 5 ≤ EF < 10: Severe moderate enrichment; 10 ≤ EF < 25: Severe enrichment; 25 ≤ EF < 50: Very severe enrichment; EF ≥ 50: Extremely severe enrichment.

or no enrichment categories. Ni showed minor enrichment at most sites, except for moderate enrichment at Chikalakala and Christella. Cu displayed severe enrichment at multiple sites, including Chikalakala, Christella, Confluence, Kalende, and Mubanga, with moderate enrichment at the other sites. The colour gradients in the heat map aid in the quick identification of patterns, with red shades indicating severe enrichment, orange representing moderate enrichment, yellow denoting minor enrichment, and pale yellow or white indicating no enrichment. The spatial variations in enrichment factors highlight the need for site-specific monitoring and management interventions to mitigate potential ecological and health impacts.

Geoaccumulation index (I_{geo}) assessment of heavy metal contamination

The I_{geo} values for heavy metals across ten sampling sites in the Kabompo River are presented in Table 3. The I_{geo} values for Zn, Co, Pb, Ni, Cu, and Fe ranged from −4.81 to −0.10. Based on the I_{geo} classification, most metals at all sites fell into Class 0, indicating no contamination, as their values are below 0. However, Cu exhibited values nearing 0 at several sites, such as Christella (−0.32) and the Confluence (−0.10), suggesting a borderline shift towards Class 1, which denotes unpolluted to moderately polluted conditions. The remaining metals, including Zn, Co, Pb, Ni, and Fe, consistently demonstrated low I_{geo} values, indicating no contamination throughout the sites.

Table 3. Geoaccumulation index (I_{geo}) values for heavy metals in water and sediments across ten sites in the Kabompo River.

Site	Zn	Co	Pb	Ni	Cu	Fe
Chikalakala	−3.25	−3.39	−4.34	−3.65	−0.95	−4.28
Christella	−2.70	−2.93	−3.27	−3.06	−0.32	−4.26
Confluence	−2.06	−2.70	−2.81	−2.85	−0.10	−4.05
Jivundu	−3.07	−3.03	−3.68	−3.49	−0.56	−4.22
Kalende	−2.39	−2.61	−2.80	−3.40	−0.23	−4.24
Kashima	−2.96	−3.26	−4.07	−4.81	−0.74	−4.26
Kauchimba	−3.09	−3.61	−4.69	−3.81	−1.14	−4.24
Mubanga	−2.48	−2.83	−3.35	−3.41	−0.38	−4.24
Mukoka	−2.72	−3.05	−3.16	−3.33	−0.65	−4.23
Ntabo	−2.68	−3.30	−3.82	−4.28	−0.82	−4.22

Key for I_{geo} as described Håkanson [38], and Mavakala et al. [29]: Class 0 ($I_{geo} \leq 0$): Unpolluted – Metal concentrations are at or below natural background levels, indicating no pollution; Class 1 ($0 < I_{geo} \leq 1$): Unpolluted to moderately polluted – Metal concentrations slightly exceed the background level, showing minor pollution; Class 2 ($1 < I_{geo} \leq 2$): Moderately polluted – Metal concentrations are significantly above the background level, indicating moderate pollution; Class 3 ($2 < I_{geo} \leq 3$): Moderately to heavily polluted – Metal concentrations are well above the background level, showing significant pollution; Class 4 ($3 < I_{geo} \leq 4$): Heavily polluted – Metal concentrations are much higher than the background level, reflecting heavy pollution; Class 5 ($4 < I_{geo} \leq 5$): Heavily to extremely polluted – Metal concentrations are severely enriched, indicating very high pollution; Class 6 ($I_{geo} > 5$): Extremely polluted – Metal concentrations are extraordinarily high, reflecting extreme pollution.

Heatmap analysis of heavy metal distribution across sampling sites

Cu showed significantly higher concentrations (indicated by the bright red colour) at most sites, particularly at the Confluence, Kalende and Christella. Other metals, such as Zn, had moderately high values, while Fe, Ni and Co showed lower and more consistent concentrations across the sites. On the other hand, Pb had a more varied distribution, with moderate levels at some sites and lower levels at others. This heatmap highlights the variations in heavy metal contamination levels and helps identify areas with potential pollution concerns, with the Confluence standing out due to the high Cu concentrations (Figure 4).

Spatial variability in heavy metal contamination across sampling sites

The contamination degree of multiple heavy metals at ten sampling sites along the Kabompo River is presented on Figure 5. The Confluence site exhibited the highest contamination degree, followed by Kalende, indicating significant heavy metal accumulation at these locations. In contrast, Chikalakala and Kauchimba showed the lowest contamination degrees, reflecting minimal heavy metal accumulation. These variations suggest spatial heterogeneity in contamination, potentially influenced by site-specific environmental and anthropogenic factors.

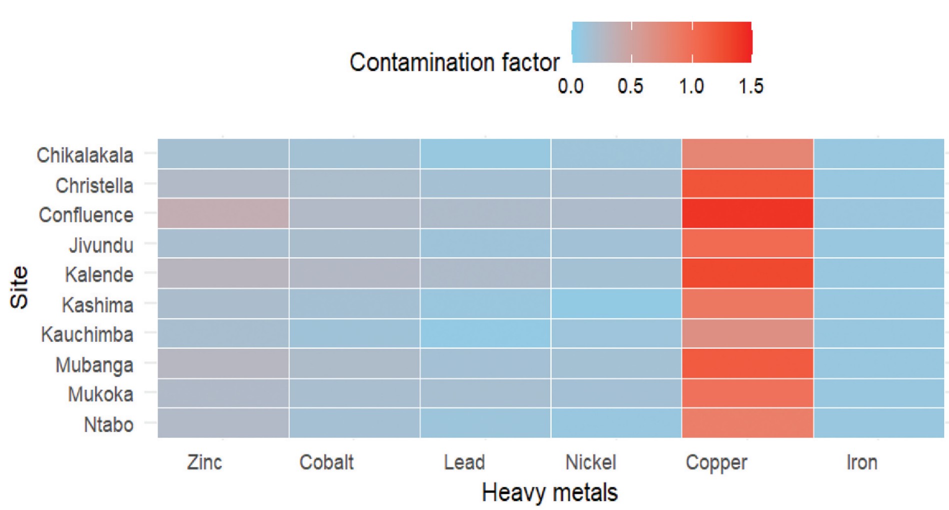

Figure 4. The heatmap shows the contamination factors of heavy metals across ten sampling sites in the Kabompo River.

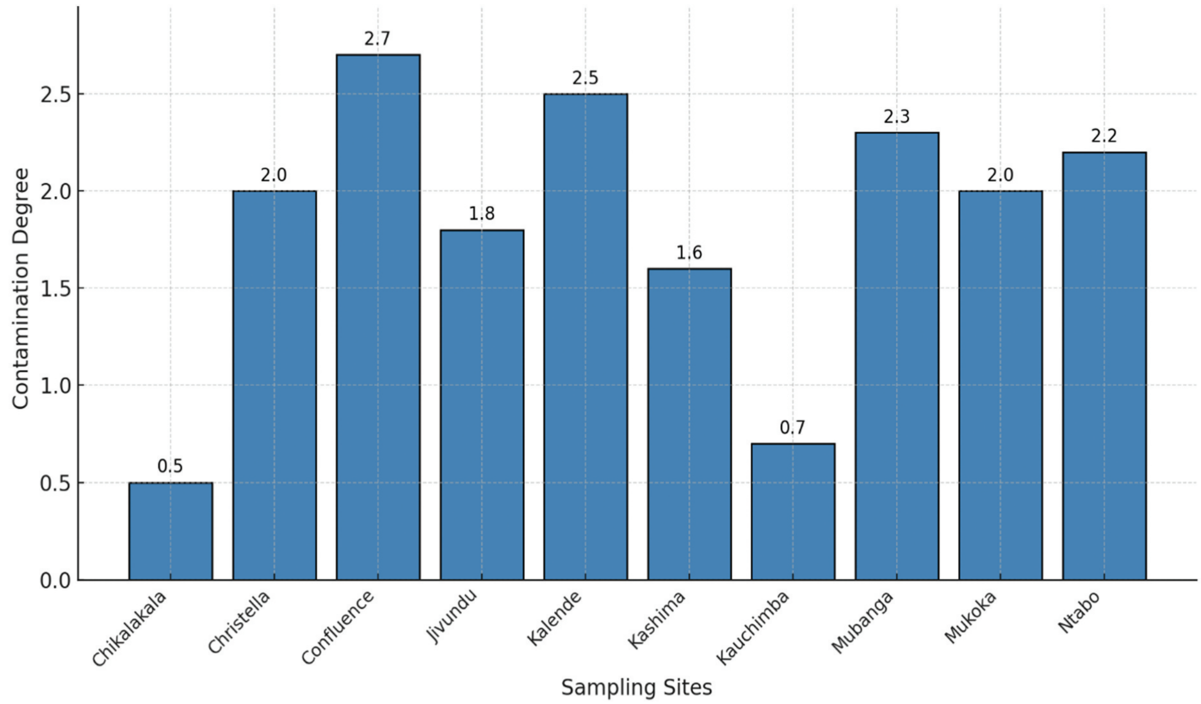

Figure 5. Contamination degree of ten sampling sites in the Kabompo River based on multiple heavy metals.

Ecological risk assessment (ERI) of heavy metal contamination across sampling sites

ERI of heavy metals across ten sampling sites are presented in Table 4. All sites showed low ecological risk for each metal. Confluence and Kalende had relatively higher concentrations of Zn, Pb, and Cd, but these values were still below concerning thresholds. No immediate ecological threat is indicated; however, Confluence and Kalende might warrant periodic monitoring due to relatively higher metal levels.

Spatial variability in heavy metal risk indices across sampling sites

The risk indices varied across the sampling sites in the Kabompo River, highlighting spatial differences in potential environmental risks (Figure 6). The Confluence site exhibited the highest risk index (1.15), indicating the most significant level of concern, followed closely by Kalende (1.10), which also displayed elevated risk levels. In contrast, the lowest risk indices were observed at Kauchimba and Chikalakala, suggesting minimal risk levels at these sites.

Table 4. Ecological risk index (ERI) values of heavy metals across ten sampling sites in the Kabompo River.

Site	Zn	Mn	Cu	Pb	Cd	Fe
Chikalakala	0.16	0.05	0.01	0.12	0.16	0.08
Christella	0.23	0.07	0.03	0.18	0.24	0.08
Confluence	0.36	0.08	0.04	0.21	0.28	0.09
Jivundu	0.18	0.06	0.02	0.13	0.20	0.08
Kalende	0.29	0.08	0.04	0.14	0.26	0.08
Kashima	0.20	0.05	0.02	0.05	0.18	0.08
Kauchimba	0.18	0.04	0.01	0.11	0.14	0.08
Mubanga	0.27	0.07	0.03	0.14	0.23	0.08
Mukoka	0.23	0.06	0.03	0.15	0.19	0.08
Ntabo	0.23	0.05	0.02	0.08	0.17	0.08

Ecological Risk Index (ERI) categories for single metals (Potential Ecological Risk Factor, E_r) as described by Håkanson [38]; Mavakala et al. [29]: $E_r < 40$, Low Risk; $40 \leq E_r < 80$, Moderate Risk; $80 \leq E_r < 160$, Considerable Risk; $160 \leq E_r < 320$, High Risk; $E_r \geq 320$, Very High Risk.

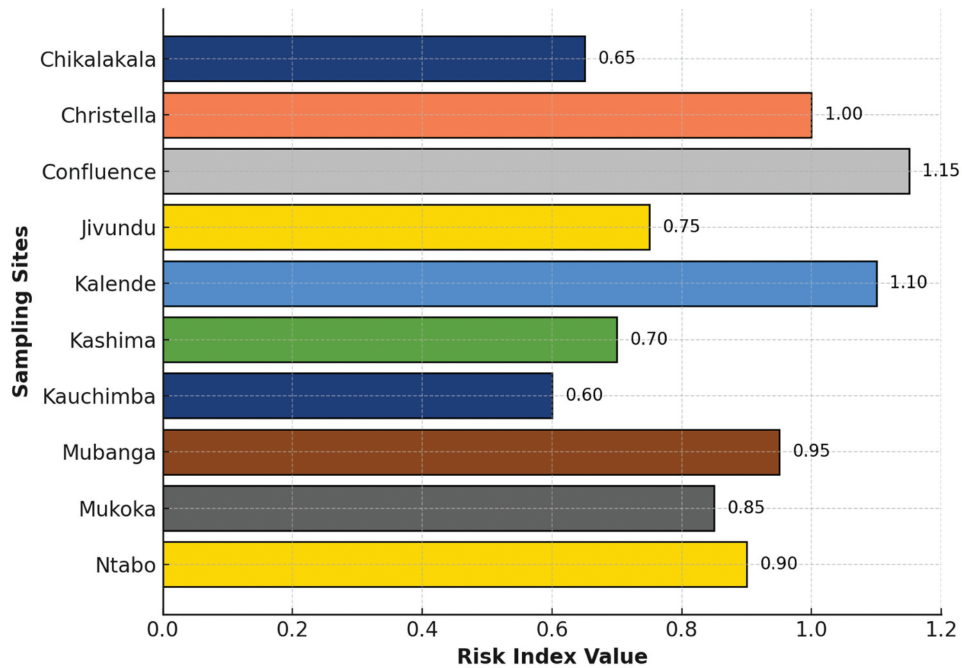

Figure 6. Variations in risk index values across the ten sampling sites in the Kabompo River.

Discussion

Overall contamination status and bioavailability implications

Our assessment indicates minimal heavy metal contamination in the Kabompo River's water column, with concentrations below detection limits and compliant with Zambian drinking water standards. This suggests current water use for domestic purposes remains safe. Crucially, the absence of detectable metals in water, despite sediment enrichment for some elements, highlights the limited bioavailability of these contaminants under prevailing conditions. This is likely governed by factors favouring metal partitioning to sediments: the neutral to alkaline pH promotes precipitation and sedimentation [46], while low electrical conductivity correlates with reduced soluble metal fractions [47]. This dynamic aligns with observations that rivers can effectively retain metals in sediments unless subjected to recent inputs or significant disturbance [3,48].

Sediment contamination: sources, patterns, and risk assessment

Spatial analysis revealed distinct patterns in sediment metal concentrations. Fe dominated across sites, consistent with natural geological enrichment reported in similar riverine systems [49,50]. Conversely, Pb levels were consistently low, indicating minimal associated risk. EF analysis confirmed moderate enrichment overall, with Cu showing severe enrichment at all sites and Zn exhibiting severe to moderate enrichment at Kalende, Mubanga, and Confluence. This enrichment likely stems from a combination of the region's inherent geochemistry [51,52] and localized anthropogenic inputs, particularly from Artisanal and Small-scale Mining (ASM) activities prevalent in Northwestern Province [3]. While ASM operations, often lacking formal waste management, are known sources of Cu, Pb, and Zn via tailings and runoff [3,30,53], their impact here appears spatially confined rather than basin-wide.

Despite Cu and Zn enrichment, the I_{geo} classified the Kabompo as unpolluted. Similarly, CF indicated minimal contamination for most metals, except Cu which showed higher levels. This discrepancy between EF/CF for Cu and the overall 'unpolluted' status underscores the importance of integrated risk assessment. The river's slow-moving, low-turbulence nature [54] likely facilitates Cu sedimentation, potentially limiting its immediate bioavailability but warranting monitoring. The calculated overall ecological risk remains low, contrasting sharply with systems heavily impacted by industrial mining or dredging (e.g. [41,55]). Higher contamination degrees at Kalende, Confluence, and Mubanga align with plausible local stressors: potential transboundary inputs from Democratic Republic of the Congo (DRC) mining upstream [56], local fishing/sediment resuspension, wildlife activity (e.g. nutrient cycling by hippos/crocodiles [57]), and proximity to ASM. These site-specific variations highlight the influence of land use, hydrology, and sediment composition (e.g. clay content enhancing metal binding [58,59]) on contaminant distribution and potential bioavailability.

Contextualization and implications for management

The Kabompo's relatively low contamination levels, particularly the absence of water column pollution and low ecological risk, positions it favourably compared to rivers in intensely mined or industrialised regions (e.g [41,53,60]). This underscores its current value for aquaculture (e.g. as a potential broodstock source for *Clarias gariepinus*, *Coptodon rendalli*, *Oreochromis spp.*) and agriculture. However, the identified Cu enrichment and localized hotspots near ASM activities signal vulnerability. Continuous monitoring, integrating essential water quality parameters (pH, DO, EC, TDS) omitted here but critical for understanding metal speciation and bioavailability [24,61], is imperative. Proactive pollution mitigation strategies targeting ASM waste management and conservation efforts are crucial to preserving this resource, especially given potential future regional development.

Limitations and future research directions

Like many other studies, this research provides vital baseline data but has limitations. The single sampling campaign cannot capture seasonal dynamics in metal flux or bioavailability. Future work should adopt longitudinal sampling. The focus on total sediment and water metal concentrations, while foundational, limits direct ecological risk interpretation. Incorporating bioavailability-directed analyses (e.g. sequential extraction of sediments) and biomonitoring (e.g. tissue metal levels in key fish or invertebrate species) would provide a more ecologically relevant risk assessment. Quantifying specific anthropogenic sources (e.g. via land-use mapping, geospatial modelling, or source apportionment techniques) is needed to clarify drivers, particularly for Cu enrichment. Predictive modelling of contaminant transport under varying flow regimes would also enhance management planning.

Conclusion

The present study confirms that the Kabompo River maintains a high level of ecological integrity, with heavy metals in water remaining below detection limits in compliance with Zambian standards (ZABS) for safe domestic use, while surface sediment concentrations generally remain below critical ecological thresholds. Integrated assessment (Geo-accumulation Index, Contamination Factors, Risk Indices) indicates minimal overall ecological risk. Crucially, the absence of dissolved metals despite sediment enrichment (notably Cu) demonstrates limited contaminant bioavailability, governed by physicochemical drivers (neutral-alkaline pH, low conductivity) favoring metal partitioning to surface sediments. Spatial heterogeneity revealed localized Cu and Zn enrichment hotspots (Kalende, Confluence, Mubanga), attributable to natural geochemistry and artisanal/small-scale mining (ASM) inputs. While the system remains 'unpolluted' overall, these vulnerabilities necessitate proactive management: 1) Bioavailability-focused monitoring incorporating pH, DO, EC, TDS and biomonitoring; 2) ASM waste regulation to mitigate tailings runoff; 3) Integration of pollution control within catchment conservation. This work establishes the first bioavailability-informed baseline for the Kabompo River, providing policymakers and regulators critical evidence to safeguard this vital resource for sustainable fisheries, aquaculture, and agriculture amidst regional development pressures.

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Author contributions

All the authors contributed to the study conception and design of methodology. Data collection and analysis as well as preparation of the first draft of the manuscript were prepared by OJH. HY and HSG supervised the work and reviewed previous versions of the manuscript. OJH and HY acquired the acquired funding. All authors read and approved of the final version of the manuscript for submission to the journal.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The datasets and analyses generated during this study are available with the corresponding author upon reasonable request.

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