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Assessment of Environmental Risks Associated with Heavy Metals in Sediments on the Burundian Shore of Lake Tanganyika

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Abstract: This study aims to determine the concentrations of Zn, Cu, Mn, Ni, Cd, and Pb in the sediments of Lake Tanganyika and to conduct an integrated environmental risk assessment by combining international guideline values:Threshold Effect Level (TEL) and Probable Effect Level (PEL) using Consensus-Based Sediment Quality Guidelines (CSQGs) with ecotoxicological and toxicological indices. The sediments were microwave-digested (Milestone Ethos Easy) with concentrated nitric acid, in accordance with standard NF EN 16173:2012-09 and then analyzed by Atomic Absorption Spectrometry (AAS). The concentrations were subjected to descriptive statistics (SPSS v. 22.0), a Pearson correlation matrix to identify potential common sources and the calculation of Overall Risk Index (RI) and the Toxicological Risk Index (TRI). The results show moderate overall contamination, but with strong spatial variations and several hotspots. Site R6 exhibits the highest concentrations of Zn, Cu, Pb, and Cd, indicating a strong anthropogenic influence. Site R3 shows a Cd concentration of 3.73 mg/kg, exceeding the first reference level (1.5 mg/kg) and approaching the PEL (4.98 mg/kg), indicating a localized ecotoxicological risk. According to the SQG, Zn and Ni remain below the TEL/PEL thresholds, Cu approaches the TEL at R6 and several sites exceed the TEL for Cd, revealing widespread contamination by this metal. The RI classifies most sites as low to moderate risk, but identifies a moderate risk at KN (RI = 211.29) and a very high risk at R3 (RI = 377.48). The very high TRI values at MZ and RZ (> 500), high at NG and R6 (> 400), and moderate at R3 confirm severe pollution in several areas, with risks of acute mortality, sublethal effects and bioaccumulation. The study recommends regular monitoring of sediments at high RI/TRI sites, precise identification of pollution sources and integration of these results into public policies.

1. Introduction

The Lake sediments represent the fundamental compartment of aquatic ecosystems, serving both as a habitat for numerous benthic organisms and as a reservoir for various chemical contaminants, particularly heavy metals (Rossi *et al.*, 2013). Due to their physicochemical properties, they record the impact of natural and anthropogenic pressures on water bodies and thus enable the assessment of the ecological status and environmental quality of lakes (Jones and White, 2016).

The heavy metals which are found in sediments originate primarily from industrial, agricultural and domestic activities. As well as from surface runoff, the riverine inputs and atmospheric deposition (Smith *et al*., 2018). Once deposited, these elements are adsorbed and stored in sediments, where they regulate their biogeochemical cycle through processes of speciation, the long-term storage and remobilization into the water column in response to physical, redox or biological disturbances (Zhang *et al*., 2014). These dynamics directly influence their bioavailability and toxicity on aquatic organisms (Geng *et al*., 2024).

The numerous studies have shown that the accumulation of heavy metals in sediments can have major ecotoxicological effects. These contaminants impair the growth, reproduction and survival of benthic fauna, altering the structure and functioning of aquatic communities (Mrozińska and Bąkowska, 2020). Through bioaccumulation and biomagnification, these contaminants are transferred up the food chain to fish and humans, causing cytotoxic and genotoxic effects as well as chronic diseases, particularly neurological, renal and carcinogenic conditions (Almashhadany *et al*., 2024).

The presence of persistent contaminants, such as heavy metals, can testify the past or ongoing pollution, even when sources have been reduced or eliminated (Zhao *et al*., 2021 ; Akartasse *et al*., 2022). Lake sediments are thus objectively verifiable indicators for understanding the impact of human activities on water quality and the functioning of aquatic ecosystems, while providing essential data for the management and conservation of these environments (Miller and Roberts, 2018). Sediment analyses are therefore a key tool for assessing the health of aquatic ecosystems and guiding environmental management strategies (Brown and Green, 2020).

Globally, the numerous studies have highlighted significant contamination of lake sediments by heavy metals. In the United Kingdom, (Yang and Rose, 2005) showed that contamination levels vary greatly by region and are closely linked to the intensity of local industrial activities. In Europe, (Ferrari *et al*.,2015) reported significant pollution of surface sediments in Lake Leman, while in China, (Xiongyi *et al*., 2022) reported high concentrations of cadmium and zinc in sediments in the Liujiang River basin. In Turkey, (İşeri and Soytürk, 2020) observed a marked contrast between zinc concentrations in the water column and those measured in the sediments of Lake Beyşehir, highlighting the role of agricultural activities in sedimentary metal enrichment.

In East Africa, several studies confirm that lake sediments represent the primary receptors of metal contamination, (Olando *et al*., 2020) showed that pollution load index values (PLI >1) in the sediments of Lake Naivasha (Kenya) reflect a gradual decline in sediment quality. Similarly, (Outa *et al*., 2019) found concentrations of Cr, Cu, Zn, and Pb in the Kenyan portion of Lake Victoria that exceeded the thresholds for probable effects, while (Kishe and Machiwa, 2003) reported high levels of Cu, Pb, Hg and Zn in sediments from the Gulf of Mwanza in Tanzania.

The Lake Tanganyika, as one of the largest and deepest freshwater lakes in the world, plays a strategic role in regional biodiversity and the socioeconomic development of the bordering countries, including Burundi. Early studies of this lake focused primarily on sediment dynamics, organic matter and general biogeochemical processes (Huc et al., 1990, Cohen et al., 1993). However, these studies, which are now outdated, did not provide detailed data on heavy metal contamination in the sediments or on the associated environmental risks, despite the recent intensification of urban, agricultural and industrial activities along the Burundian shoreline.

Consequently, the knowledge concerning the origin, the levels and spatial distribution of heavy metals

in the sediments along the Burundian shore of Lake Tanganyika remains very limited. This scientific gap hinders a reliable assessment of ecological risks to benthic organisms and health risks to human populations that depend on the lake as their primary source of water and fishery products.

In this context, the present study is based on the hypothesis that sediments along the Burundian shore of Lake Tanganyika are enriched with heavy metals of primarily anthropogenic origin and that this contamination is likely to pose significant environmental risks. The overall objective of this study is to determine the levels of heavy metal contamination in the sediments of Lake Tanganyika along the Burundian shore and to assess the associated environmental risks. More specifically, the study aims to: (i) determine the concentrations of heavy metals in surface sediments; (ii) identify their potential sources, whether natural or anthropogenic and (iii) assess the associated ecotoxicological risks using pollution and environmental risk indices.

2. Methodology

2.1. Description of the Study Area

The study was conducted on Lake Tanganyika, located in the Albertine Rift Valley, between Burundi, the Democratic Republic of the Congo,Tanzania and Zambia. Estimated to be between 9 and 12 million years old and with a maximum depth of 1.470 meters.The lake Tanganyika is the oldest and deepest lake in Africa. It is 673 km long, and has a shoreline of 1.828 km, an average width of 50 km, a surface area of approximately 32.600 km² and an estimated volume of 18.900 km³ (Tiercelin and Mondeguer, 1991). The biodiversity around the lake and in its waters is significant, with more than 500 endemic species of aquatic invertebrates and vertebrates recorded (Cazenave-Piarrot *et al*., 2015).

The study was conducted at the Burundian part of the lake located between latitudes 3°25’S and 4°28’S and longitudes 29°00’E and 29°40’E. The area is characterized by high population density, as well as the agricultural , industrial and urban activities that generate potential pollutant discharges into the lake (UNEP, 2006).

2.2. Sediment Sampling

The Sampling sites were selected based on their exposure to anthropogenic sources (urban areas, river mouths, agricultural areas, and relatively unspoiled sites) and were mapped using a MAP 64S GPS device. The Sampling was conducted during the dry season to minimize the diluting effects of precipitation on the measured concentrations. Surface sediments (0 to 10 cm deep) were collected using an Eckman-type grab. At each station, three samples spaced 10 m apart were collected to form a composite sample. A total of ten sites Figure 1 were sampled along the entire coastline of the city of Bujumbura.

2.3. Transport and Pretreatment of Samples

After collection, the sediment samples were placed in polyethylene containers that had been previously cleaned with ultrapure water and nitric acid (10% HNO_3). During transport to the laboratory of the Burundi Institute of Agricultural Sciences (ISABU in french accronym), the samples were stored in a cooler at 4 °C to preserve their integrity.

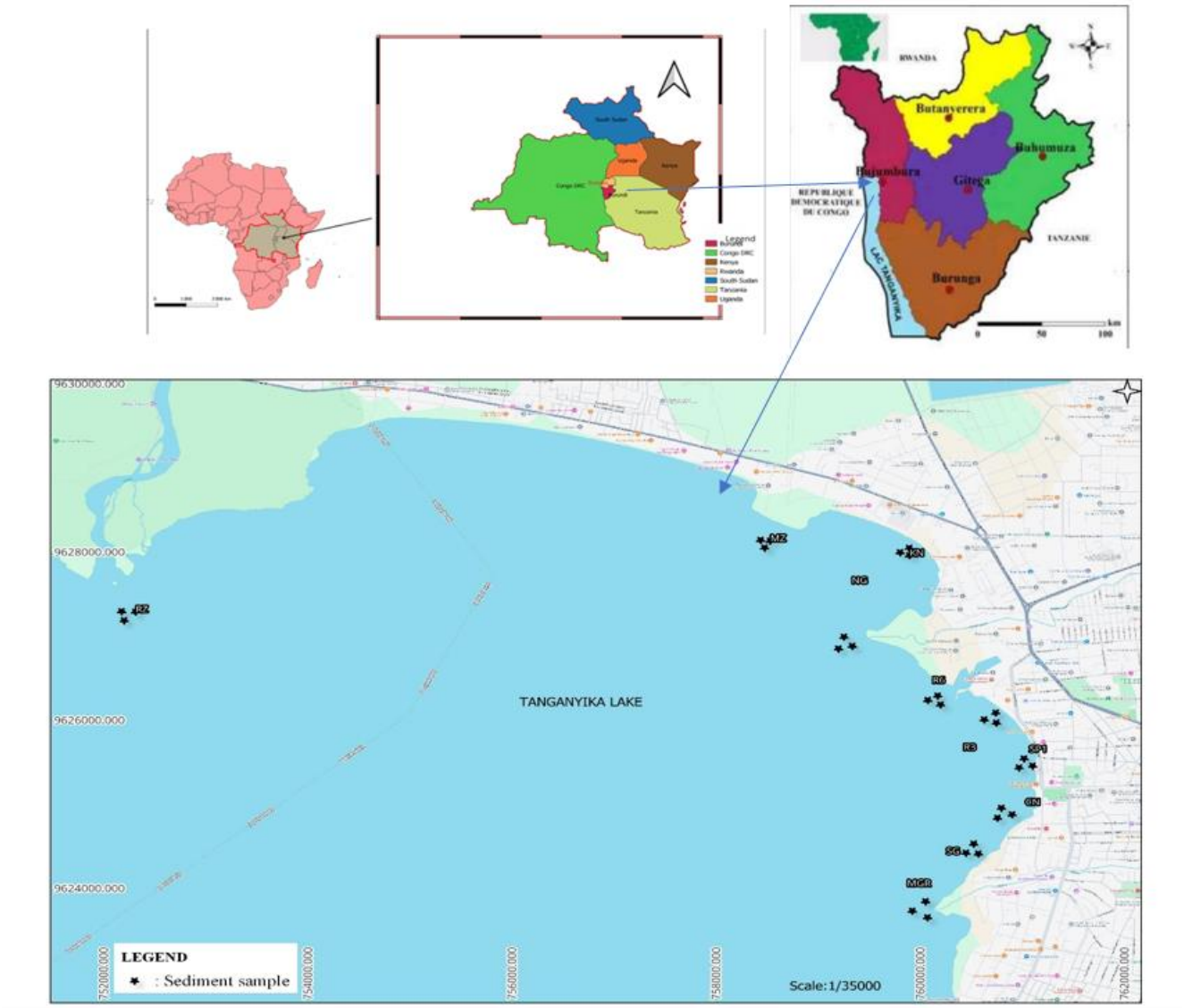


Figure 1. Location of sampling points

At the laboratory, the sediments underwent pretreatment in accordance with ISO 11464. The sediments were first air-dried at room temperature. Subsequently , for each station, the three collected samples were homogenized and mixed to form a composite sample representative of that station, thereby reducing local spatial variability. The composite samples were then sieved to 0.5 mm to remove coarse debris and facilitate subsequent analyses. Finally, the stratification method was used to select representative samples for analysis.

2.4. Heavy Metal Analysis

In order to carry out the samples for chemical analysis, each representative sample was digested using the Milestone microwave digestion system (Ethos Easy No: 19084372), an advanced digestion device. Digestion was performed using concentrated nitric acid (HNO) under controlled internal pressure of approximately 20 to 40 bar and at a controlled temperature (T= 200 °C). The digested samples were then filtered using fine crystalline filter paper. and the resulting solutions were analyzed by Atomic Absorption Spectrometry (AAS) in accordance with standard NF EN 16173 :2012-09.

2.5. Comparison with SQGs Guideline Values

In order to assess the level of contamination in lake sediments, we compared the analysis results (measured heavy metal concentrations) with the SQGs values.

2.6. Risk Assessment

In order to assess risks, the Overall Risk Index (RI) and the Toxicological Risk Index (TRI) were calculated for each sample to evaluate the associated environmental risks.

2.6.1. Overall Risk Index (RI)

The Overall Risk Index (RI) proposed by (Hakanson, 1980) is designed to assess the overall contamination of sediments by heavy metals. It takes into account the concentration of several metals (such as zinc, copper, manganese, nickel, cadmium and lead) and their respective toxicity. This index along with its constituent elements, as shown in Eqn. (1-3), is used to provide a general overview of a sample's pollution level.

$$RI = \sum E_r^i \quad \textbf{Eqn. 1}$$

$$E_r^i = T_r^i \times (C_i / C_n^i) \quad \textbf{Eqn. 2}$$

where:
-E_r^i: Potential risk of metal i considered individually
- T_r^i: Toxicity factor of metal i (Cd =30. Cu =5. Pb =5. Zn =1. Ni =5. Mn =1)
- C_i: Measured concentration of metal i in the sample
- C_n^i: Natural geochemical background concentration of metal i

Risk assessment follows the following scale: if RI < 150: Low risk; 150 ≤ RI < 300: Moderate risk; 300 ≤ RI < 600: High risk; RI ≥ 600: Very high risk.

2.6. 2. The Toxicological Risk Index (TRI)

This index, resumed in Eqn. 3, focuses solely on the toxicological impact of metals on aquatic fauna. It seeks to measure the risk to aquatic life by assessing the toxic effect of the metals present in the sediment sample. Unlike the Risk Index (RI), the TRI places greater emphasis on the toxicological effect of concentrations rather than on contamination alone.

$$TRI = \sum (Cm \times Tr) \quad \textbf{Eqn. 3}$$

where:

Cm = Concentration of the measured metal

Tr = Toxicity factor of the metal

The following scale is used to assess risks: if TRI > 500: Critical level, severe contamination that may lead to the death of aquatic organisms and major ecosystem disruptions; 400 < TRI ≤ 500: High level, risk of bioaccumulation and toxic effects on aquatic fauna; 200 < TRI ≤ 400: Moderate level, possible sublethal effects (reduced growth, impaired reproduction) and if TRI ≤ 200: Low immediate risk, but gradual accumulation may pose a long-term problem.

2.7. Statistical Analysis

The data on heavy metal concentrations (Zn, Cu, Mn, Ni, Cd, Pb) were analyzed using SPSS v. 22.0 in order to calculate the descriptive statistics (minimum, maximum, mean, median, standard deviation and the coefficient of variation). A Pearson correlation matrix was then constructed. The significance of the correlation coefficients was assessed at a p-value threshold of < 0.05 using the corresponding Student's t-test. In addition, univariate t-tests were applied to compare the observed means with reference guideline values for sediments (TEL/PEL), with the null hypothesis being that there is no difference between the measured mean concentration and the guideline value.

3. Results and Discussion

The metals analyzed are: Zinc (Zn), Copper (Cu), Manganese (Mn), Nickel (Ni), Cadmium (Cd) and Lead (Pb). The coding samples were collected from the following sites: RZ = Rusizi River mouth, MZ = Mutimbuzi River mouth, KN = Kinyankonge River mouth, NG = Ntahangwa River mouth, R6 = Stormwater drain next to the Port of Bujumbura, R3 = Stormwater drain R3, SP1 = in front of REGIDESO Pumping Station No. 1, CN = Cercle Nautique restaurant and bar, SG = Safari Gate Hotel, MGR = Mugere-Ruziba marine diving area. Table 1 presents the results of the analysis, by AAS, of sediment samples collected from the ten sites in the northeastern basin of Lake Tanganyika.

Table 1. Heavy Metal Concentrations in the analyzed sediments (mg/kg)

		Metal					
No	**Sample Code**	**Zn**	**Cu**	**Mn**	**Ni**	**Cd**	**Pb**
1	RZ	15.2	13.6	405	3.36	1.35	≤ 8
2	MZ	28	14.2	475	≤ 2.5	1.08	11.6
3	KN	7.93	2.2	94	3.53	2.08	≤ 8
4	NG	16.6	9.53	342	≤ 2.5	1.1	≤ 8
5	R6	41.6	24.1	71.2	≤ 2.5	≤ 1	29.4
6	R3	23	15.9	28.5	≤ 2.5	3.73	≤ 8
7	SP1	14.3	6.58	35.4	≤ 2.5	≤ 1	≤ 8
8	CN	32.4	10.5	61	≤ 2.5	≤ 1	≤ 8
9	SG	24.2	8.9	114	≤ 2.5	≤ 1	≤ 8
10	MGR	25.2	10.1	83.6	≤ 2.5	≤ 1	≤ 8

3. 1. Statistical Analysis

a. Descriptive Statistics

The calculated statistical parameters presented in Table 2 include measures of central tendency and dispersion for six heavy metals: Zn, Cu, Mn, Ni, Cd, and Pb. The statistical results generally show average heavy metal concentrations that are below or close to quality thresholds, but with localized "hot spots" (especially R3 and R6) where Cd, Pb, Mn, Zn and Cu reaching significantly the higher levels, suggesting localized anthropogenic inputs (Figure 2). The average concentrations of Zn (22.84 mg/kg) and Cu (11.56 mg/kg) remain largely below the guidance values commonly used for sediments (Zn ≈ 150-200 mg/kg. Cu ≈ 30-65 mg/kg), which recommends low to moderate pollution at the water body scale. However, the high coefficients of variation (CV) for these two metals (Zn: 43.04%, Cu:

51.10%) indicate significant spatial variability, with sites such as R6 showing marked enrichments (Zn = 41.6 mg/kg; Cu = 24.1 mg/kg) compared to KN (Zn = 7.93 mg/kg; Cu = 2.20 mg/kg), which is consistent with local inputs linked to urban or industrial discharges.

Table 2. Selected statistical parameters in mg/kg

Parameter	Zn	Cu	Mn	Ni	Cd	Pb
Min	7.93	2.2	28.5	2.5	1	8
Max	41.6	24.1	475	3.53	3.73	29.4
Average	22.84	11.56	170.97	2.69	1.43	10.5
Median	23.6	10.3	88.8	2.5	1.04	8
Standard deviation	9.83	5.91	167.99	0.4	0.87	6.74
CV (%)	43.04	51.1	98.26	14.89	60.95	64.16

The Manganese has an average concentration of 170.97 mg/kg, which is below the threshold values frequently reported for sediments (≈ 300 mg/kg), but the range of variation is very wide (28.5-475mg/kg) and the CV reaching the 98.26% and indicating extreme heterogeneity among sites. The highest values likely reflect the combination of natural contributions (erosion, inputs from the watershed) and anthropogenic sources concentrated in certain coastal areas.

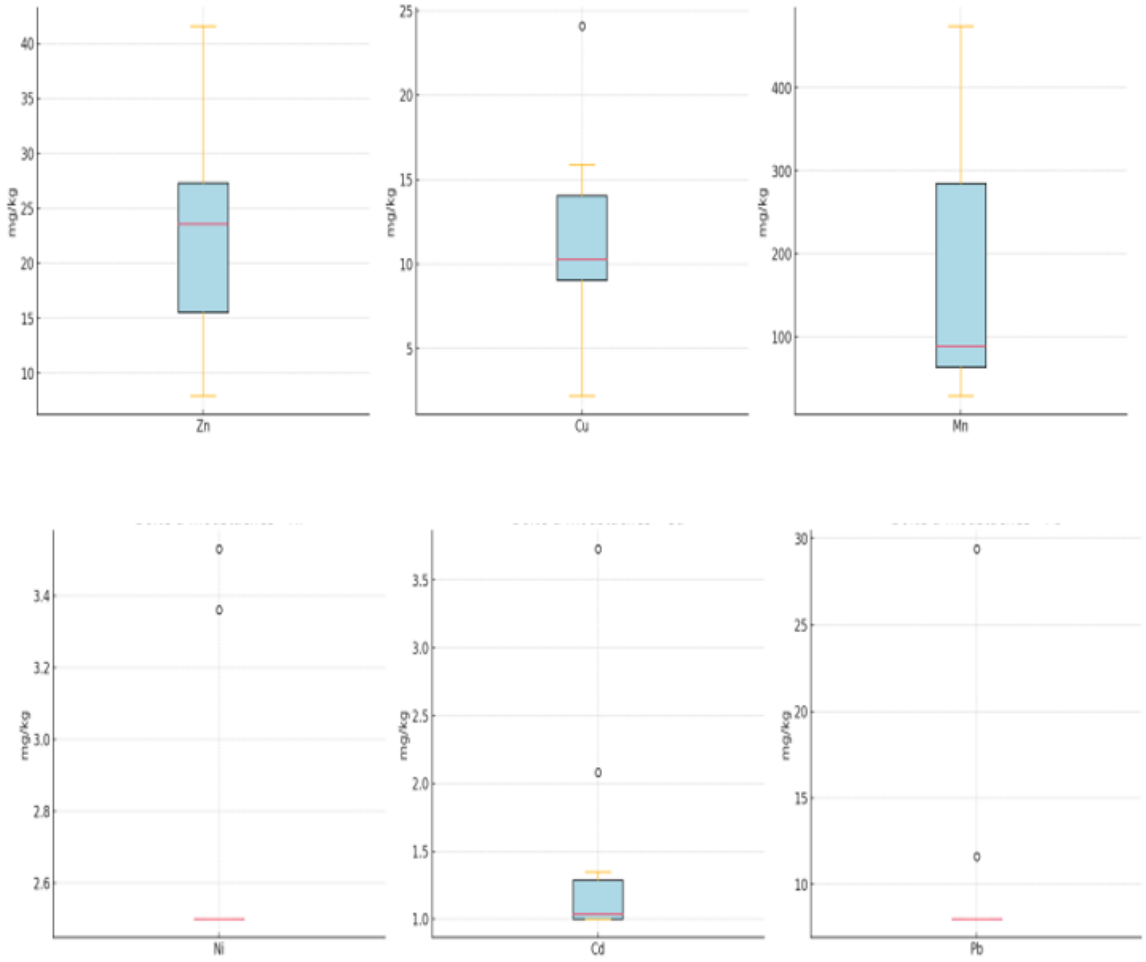


Figure 2. Box plots illustrating the distribution of concentrations for each metal analyzed.

The Nickel shows a low average (2.69 mg/kg) and a very low CV (14.89%), indicating a homogeneous distribution and the absence of any specific pollution signal from this metal, with concentrations remaining well below the standard guideline values for sediments (≈ 20-21 mg/kg). The cadmium, with an average of 1.43 mg/kg, falls within the lower range of quality standards (≈ 1.5 mg/kg for a first-effect threshold), but the high CV (60.95%) and the maximum concentration observed at R3 (3.73 mg/kg) indicate a local exceedance of reference levels and a localized toxic risk to benthic organisms

The metal (Pb) has an average concentration of 10.50 mg/kg, which is significantly lower than current guideline values (≈ 50 mg/kg), but a CV of 64.16% indicates high spatial variability.

The result from site R6, with 29.4 mg/kg of the metal (Pb), indicates an area that requires close monitoring. Indeed, this site receives stormwater from the R6 collector which also drains surface runoff from the Buyenzi neighborhood-an area, with a high population density (36.560 residents) and a large number of auto repair shops of all kinds. This result appears consistent with the presence of local sources (traffic, repair shops, used batteries, urban discharges) already described in other lakes subject to anthropogenic pressure (Mohajane and Manjoro, 2022), (Ma *et al*., 2021).

b. Correlation matrix

A correlation matrix has been established to explore the linear relationships between trace metal concentrations and ecological risk indices. Pearson's correlation coefficients were calculated for all pairs of variables.and their strength and direction were interpreted according to established guidelines (Schober *et al*., 2018).

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{[\sum_{i=1}^{n} (x_i - \bar{x})^2][\ \sum_{i=1}^{n}(y_i - \bar{y})^2]}}$$

Hypothesis :
- H_0 : no correlation (r = 0).
- H_1 : significant correlation ($r \neq 0$).

The herafter Table 3 shows the values of r (Pearson's correlation coefficient) calculated between the six metals (Zn, Cu, Mn, Ni, Cd, Pb) from the 10 sediment samples from the northeastern basin of Lake Tanganyika.

Table 3. Correlation coefficient values (r)

	Zn	**Cu**	**Mn**	**Ni**	**Cd**	**Pb**
Zn	1	0.787	-0.149	-0.619	-0.24	0.705
Cu	0.787	1	0.096	-0.37	0.053	0.776
Mn	-0.149	0.096	1	0.201	-0.264	-0.102
Ni	-0.619	-0.37	0.201	1	0.188	-0.195
Cd	-0.24	0.053	-0.264	0.188	1	-0.199
Pb	0.705	0.776	-0.102	-0.195	-0.199	1

The metals, Zn and Cu show a strong positive correlation (r = 0.79), as do Cu and Pb (r = 0.78) and Zn-Pb (r = 0.71): these anthropogenic metals (derived from port stormwater such as R6 or urban rivers such as Rusizi/Mutimbuzi) likely co-pollute via domestic and industrial discharges in Bujumbura. Mn

(natural, elevated at the RZ/MZ river mouths) is independent, indicating a distinct lithogenic origin. Ni and Cd (low variations) show no strong correlations, which is typical in tropical lake systems such as Lake Tanganyika where dilution and sedimentary sorption limit the connections. These results suggest common sources for Zn-Cu-Pb (urban/port pollution)

The heatmap Figure 3 shows the Pearson correlation coefficients between Zn, Cu, Mn, Ni, Cd, and Pb, calculated from the concentrations measured at ten sampling sites. The strong significant positive correlations between Zn and Cu, Zn and Pb, and Cu and Pb indicate common anthropogenic sources, mainly linked to urban and port-related inputs around Bujumbura. In contrast, the correlations between Mn, Ni and Cd are lower, even insignificant, suggesting distinct or more diffuse sources.



Figure 3. Heatmap of Pearson correlations between the metals Cu, Mn, Pb, Zn Cd and Ni

- **Calculation of univariate Student's t-tests**

Univariate Student's t-tests were performed on the correlated Zn-Cu-Pb metals to assess whether the mean values of the selected variables differed significantly between sampling sites. A significance threshold of $p < 0.05$ was retained, and all tests were two-tailed, in accordance with recommended practices for hypothesis testing in environmental studies (Chicco et al.. 2025). Pearson's correlation significance test was performed (n = 10 sites, ddl = 8, p-value threshold < 0.05 using Student's t-test). Only significant correlations are highlighted.

$$t = \frac{r\sqrt{(n-2)}}{\sqrt{(1-r^2)}}$$

with n = number of sites , comparison to Student's t-distribution ($p < 0.05$).
If $|r| < 0.3$: weak correlation ; $0.3 \leq |r| < 0.7$: moderate correlation and $|r| \geq 0.7$: strong correlation

Table 4. r-value and p-value Analysis

Metal X	Metal Y	r	p-value	ddl
Zn	Cu	0.787	0.0069	8
Zn	Pb	0.705	0.0229	8
Cu	Pb	0.776	0.0084	8

The Zn-Cu (p=0.007), Zn-Pb (p=0.023) and Cu-Pb (p=0.008) are statistically significant, confirming common sources (anthropogenic: port stormwater R6, urban rivers Rusizi/Mutimbuzi/Kinyankonge/Ntahangwa in the northeastern Tanganyika basin). Mn, Ni and Cd remain uncorrelated (natural origins).

c. Univariate t-test vs. guideline value

This parameter has been calculated to test whether the observed mean is significantly different from the guideline value (TEL, PEL).

$$t = \frac{\bar{X} - X_0}{S/\sqrt{n}}$$

Table 5. Univariate t-test results vs. TEL-PEL guideline value

Metal	Ref.	X_0 (mg/kg)	Average $\bar{X}$	S	t	p-value
Zn	TEL	121	22.843	9.832	-31.57	<0.0001
Zn	PEL	459	22.843	9.832	-140.29	<0.0001
Cu	TEL	31.9	11.561	5.907	-10.89	<0.0001
Cu	PEL	149	11.561	5.907	-73.57	<0.0001
Ni	TEL	22.7	2.689	0.401	-158.02	<0.0001
Ni	PEL	48.6	2.689	0.401	-362.54	<0.0001
Cd	TEL	0.99	1.434	0.874	1.61	0.143
Cd	PEL	4.98	1.434	0.874	-12.83	<0.0001
Pb	TEL	35.8	10.5	6.737	-11.88	<0.0001
Pb	PEL	128	10.5	6.737	-55.16	<0.0001

The results of the univariate t-tests indicate a low overall ecotoxicological risk in the northeastern basin of Lake Tanganyika (Burundian shore, Bujumbura), with an average concentrations of Zn, Cu, Ni and Pb mainly below the TEL and PEL thresholds, but an average Cd concentration (approximately 1.43 mg/kg) above the TEL (0.99 mg/kg) without reaching the PEL (4.98 mg/kg).

In the said area influenced by the urban and port activities of Bujumbura, the Cd levels consistently exceed the TEL at all 10 sites (e.g.:KN 2.08 mg/kg, R3 3.73 mg/kg at river mouths such as Rusizi, Mutimbuzi and near the port), linked to the industrial discharges (chemical plants, soap factories via Ntahangwa/Kinyankonge) and urban runoff, unlike other metals. which are diluted or of lithogenic origin. This “threshold effect” suggests occasional effects on benthic organisms (potential bioaccumulation in fish/chironomids), amplified locally at anthropogenically impacted sites (KN, R3, RZ), consistent with studies in Lake Tanganyika showing elevated coastal Cd levels (5-20 times higher than offshore) (Chale, 2002).

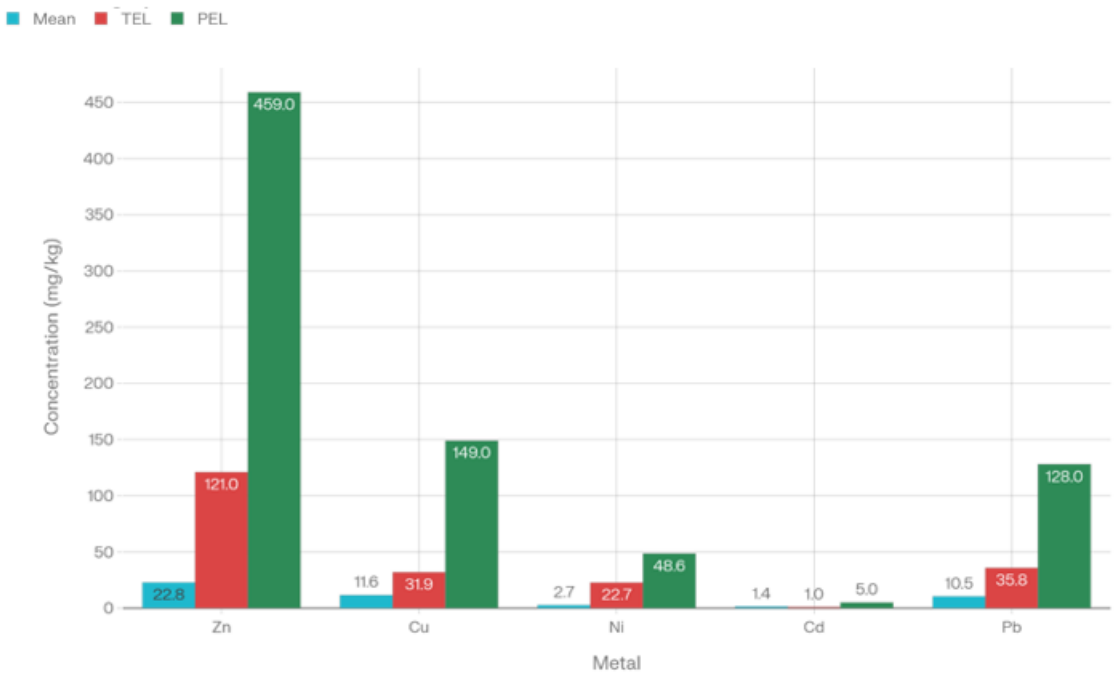


Figure 4. Mean Concentration vs. TEL-PEL

3.2 Comparative Analysis Using TEL and PEL Thresholds

The Lake sediments are assessed using international guidelines derived from the USEPA, which does not establish uniform federal standards but supports approaches such as the Consensus-Based Sediment Quality Guidelines (CBSQG) for freshwater ecosystems. with TEL (Threshold Effect Level) and PEL (Probable Effect Level) thresholds in mg/kg dry weight (MacDonald *et al.*, 2000). Thus, in the Table 6**,** we present the TEL (Threshold Effect Level) and PEL (Probable Effect Level) values for each metal, which we compare to the measured values for each sampled site.

Table 6. Comparison of analysis results with TEL-PEL values

Sample	Values (TEL-PEL) in mg/kg				
	Zn (121- 459)	**Cu (31.9-149)**	**Ni (22.7 - 48.6)**	**Cd (0.99 - 4.98)**	**Pb (35.8-128)**
RZ	15.2	13.6	3.36	**1.35**	≤ 8
MZ	28	14.2	≤ 2.5	**1.08**	11.6
KN	7.93	2.2	3.53	**2.08**	≤ 8
NG	16.6	9.53	≤ 2.5	**1.1**	≤ 8
R6	41.6	24.1	≤ 2.5	**≤ 1**	**29.4**
R3	23	15.9	≤ 2.5	**3.73**	≤ 8
SP1	14.3	6.58	≤ 2.5	**≤ 1**	≤ 8
CN	32.4	10.5	≤ 2.5	**≤ 1**	≤ 8
SG	24.2	8.9	≤ 2.5	**≤ 1**	≤ 8
MGR	25.2	10.1	≤ 2.5	**≤ 1**	≤ 8

The results indicate an overall low environmental risk at moderate level for sediments on the Burundian shore of Lake Tanganyika,with the main concern being cadmium. which consistently exceeds the TEL without reaching the PEL, while Zn, Cu, Ni and Pb remain below their thresholds or reference values.

The Cadmium (Cd) represents the primary environmental risk in sediments along the Burundian shore of Lake Tanganyika, with concentrations ranging from 1 to 3.73 mg/kg that are consistently higher than the TEL (0.99 mg/kg) but lower than the PEL (4.98 mg/kg), indicating occasional biological effects on sensitive benthic communities (Olayinka-Olagunju *et al*., 2021).

This diffuse contamination, observed at all sites (the Rusizi, Mutimbuzi and Ntahangwa river mouths; the R6 and R3 collectors), stems primarily from urban and the agricultural anthropogenic sources-such as road traffic, auto repair shops, used batteries, and basin-wide inputs-rather than localized impacts (Ma *et al*., 2021).

The temporal annual monitoring of critical sites (R6. river mouths), combined with isotopic tracing of Cd sources and basin-scale flow modeling, is essential for rigorous management. The Measures outlined in the Environmental and Social Management Plan must be strengthened through urban stormwater management, the ban on direct discharges from industrial facilities and capacity-building for all stakeholders, getting inspired from the protocols of the Dragon Lake in China (Ma et al., 2021) in order to prioritize the restoration of the northeastern areas of Lake Tanganyika.

3.3. Risk Indices:

3.3.1. Ecological Risk Index (RI)

This index measures the potential hazard of a chemical substance based on its toxicity and concentration. It is given by Eqn.1 above. The calculated values are shown in Table 7.

Table 7. RI Values and Associated Risk Levels for the Sites Studied

Sample	RI	Ecological Risk Level
RZ	139.83	Low
MZ	113.78	Low
KN	211.29	Moderate
NG	114.15	Low
R6	110.88	Low
R3	377.48	High
SP1	103.47	Low
CN	104.07	Low
SG	103.89	Low
MGR	103.99	Low

The results revealed the varying levels of heavy metal contamination across the sites. The sites SP1, SG, CNR, CN,MZ, NG and R6 present a low ecological risk to moderate. The Site RZ also presents a low risk. In contrast, the KN site shows a moderate ecological risk (RI = 211.29) while the R3 site reaches a very high risk level (RI = 377.48), indicating the considerable contamination that could have significant impacts on aquatic organisms and ecosystem quality (Chale. 2002). This R3 stormwater collector has an ecological risk index (RI) of 377.48, exceeding the high threshold (>300 according to Häkanson), notifying a priority hotspot within the northeastern study area of Lake Tanganyika (Bujumbura). Located downstream from the Cercle Nautique (Muha/Kanyosha), the said site is believed to discharge a high pollutant load via urban runoff: the cadmium (Cd: 1-3.73 mg/kg > TEL

0.99 mg/kg) and accumulated heavy metals that threaten the sensitive benthic invertebrates and cause bioaccumulation in endemic cichlids (Olayinka-Olagunju et al., 2021). The said localized risk (R3: high RI vs. R6: RI = 110.88, low to moderate) reflects the concentrated inputs from auto repair shops. road traffic. and flash floods. which confirms the warnings of (Ndayishimiye *et al*., 2023) regarding coastal degradation caused by untreated discharges. necessitating enhanced monitoring and a targeted Environmental and Social Management Plan (ESMP).

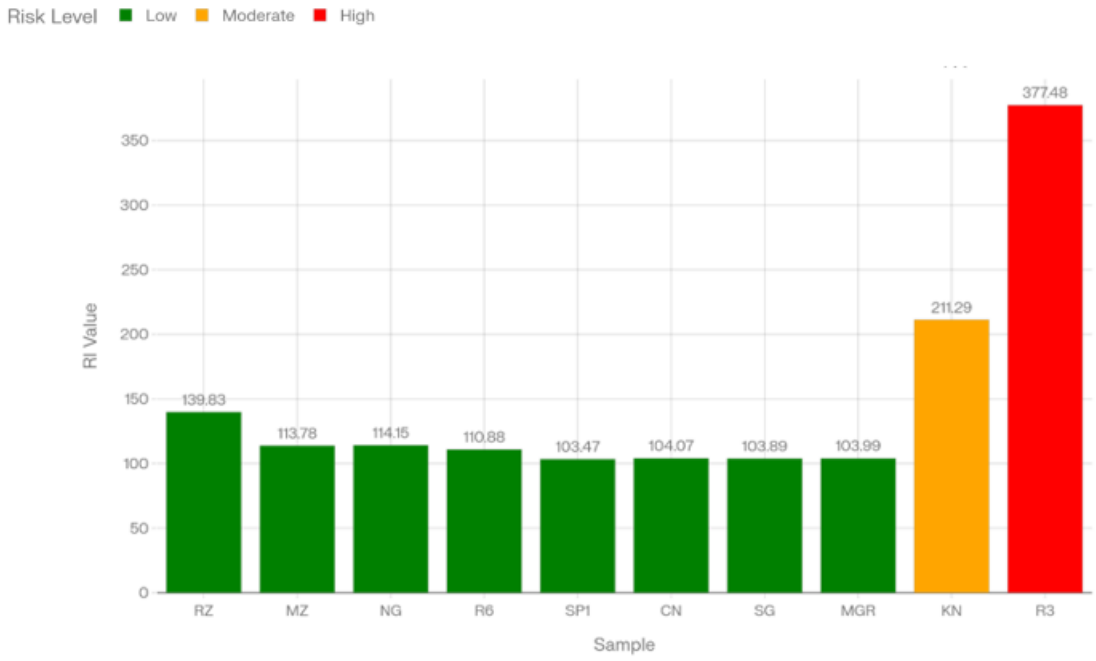


Figure 5. Ecological Risk Index (RI) by Sample

3.3.2 Toxicological Risk Index (TRI)

The assessment of ecotoxicological risks using the Toxicological Risk Index (TRI) reveals the marked spatial variability in sediment contamination along the Burundian shore of Lake Tanganyika, reflecting the differing influences of anthropogenic and natural pressures on local aquatic ecosystems (Branchu *et al*., 2005).

Table 8. Synthetic table of Risk Assessment

Sample site	TRI Values	Risk level	Potential ecological impacts
RZ	585.5	Very high	Lethal effects. major ecosystem disruptions
MZ	676.9	Very high	High mortality. alteration of food chains
KN	232.98	Moderate	Progressive biological alteration
NG	491.75	High	Bioaccumulation. chronic toxicity
R6	422.8	High	Toxic effects on aquatic wildlife
R3	295.4	Moderate	Sublethal effects. reproduction affected
SP1	165.1	Low	Low risk but possible long-term accumulation
CN	228.4	Moderate	Local ecological disruptions
SG	265.2	Moderate	Physiological stress of organisms
MGR	241.8	Moderate	Reduction of ecological resilience

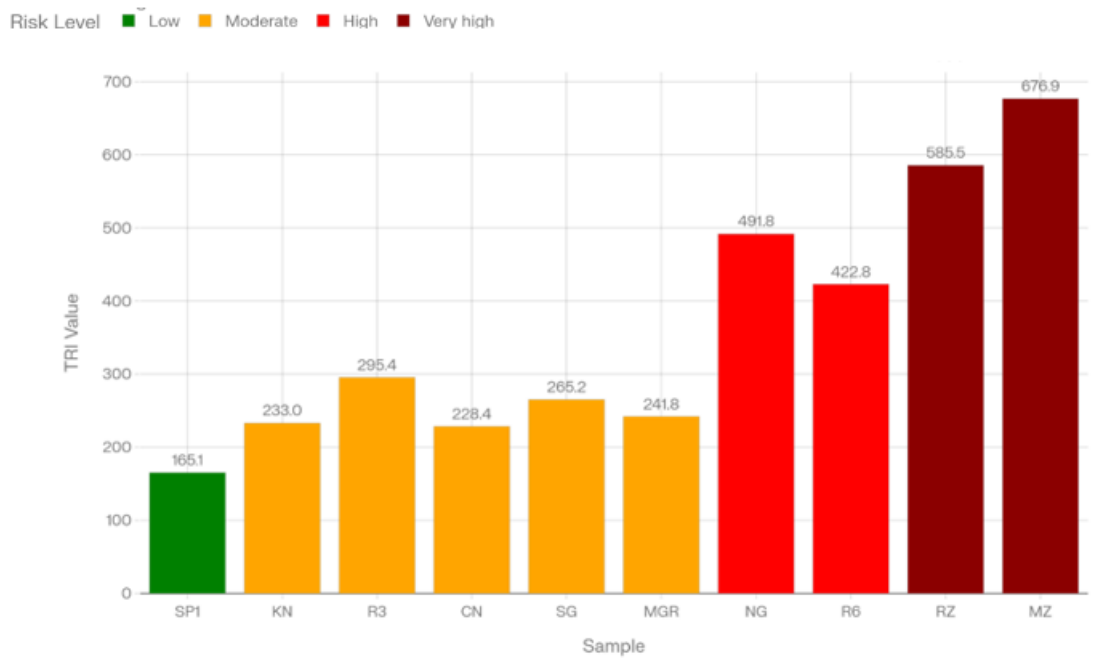


Figure 6. Toxic Risk Index (TRI) by sample

The RZ (TRI = 585.5) and MZ (TRI = 676.9) sites which exhibit the critical levels of ecotoxicological risk. These values, which are largely above the threshold of 500, indicate severe contamination likely to cause lethal effects on benthic organisms, the profound alterations of the trophic chains and major ecosystem disturbances. These areas correspond to heavily anthropogenized sectors, characterized by dense urbanization, untreated domestic wastewater and significant land-based inputs via waterways (Han *et al*., 2023).

The NG (TRI = 491.75) and R6 (TRI = 422.8) sites are classified as having a high level of risk. Although slightly below the critical threshold,these levels indicate a significant potential for heavy metal bioaccumulation in aquatic organisms, with the chronic toxic effects likely to affect the growth, reproduction and long-term survival of aquatic fauna.

The sites KN (TRI = 232.98), CN (TRI = 228.4), SG (TRI = 265.2), MGR (TRI = 241.8) and R3 (TRI = 295.4) fall into the moderate-risk category. At these levels, the expected effects are primarily sublethal, including physiological and biological disturbances that may reduce the resilience of aquatic populations to other environmental stresses.

Finally, the site SP1 (TRI = 165.1) presents a low immediate ecotoxicological risk. However, even at this level, a gradual accumulation of heavy metals in sediments and organisms may, in the long term, be considered as a threat to the lake ecosystem (Ayari *et al*., 2016). The assessment of ecotoxicological risks using the Toxicological Risk Index (TRI) highlights marked spatial variability in sediment contamination along the Burundian shore of Lake Tanganyika, reflecting the differing influences of anthropogenic and natural pressures on local aquatic ecosystems (Branchu *et al*., 2005). The sources of heavy metals polluting the sediments of Lake Tanganyika are multifactorial and dominated by localized anthropogenic pressures.These sources include untreated domestic and urban wastewater from the city of Bujumbura, riverine inputs (e.g. the Ruzizi, Mutimbuzi, Kinyankonge., Ntahangwa. etc.) draining basins eroded by intensive agriculture and artisanal mining (Cu. Co). The diffuse

industrial discharges (textile, agri-food), as well as the urban runoff. This is also confirmed by the work of Campbell et al. (2003), who identify river mouths as primary hotspots. These results are also consistent with studies conducted in the African Great Lakes, especially those by (Förstner and Wittmann, 1983), (MacDonald *et al*., 2000) and (Chale, 2002), which showed that the urbanized shoreline areas of Lake Tanganyika and river mouths constitute hotspots of metal contamination.

Table 9. Spatial Summary Table (from the north to the east of Lake Tanganyika)

Area	Relative location	Pollution profile
RZ -MZ-KN	North of the lake (river mouths)	River inputs rich in Mn and Zn. Diffuse pollution.
Bujumbura City (R3 - R6-SP1-NG- CN-SG)	Center	Multiple pollutants (Zn. Cu. Pb. Cd) linked to urban and industrial effluents. R6 and R3 are the most contaminated points.
MGR (Ruziba)	East of the lake	Moderate concentrations (Zn. Cu. Mn). Less pollution

The high levels of Zn, Cu and Pb in sediments near Bujumbura (sampling sites R3 and R6) directly reflect anthropogenic urban discharges (domestic, industrial and stormwater), While the river mouths such as Ruzizi and Mutimbuzi are the primary sources of Mn, originating from the Mirwa rock massives (feldspar weathering into kaolins with iron-Mn exchanges) and the Rwandan-Congolese volcanic zones (Bakundukize, 2012).

The heavy metals in Lake Tanganyika sediments can migrate into the water column through interconnected physicochemical and biological processes, amplified by the lake's local conditions (alkaline waters (pH 8.5-9.5), marked thermal stratification (thermocline 25-75 m. oxycline 100-225 m) and an anoxic/H_2S zone >200 m (95% of the lake's volume)). The Sediment resuspension caused by winds, the currents waters or human activities such as artisanal fishing and sand mining, releases adsorbed metals (Zn, Cu, Pb) or ionic metals (Cd) into the overlying water, particularly at sites R6 and R3 where the concentrations exceed SQGs thresholds (Brucker *et al*., 2011).

The diffusion from the interstitial water towards the unstoppable water is facilitated by concentration gradients under anoxic conditions at depth, which remobilize Cd and Pb through the reduction of iron sulfides, while bioturbation by benthic invertebrates accelerates this transfer (Kalnejais *et al*., 2007), (Mubhya and Muyisenge, 2002).

- **Summary: Risks to Lake Users**

The TRI/RI results reveal critical ecotoxicological risks to fishermen and artisanal communities in the northeastern part of Lake Tanganyika, primarily through the bioaccumulation of cadmium (Cd: 1-3.73 mg/kg > TEL 0.99 mg/kg) and other metals (Zn, Cu, Pb) in endemic cichlid fish, exceeding WHO thresholds for regular human consumption (Chale, 2002). The skin exposure during fishing or sand extraction (sites R3/R6), combined with the inhalation of sedimentary dust, exacerbates chronic nephrotoxic and carcinogenic effects, particularly among children living along the lakeshore who rely on lake-derived protein (70% of protein intake in northern Burundi) (Ilunga *et al*., 2023).

At the ecosystem and economic levels, the critical hotspots (RZ/MZ : TRI > 500; R3 RI=377.48) threaten sensitive benthic invertebrates and the trpphic chains , reducing stocks of endemic species and

impacting fisheries (the primary source of protein) as well as ecotourism (Ndayishimiye *et al*., 2023). Anoxic remobilization (at depths >200 m) amplifies long-term bioaccumulation reducing resilience to increasing climatic and urban stresses (Brucker *et al*., 2011).

4. Conclusion

The results of this study reveal a moderate heavy metal contamination in the sediments of the northeastern Burundian shore of Lake Tanganyika, with marked spatial variations and localized hotspots (R3, R6, RZ, MZ, NG) where the concentrations of Cd, Pb, Cu, Mn, Zn and Ni often exceed the toxicity thresholds of the SQGs (TEL/PEL). The Cadmium emerges as the primary contaminant , consistently exceeding the TEL without reaching the PEL, while the RI and TRI confirm generally to a moderate low ecological risks overall (average RI ~140). but high to very high risks in critical areas (RI = 377.48 at R3; TRI > 500 in RZ and MZ), threatining the benthic organisms, trophic chains and bioaccumulation.

These hotspots reflect the significant human influence due to the untreated urban and domestic wastewater from Bujumbura , the sediment inputs from eroded rivers (Ruzizi, Mutimbuzi, Ntahangwa and Kinyankonge), the urban runoff, artisanal mining activities and the diffuse industrial discharges, positioning these sites as potential reservoirs of metals that could be remobilized in the event of physicochemical disturbances in the water column. This pattern is consistent with what has already been observed in other major lakes, where the river mouths and urbanized coastal zones concentrate these pressures and constitute areas of heightened ecological vulnerability.

Following this said prospective degradation and significant, an urgent targeted management program is needed: annual monitoring of high-risk sites (R3, R6, RZ, MZ, NG), precise the identification of pollution sources, strengthening of stormwater and wastewater collection and treatment systems, creation of vegetated buffer zones to prevent erosion, community awareness-raising and integration of the results into national and regional policies for integrated lake management.These preventive measures, coordinated with existing transboundary frameworks are essential to preserve the ecological integrity of Lake Tanganyika, by preventing the worsening of health and environmental risks and support the resilience of ecosystems and riparian communities that are strongly dependent on the lake's ecosystem services.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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