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Original Article

Assessment of Heavy Metal Contamination in Urban Tributaries Draining into Lake Victoria at Musoma and Tarime Towns, Tanzania

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Abstract

Water contamination by heavy metals poses serious environmental and public health threats, particularly in urban and agricultural regions where human activities intensify pollution. This study aimed to determine the levels of heavy metal contamination in urban tributaries along Musoma and Tarime towns to safeguard aquatic ecology and public health. Seventy-eight water samples were collected from twenty-six strategically selected sites across the two urban areas. Physicochemical parameters (pH, EC, TDS, turbidity, and temperature) were analyzed on-site using the potentiometric method, while heavy metals (Hg, As, Cr, Pb, Cd, Zn, and Cu) were determined using ICP–OES. Results showed wide spatial variations with pH (7.3–8.94), EC (94–3900 µS/cm), TDS (56–2360 mg/L), turbidity (9.4–2098 NTU), and temperature (22.4–27.8 °C). Metal concentrations ranged from Pb (0.005–0.082 mg/L), Cd (0.002–0.019 mg/L), Cr (0.004–0.021 mg/L), As (0.0003–0.001 mg/L), Cu (0.006–0.118 mg/L), Zn (0.032–0.264 mg/L), and Hg (0.0001–0.0004 mg/L). Pb and Cd Concentrations exceeded WHO drinking water limits, suggesting contamination from mining and domestic discharges. Overall, findings reveal moderate but spatially variable contamination, highlighting the need for continuous monitoring, stricter pollution control, effective remediation to protect water quality in the Lake Victoria Basin.

Keywords: Heavy metals, Lake Victoria Basin, Musoma, Tarime, Tributaries, Water quality

1. Introduction

Heavy metal contamination is a critical global environmental issue affecting both developed and developing nations. The World Health Organization (WHO, 2004) identifies metals such as Lead (Pb), Cadmium (Cd), Mercury (Hg), arsenic (As), chromium (Cr), Copper (Cu), and Zinc (Zn) as among the most hazardous pollutants due to their toxicity, persistence, and bioaccumulative nature (Organization, 2004). These elements enter aquatic and terrestrial environments through industrial discharges, mining, smelting, urban runoff, wastewater irrigation, agricultural inputs, and atmospheric deposition

(Alloway, 2012). Globally, industrialized regions in Asia, Europe, and North America report severe contamination in rivers and lakes. For instance, Pb, Cd, and Cr frequently exceed safe limits in the Yangtze and Ganges Rivers (Yang *et al.*, 2018; Singh, Agrawal and Agrawal, 2021), while legacy mining and urban runoff continue to affect the Danube, Rhine, Mississippi, and Great Lakes (Chakraborti *et al.*, 2017; Natasha *et al.*, 2022). Chronic human exposure to heavy metals can lead to neurological, renal, reproductive, and carcinogenic effects, emphasizing the need for monitoring and pollution control worldwide (Landrigan *et al.*, 2018).

In Sub-Saharan Africa, heavy metal pollution is intensified by rapid urbanization, weak governance, and extensive artisanal mining. For example, artisanal and small-scale gold mining (ASGM) contributes significantly to mercury pollution in countries such as Indonesia, Ghana, and Peru (Budnik et al, 2019). Arsenic contamination in groundwater is a major public health crisis in Bangladesh and parts of India, affecting over 200 million people (Chakraborti *et al.*, 2017). In the Lake Victoria Basin (LVB), studies show elevated concentrations of Pb, Cd, Hg, As, and Cr in water and sediments (Shikuku *et al.*, 2017a), threatening aquatic ecosystems, fisheries, livestock, and human health. The Mara River catchment, a major LVB tributary, is particularly impacted by large-scale and artisanal gold mining, urban effluents, and agricultural runoff. Research indicates that at least seven studies have assessed heavy metals along the Mara River and some main tributaries (Nzeyimana, 2003; Rwetabula and De Smedt, 2006; Nkinda *et al.*, 2020) yet smaller tributaries near Musoma and Tarime towns remain under-studied.

Musoma and Tarime are urban centers with dense settlements, artisanal gold mining, small-scale agriculture, and domestic wastewater discharge all potential sources of heavy metals into tributaries feeding Lake Victoria. Therefore, this study aims to assess heavy metal contamination in these urban tributaries, quantify associated risks, and provide critical data to guide local and transboundary water management, policy development, and public health protection in the Mara River catchment and the broader Lake Victoria Basin.

2. Materials and Methods

2.1 Description of the Study Area

2.1.1 Location

The study was conducted along tributaries in Musoma and Tarime, towns Mara Tanzania. These towns lie within the Mara River Basin which lies between 35.78° E and 0.43° S in the southwest of Kenya and 33.78° E to 1.48° S in northeast of mainland Tanzania (Mutie *et al.*, 2005).

2.1.2 Drainage Patterns and Climate

The Lake basin tributaries are the critical for water resource management and environmental conservation in the region. The climate of the Mara River Basin is primarily influenced by the Intertropical Convergence Zone (ITCZ) and variations in Indian Ocean surface temperatures (Zhu *et al.*, 2024). Annual precipitation varies significantly across the basin, averaging about 1,500 mm in the upper catchment and decreasing to approximately 800 mm near the river mouth (McClain *et al.*, 2014). Flood flows in the upper catchment range from 8 to over 150 m^3/s, with an average of 30 m^3/s, whereas in the lower catchment, flows range from 90 to over 400 m^3/s, averaging 300 m^3/s (McClain *et al.*, 2014). The rainfall pattern is bimodal, with the wet season extending from November to June and the dry season occurring between July and October (Bartzke *et al.*, 2018). However, recent climatic fluctuations within the Mara Serengeti ecosystem have disrupted these traditional patterns, resulting in severe droughts during typically wet months and intermittent heavy rainfall during dry periods, as observed in 2019 (Nkinda *et al.*, 2020).

2.1.3 Population and Human Activities

Musoma and Tarime are located in the Mara region of northern Tanzania with population of 164,172 and 133,043 respectively (Census, 2022), The towns serve

as important reference points for studies concerning geography, hydrology, and socio-economic activities due to their proximity to the Mara River and Lake Victoria. Musoma and Tarime towns in Tanzania's Mara Region are major socio-economic centers where diverse human activities contribute to heavy metal contamination in local water bodies. Musoma, situated along the shores of Lake Victoria, supports intensive fishing, fish processing, small-scale manufacturing, boat repair, and metal fabrication industries that discharge effluents rich in Pb, Cu, Zn, and Cr into nearby drains and tributaries (Kihampa and Wenaty, 2013). Domestic wastewater, solid waste disposal, and stormwater runoff from densely populated residential and market areas further intensify contamination (Mwegoha et al, 2016). Surrounding agricultural lands, where fertilizers and pesticides are routinely applied, introduce Cd, Cu, and Zn through leaching and surface runoff during rainfall events (Alloway, 2012; Mburu *et al.*, 2021). In Tarime, large-scale and artisanal gold mining (ASGM), notably near the North Mara Gold Mine, are dominant sources of Hg, As, Cd, and Pb, originating from tailings, amalgamation, and waste rock (Bitala et al, 2009; Shikuku et al., 2017). Additional agricultural and livestock activities, combined with rapid urban growth and inadequate waste management, intensify heavy metal input into the tributaries draining toward Lake Victoria (Shikuku et al., 2017).

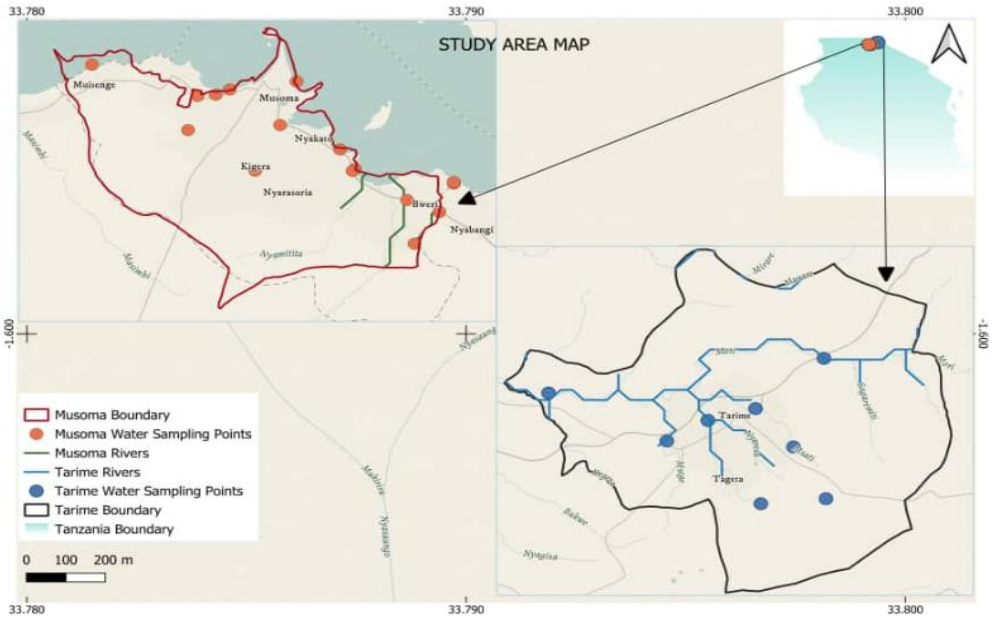

Figure 1: Sampling points in Musoma and Tarime towns

2.2 Data Collection

2.2.1 Sample Collection

A total of seventy-eight (78) surface water samples were collected from twenty-six (26) sampling points, 27 samples (9 points) taken from Tarime town and 51 (17 points) from Musoma town Figure 1, in April 2025 during the rainy season. The sampling locations included River Mori, Mara River, Musoma wastewater stabilization ponds (WSP), Musoma Lake bays, and various town tributaries which were the major drainages along the Urbans. Lake bays and WSP sites were specifically included to evaluate the concentrations of heavy metals in the lake, particularly at the discharge points of tributaries and treated domestic wastewater into Lake Victoria

The sampling points in Musoma and Tarime were strategically selected to capture the influence of

dominant human activities on tributary water quality. In Musoma, upstream sites represent relatively uncontaminated inflows, while midstream and downstream points receive inputs from fish processing plants, garages, markets, and residential drains. In Tarime, sites near artisanal mining zones capture potential discharges of Hg, As, Pb, and Cd from tailings and amalgamation processes. Downstream points receive agricultural runoff and urban effluents, reflecting cumulative contamination before entering Lake Victoria, providing spatial insight into pollution sources and transport mechanisms.

Each water sample was collected triplicate using pre-cleaned, high-density polyethylene (HDPE) bottles of 1-liter capacity. HDPE bottles were chosen due to their chemical inertness and suitability for storing water samples without leaching contaminants, particularly for trace metal analysis. All physical parameters (pH, EC, TDS, Turbidity, and Temperature) were analyzed at site. To ensure the accuracy and integrity of heavy metal measurements, samples intended for metal analysis were acidified onsite to pH <2 using nitric acid (HNO_3) as a preservative (APHA., 2017). This acidification prevents metal adsorption to container walls and inhibits biological activity. For general water quality parameters, separate bottles were kept unacidified and stored in cool boxes at 4°C during transportation to the laboratory, in order to slow down any chemical or biological changes in the samples.

2.2.2 Sample Preparation and Digestion

Prior to digestion, all samples were first filtered using 0.45 µm membrane filters to separate dissolved metals from particulate-bound forms at Water Institute Water Quality Laboratory. Filtration was essential to focus the analysis on the dissolved phase, which represents the bioavailable and mobile fraction of metals in aquatic systems.

Following filtration, 10 mL of each well-mixed sample was transferred into pre-cleaned polypropylene digestion tubes. To eliminate contamination, all tubes and caps were soaked overnight in 2N nitric acid (HNO_3) and rinsed three times with ultrapure, metal-free deionized water prior to use. This cleaning step was critical to minimize the risk of sample contamination from residual metals on container surfaces.

To each sample, including blanks, matrix spikes, standards, and quality control (QC) samples, 0.5 mL of concentrated HNO_3 was added. The acidified samples were then digested in a block heater at 105°C for 2 hours to break down organic matter and release metals into solution for accurate detection. For spiked samples, a known quantity of analytes was added to assess matrix effects and recovery efficiency. In this study, total metal concentrations were analyzed rather than dissolved metals. The choice to assess total metals was based on the need to capture the overall contamination level and potential ecological and human health risks associated with both particulate-bound and dissolved fractions of metals.

2.2.3 Analytical Procedure

Heavy metal analysis was performed at Ministry of Water Central Laboratory using an Agilent 8000 ICP-OES, with method detection limits ranging from 0.01–0.20 µg/L and quantification limits between 0.03–0.60 µg/L depending on the element (As, Cd, Cr, Pb, Hg, Zn, Cu). All analytes were above LOQ values, confirming data validity. The instrument conditions were Power1550 W, Plasma gas flow 15 L/min (Argon), Auxiliary gas flow 0.8 L/min, Nebulizer gas flow 1.0 L/min, Sampling depth 5.0 mm and Integration time 0.3 s per mass. To ensure high analytical performance, ultrapure water and trace-metal grade reagents were used throughout sample preparation and analysis. Working standard solutions were prepared by serial dilution of certified multi-element reference stock solutions (1000 mg/L) in 2% v/v ultrapure HNO_3. Quality assurance was maintained through the inclusion of certified reference materials (CRMs). Specifically, NIST SRM 1643f (Trace Elements in Water) was used as a reference material for validation of ICP-OES measurements, laboratory blanks, and field triplicates in each analytical batch.

Matrix spike recoveries ranged from 90% to 103%, falling well within the commonly accepted warning limits of 80–120%, similar to the recovery performance reported in comparable studies. This confirmed both the accuracy and precision of the ICP-OES method while benefiting from its superior detection limits and multi-element analysis capability.

2.2.4 Data Analysis

Descriptive statistics, including mean, median, standard deviation, minimum, and maximum values, were computed to summarize concentration levels for each analyte. Data normality was assessed using the Shapiro Wilk test to determine the appropriate statistical approach. Normally distributed data were analyzed using Pearson's correlation coefficient, whereas non-normally distributed data were analyzed using Spearman's rank correlation to identify potential relationships among the heavy metals and inter common contamination sources. Outliers identified by boxplot inspection and the interquartile range (IQR) method were carefully examined; values attributable to analytical or transcriptional errors were excluded, while genuine extreme values were retained for environmental interpretation. Analytical precision was evaluated through replicate measurements, and the relative standard deviation (RSD) for all metals was determined to assess analytical uncertainty, with values generally below 10%, indicating good reproducibility of the ICP-OES results. Statistical significance was set at $p < 0.05$, and all analyses were performed using (Origin, 2024).

2.2.5 Quality Assurance and Control

The analytical quality assurance and control framework for this heavy metal analysis was designed to ensure the highest standards of data reliability, accuracy, and precision throughout the entire analytical process. All heavy metal analyses for lead (Pb), chromium (Cr), cadmium (Cd), mercury (Hg), zinc (Zn), copper (Cu), and arsenic (As) were conducted at the Ministry of Water Central Laboratory using Inductively Coupled Pasma Optical Emission Spectrometry (ICP-OES) under rigorously controlled instrumental conditions as mentioned in section 2.4.

The calibration strategy employed a minimum of five calibration points spanning the expected concentration range, with calibration curves demonstrating excellent linearity coefficients ($r^2 \geq 0.9995$) for all target elements, while calibration verification standards were analyzed every ten samples to monitor instrumental drift and ensure continued accuracy throughout extended analytical sequences. Matrix spike recovery studies were conducted systematically across representative sample matrices to evaluate potential matrix effects and method accuracy, with recovery percentages ranging from 90% to 103%. All target elements, falling well within the commonly accepted warning limits of 80–120% established by EPA guidelines and demonstrating performance comparable to recovery ranges reported in peer-reviewed literature for similar environmental matrices.

3.0 Results and Discussion

3.1 Results

3.1.1 Descriptive Statistics of Heavy Metals Tarime and Musoma Town Tributaries

Table 1 and 2, presents statistical descriptive of heavy metals at Tarime and Musoma (p=0.05), the results indicate notable variations in their mean concentrations and associated dispersion parameters (standard deviation and standard error of the mean). The analyses of 26 points collected from river tributaries and lake bays in the Tarime and Musoma regions Table 3 and 4, revealed widespread heavy metal contamination, with particular concern for lead and Cadmium levels that significantly exceeded WHO drinking water guidelines. The comprehensive assessment of seven heavy metals (As, Cd, Cr, Cu, Hg, Pb, Zn), using ICP-OES analysis demonstrated that 58% of sampling locations (15 out of 26 sites) exceeded the WHO drinking water limit of 0.01 mg/L for lead, indicating substantial contamination across both study regions. The contamination was most severe

Table 1: Descriptive statistics of heavy metals in water samples at Tarime

Metal	Mean	Standard Deviation	SE of Mean
As	5.4E-4	2.37802E-4	7.92675E-5
Cd	0.00949	1.27574E-4	4.25245E-5
Cr	0.00711	2.55038E-4	8.50127E-5
Cu	0.02666	0.00728	0.00243
Hg	2.68889E-4	8.70983E-5	2.90328E-5
Pb	0.05691	0.02458	0.00819
Zn	0.02125	7.45369E-4	2.48456E-4

Table 1: Descriptive statistics of heavy metals in water samples at Musoma

Metal	Mean	Standard Deviation	SE of Mean
As	3.81753E-4	2.5162E-4	6.10268E-5
Cd	0.00949	5.65425E-5	1.37136E-5
Cr	0.00659	6.45702E-4	1.56606E-4
Cu	0.02664	0.00269	6.51924E-4
Hg	2.52159E-4	1.39475E-4	3.38277E-5
Pb	0.03359	0.02454	0.00595
Zn	0.02069	0.00153	3.71668E-4

at water treatment facilities, with the MUWASA water supply system showing alarming lead concentrations of 0.08671 mg/L in influent water and 0.07679 mg/L in treated effluent, representing contamination levels 8.7 and 7.7 times higher than acceptable drinking water standards, respectively.

3.1.2 Mercury and Arsenic Distribution and Contamination Assessment

Mercury (Hg) was detected at low concentrations ranged from Musoma and Tarime 0.0001233 mg/L (M7) to 0.00063 mg/L (M6), Mean = 0.000254 ± 0.000146 mg/L (CV = 57.5%) and 0.00012 mg/L (T3) to 0.00037 mg/L (T9), Mean = 0.00025 ± 0.00008 mg/L respectively Table 1 and 2. Arsenic in Tarime tributaries displaying concentrations ranging Table 3 and 4, from 0.0003 mg/L (T7) to 0.0011 mg/L (T1) (mean = 0.00053 ± 0.00025 mg/L), while Musoma, tributaries demonstrated significantly greater variability ranging from 0.0000117 mg/L (M17) to 0.00089 mg/L (M4) (mean = 0.000396 ± 0.000224 mg/L, CV = 56.6%). In Musoma the AIC Hospital Tributary (M6) exhibited Mercury concentrations 5.1 times higher than the minimum level while in Tarime the Mori River downstream showed the highest mercury levels. The relatively narrow concentration range, with a coefficient of variation of 32% at Tarime, indicates moderate spatial heterogeneity in mercury distribution across the sampling network, suggesting the influence of both natural geochemical processes

and potential anthropogenic inputs (Pavithra *et al.*, 2023).

Mercury and Arsenic contamination in African river systems has been extensively documented in relation to small-scale gold mining operations, which use Hg and As amalgamation techniques and can significantly elevate downstream Hg and As (Pretty and Odeku, 2017). These findings contrast with the more severe arsenic contamination documented, where (Nkinda *et al.*, 2021) reported arsenic concentrations up to 30.81 ± 0.02 mg/kg in sediments from Mara River tributaries, and studies from Tanzania and Ethiopia have documented high arsenic levels in human tissues including toenails and urine among pregnant women exposed to contaminated groundwater (Mengistu, 2021).

Arsenic and mercury are highly toxic metalloids that are extensively distributed in soils and water bodies, resulting in a variety of toxicity mechanisms and harmful effects on humans and environmental health (Annar, 2022; Kumar *et al.*, 2022). It's known to cause high spread of kidney cancers in US and worldwide (Hasan *et al.*, 2024). The World Health Organization WHO, 2017 guidelines for drinking water quality establish a maximum allowable concentration of 0.006 mg/L for inorganic mercury and 0.01mg/L for Arsenic to protect human health and ecology. All measured concentrations in this study fall well below the WHO guideline.

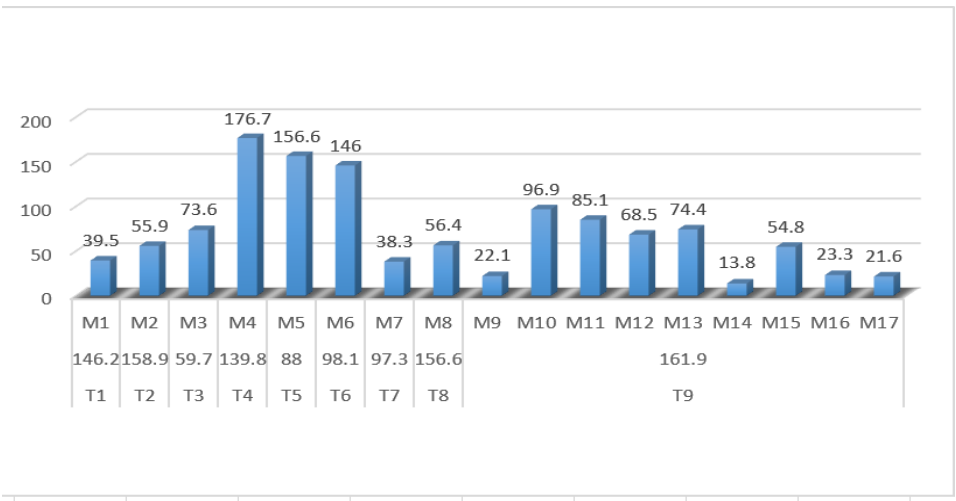

Figure 2: Presents Pollution index, HPI of heavy metals at Musoma and Tarime Town

3.1.3 Lead and Cadmium Distribution and Contamination Assessment

Lead and Cadmium in Tarime showed the most significant contamination concern, with concentrations ranging from 0.0039 mg/L (T3) to 0.0791 mg/L (T9),

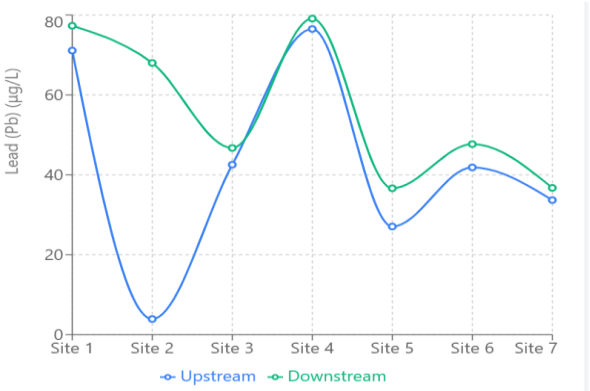

Figure 3: Paired Lead Upstream-Downstream Contamination trend in Musoma and Tarime

mean = 0.05647 ± 0.02434 mg/L (CV = 43.1%) and from 0.00931 mg/L (T5) to 0.00971 mg/L (T6) (mean = 0.00947 ± 0.00013 mg/L, CV = 1.4%) respectively Table 1 and 2. While in Musoma Pb and Cd showed the also contamination concern and spatial variability, ranging from 0.00465 mg/L (M14) to 0.08671 mg/L (M4), mean = 0.03615 ± 0.02409 mg/L (CV = 66.7%) and 0.00943 mg/L (M17) to 0.00958 mg/L (M3) (mean = 0.009475 ± 0.000043 mg/L, CV = 0.45%) respectively. This concentration exceeded the WHO guideline value of 0.01 mg/L and 0.005mg/L for drinking water Table 3 and 4. Lead concentrations (mean = 41.66 ± 26.59 µg/L) exceeded WHO limits (10 µg/L) in 21 of 26 samples (80.8%). Similarly, cadmium concentrations (mean = 9.49 ± 0.085 µg/L) exceeded WHO limits (3 µg/L) in 24 of 26 samples (92.3%). One-sample t-tests confirmed that both metals were significantly elevated compared to WHO standards (Pb: $t(25) = 6.07$, $p < 0.001$; Cd: $t(25) = 388.25$, $p < 0.001$). This high level of Pb and Cd might be associated with surface waste mining and domestic materials from the anthropogenic operations (Masindi, Mkhonza and Tekere, 2021).

Table 3: Presents the average heavy metals concentrations from Tarime Town

S/Code	As	Cd	Cr	Cu	Hg	Pb	Zn
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
T1	1.10E-03	9.50E-03	7.30E-03	1.57E-02	3.00E-04	7.11E-02	2.14E-02
T2	5.20E-03	9.60E-03	6.60E-03	2.60E-02	3.60E-04	7.73E-02	2.21E-02
T3	5.00E-04	9.50E-04	7.20E-03	2.60E-02	1.20E-04	3.90E-03	2.01E-02
T4	6.00E-04	9.30E-03	6.90E-03	2.63E-02	2.20E-04	6.80E-02	2.11E-02
T5	3.90E-04	9.30E-03	7.30E-03	1.56E-02	1.80E-04	4.25E-02	2.09E-02
T6	4.30E-04	9.70E-03	7.40E-03	3.50E-02	3.60E-04	4.67E-02	2.27E-02
T7	3.00E-04	9.50E-03	6.90E-03	2.70E-02	2.50E-04	4.70E-02	2.10E-02
T8	3.70E-04	9.50E-03	7.10E-03	3.43E-02	2.60E-04	7.65E-02	2.09E-02
T9	6.50E-04	9.50E-03	7.10E-03	3.40E-02	3.70E-04	7.91E-02	2.11E-02
WHO Standards	0.01	0.003	0.05	2	0.006	0.01	3
TZS-2018	0.01	0.003	0.05	1	0.001	0.01	5

The Mara River Basin, where Musoma is located, has experienced significant impacts from mining and

Table 4: Presents the average heavy metals concentrations from Musoma Town

S/Code	As	Cd	Cr	Cu	Hg	Pb	Zn
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
M1	2.10E-04	9.61E-03	8.06E-03	3.04E-02	1.30E-04	1.87E-02	2.10E-02
M2	4.00E-04	9.55E-03	7.60E-03	2.56E-02	1.90E-04	2.71E-02	2.10E-02
M3	1.10E-04	9.58E-03	7.48E-03	2.50E-02	2.30E-04	3.66E-02	2.11E-02
M4	8.90E-04	9.55E-03	7.18E-03	2.60E-02	1.90E-04	8.67E-02	2.11E-02
M5	4.90E-04	9.53E-03	6.98E-03	2.50E-02	1.30E-04	7.68E-02	2.10E-02
M6	7.70E-04	9.52E-03	6.70E-03	2.56E-02	6.30E-04	6.72E-02	2.10E-02
M7	4.40E-04	9.51E-03	6.54E-03	2.60E-02	1.20E-04	1.87E-02	2.11E-02
M8	2.20E-04	9.44E-03	5.82E-03	2.56E-02	5.00E-04	2.67E-02	1.47E-02
M9	6.40E-04	9.45E-03	6.14E-03	2.57E-02	3.30E-04	6.83E-03	2.11E-02
M10	3.40E-04	9.46E-03	6.16E-03	2.63E-02	1.80E-04	4.77E-02	2.11E-02
M11	2.10E-05	9.46E-03	6.15E-03	2.56E-02	2.20E-04	4.19E-02	2.11E-02
M12	3.80E-04	9.43E-03	6.12E-03	2.60E-02	1.30E-04	3.37E-02	2.11E-02
M13	1.40E-04	9.44E-03	6.47E-03	2.60E-02	1.30E-04	3.67E-02	2.11E-02
M14	3.80E-04	9.45E-04	6.11E-03	2.56E-02	1.90E-04	4.65E-03	2.10E-02
M15	6.40E-04	9.44E-03	6.10E-03	2.60E-02	2.40E-04	2.68E-02	2.11E-02
M16	4.20E-04	9.45E-04	6.11E-03	3.60E-02	3.80E-04	7.65E-03	2.11E-02
M17	1.20E-05	9.43E-03	6.32E-03	2.65E-02	3.10E-04	6.69E-03	2.11E-02
WHO	0.01	0.003	0.05	2	0.006	0.01	3
TZS-2018	0.01	0.003	0.05	1	0.001	0.01	5

farming activities on water quality (Nkinda *et al.*, 2021), with extensive artisanal gold mining operations being a major contributor to heavy metal pollution. These mining activities often involve the use of Lead-based materials, mercury amalgamation processes, and inadequate waste management practices that allow Lead-containing tailings and processing chemicals to leach into surface water and groundwater systems. Cadmium (Cd) is a non-essential but very toxic metal with a chronic effect on human health due to its accumulation mainly in the liver, but also in the blood, bones, muscles, and kidneys (Pedrini-Martha *et al.*, 2021)[. Studies carried out in several countries have shown that most foods have a Cd content between 0.005–0.1 mg/kg, but some foods like seafood may contain higher concentrations. The sources of lead nd Cadmium are Industrial waste, some fertilizers, etc., are responsible for about 50% of the Cd and Pb that reaches the sea (Pedrini-Martha *et al.*, 2021; Collin *et al.*, 2022). Therefore, the finds align with the other studies which mentioned high amount of lead and cadmium with their respective ecological effects to humans and environment.

3.2 Chromium Distribution and Contamination Assessment

The detrimental effects of using water with high amount of Chromium are bronchial asthma, lung cancer, nasal ulcers, skin allergies, carcinogenicity, and genotoxicity to protect from these adverse effects, WHO has suggested a provisional guideline as 0.05 mg/L (Pokhrel and Pokhre, 2022). From this study

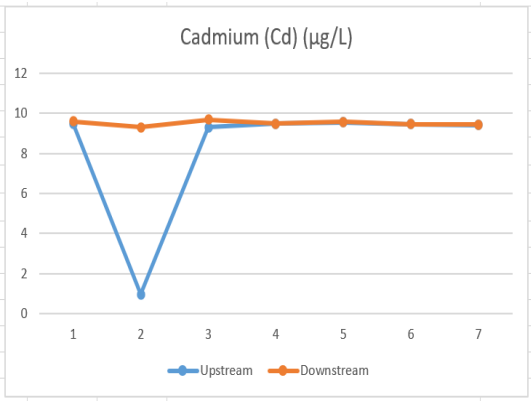

Figure 4: Paired Cadmium Upstream-Downstream Contamination trend in Musoma and Tarime

Chromium in Musoma and Tarime levels ranged from 0.00582 mg/L (M8) to 0.00806 mg/L (M1), mean = 0.006516 ± 0.000616 mg/L (CV = 9.45%) and 0.00662 mg/L (T2) to 0.00746 mg/L (T6), with a mean of 0.00708 ± 0.00026 mg/L respectively. The (M1) exhibited the highest Chromium concentration meanwhile in Tarime T6 location showed elevated chromium concentrations. This spatial pattern suggests potential point-source contamination upstream of the bridge location, possibly related to industrial discharge, mining activities, or agricultural runoff containing chromium-based compounds.

Similar patterns of elevated Chromium concentrations at specific sampling locations have been documented in other African river systems, where point sources such as tanneries, mining operations, and industrial facilities contribute to localized contamination hotspots (Masindi, Mkhonza and Tekere, 2021). Also, the pollution sources align with Anubhav et al, 2022, mentioned heavy metals can enter surface water bodies through various sources, including mining, the discharge of metal-containing wastes, effluent from industrial areas, leaded gasoline and paints, fossil fuel combustion, agricultural fertilizers and pesticides, animal manures, sewage sludge, wastewater from residential areas (Singh *et al.*, 2022).

When compared to international water quality standards, the measured Chromium concentrations require careful evaluation. The World Health Organization (Organization, 2022) guidelines for drinking water quality establish a maximum allowable concentration of 0.05 mg/L for total Chromium, while the US Environmental Protection Agency (USEPA, 2014) and Tanzania National Standards (EAS 12: 2018) set the maximum contaminant level at 0.05 and 0.05 mg/L respectively. All measured concentrations in this study fall withing these regulatory thresholds.

3.3 Copper and Zinc Distribution and Contamination Assessment

Copper (Cu) demonstrated the highest variability among trace metals, in Tarime ranging from 0.01567 mg/L (T5) to 0.035 mg/L (T6), mean = 0.02574 ± 0.00647 mg/L (CV = 25.1%) and Musoma varied from 0.025 mg/L (M3, M5) to 0.036 mg/L (M16), mean = 0.02606 ± 0.00289 mg/L (CV = 11.1%). Notable concentration peaks occurred at T6, T8, and T9, for Tarime while in Musoma, Palm Beach Lake Bay

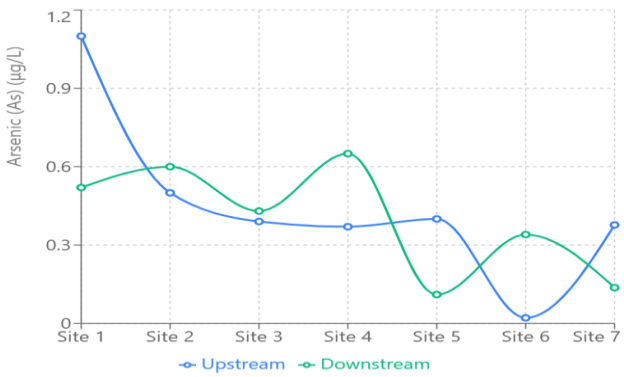

Figure 5: Paired Arsenic Upstream-Downstream Contamination trend in Musoma and Tarime

(M16) showed elevated Copper levels. This level of spatial heterogeneity is consistent with findings from other aquatic systems, where considerable spatial variability in heavy metal concentrations has been documented in river systems, particularly in basins influenced by mixed anthropogenic activities (Jiménez-Oyola *et al.*, 2023).

While Zinc (Zn) concentrations at Tarime were relatively stable, ranging from 0.02011 mg/L (T3) to 0.0227 mg/L (T6), with a mean of 0.02122 ± 0.00060 mg/L (CV = 2.8%) while in Musoma were relatively uniform, ranging from 0.01474 mg/L (M8) to 0.0211 mg/L (M14), mean = 0.02089 ± 0.00151 mg/L (CV = 7.23%). The spatial comparison reveals that Tarime locations exhibited more consistent Zinc levels with lower variability (CV = 2.8%) compared to Musoma

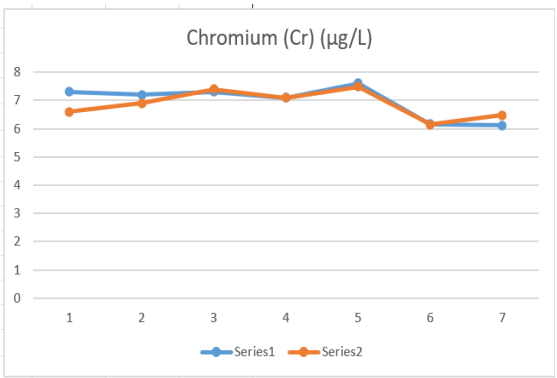

Figure 6: Paired Chromium Upstream-Downstream Contamination trend in Musoma and Tarime.

(CV = 7.23%), suggesting different contamination dynamics between the two geographical areas. Such spatial variability in Zinc contamination has been documented in river catchments where both point and diffuse sources contribute to overall contamination patterns (Az-Zahrah *et al.*, 2024).

This believes that intake of copper and zinc at concentrations greater than the prescribed limit can cause acute health problems namely gastrointestinal disturbance, central nervous problems, mucosal irritation, Wilson's diseases, damage of liver and kidney, wide spread capillary damage, hepatic and renal damage as stated by Bashir et al, 2021 and Gomaa et al, 2021 (Bashir *et al.*, 2021; Gomaa *et al.*, 2021). The WHO set guidelines of copper and zinc as 2mg/L and 3mg/L respectively. But from this study Copper and Zinc were within the WHO guidelines.

3.4 Heavy Metal Pollution Index.

HPI is expressed as arithmetic mean of the analyzed metal pollutants. The extent of metal pollution was determined using the method developed by (Mohan et al, 1996). The HPI model is given by equation 1.

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (1)$$

where, Q_i is the sub-index of the i^{th} parameter. W_i is the unit weightage of i^{th} parameter, and n is the number of parameters considered. The sub index (Qi) of the parameter is calculated by Equation 2

$$Q_i = \sum_{i=1}^{n} \frac{\{M_i(-)I_i\}}{(S_i - I_i)} \quad (2)$$

where M_i is the monitored value of heavy metal of i^{th} parameter, I_i is the ideal value (maximum desirable value for drinking water) of the i^{th} parameter and S_i is the standard value (highest permissive value for drinking water) of the i^{th} parameter. The sign (-) indicates numerical difference of the two values, ignoring the algebraic sign.

According to Indian norms (IS, 2012), the prescribed range of water quality standard alongside WHO rules (WHO, 2011). 100 is the proposed value, which is critical for drinking water (Ahirvar *et al.*, 2023).

The study found that 5 out 9 sampling points exceeded the limit of 100 (HPI>100) at Tarime Urban while in Musoma 3 out of 17 points exceeded limit of 100 (HPI>100) Figure 2. This indicates that high level pollution of heavy metals at Tarime than Musoma. The findings align with other studies conducted at Mara

which point high level of pollution of heavy metal in Tarime district (Nkinda et al., 2021).

3.5 Correlation Between the Heavy Metals in Tarime and Musoma

Pearson's correlation analysis was conducted to assess the relationships among heavy metal concentrations in surface water samples collected from Tarime town tributaries Table 4. Strong positive correlations were observed between Pb and Hg (r = 0.715, p =0.03) and between Hg and Zn (r = 0.785, p =0.01), suggesting that these metals may share similar anthropogenic sources, linked to urban runoff and domestic wastewater inputs (Wei *et al.*, 2018). A significant positive correlation between Cd and Hg (r = 0.621, $p < 0.08$) indicated possible co-contamination from industrial, mechanical activities and mining activities in the area (Gelaye, 2024). This relates with the study area where samples were collected from near mechanical garages, artisan mining area and industrial area.

The correlation analysis of heavy metals in Musoma location (17 sampling points, M1 - M17) Table 5. reveals inter-elemental relationships that provide insights into pollution sources, geochemical processes, and environmental contamination patterns across the Mara River system and Lake Victoria tributaries. Cd and Cr showed strong correlation with r = 0.9449 which indicates these metals share common geochemical behavior and likely originate from similar geological sources and potential anthropogenic inputs from agricultural activities, mining and urban runoff (Wei *et al.*, 2018). This strong correlation aligns with the study area where samples were collected from tributaries and waste treatment plant, which received discharges from garages, domestics, industrial, artisan mining and agricultural activities which may contribute the sources of correlation.

3.6 Upstream-Downstream Contamination Patterns

To determine the impact of anthropogenic activities on water quality in the study area, paired upstream-downstream comparisons were conducted at seven locations (n = 7 paired samples) four in Tarime and three in Musoma. The sites number 1 to 7 are Kebaga Upstream-Downstream, Nyandurumo Upstream-Downstream, Kendagora Upstream-Downstream, Mori River Upstream-Downstream, Bweri Upstream-Downstream, Musoma bus Upstream-Downstream and Mgaranjabo Upstream-Downstream. Paired t-tests

Table 5: Pearson correlations of Heavy Metals Concentrations in Tarime Town Tributaries

	As	Cd	Cr	Cu	Hg	Pb	Zn
As	1						
Cd	0.32229	1					
Cr	-0.69328	0.03471	1				
Cu	-0.09844	0.52477	-0.1110	1			
Hg	0.42536	**0.62061**	-0.1770	0.41835	1		
Pb	0.3579	0.02643	-0.3797	0.1711	**0.71543**	1	
Zn	0.4173	**0.62406**	-0.0376	0.24023	**0.78468**	0.40149	1

The bolded parameters indicate variables with the strong correlation

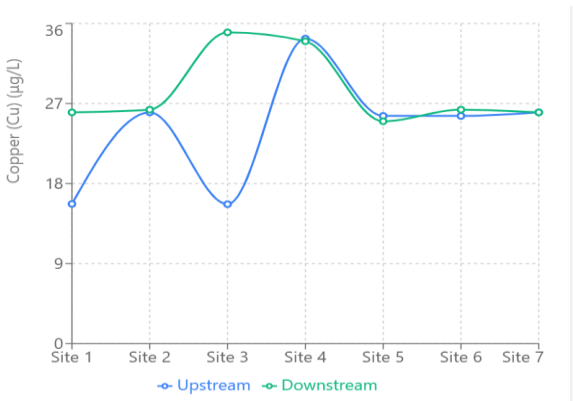

Figure 7: Paired Copper Upstream-Downstream Contamination trend in Musoma and Tarime.

were used to determine whether metal concentrations changed significantly between upstream and downstream sampling points. However, a paired t-test indicated that the differences were not statistically significant for Pb ($t(6) = 1.61$, $p > 0.05$), Cd ($t(6) = 0.71$, $p > 0.05$), As ($t(6) = -0.43$, $p > 0.05$), Cr ($t(6) = -0.63$, $p > 0.05$), Cu ($t(6) = 1.46$, $p > 0.05$), while Hg ($t(6) = 2.32$, $p > 0.05$) and Zn ($t(6) = 2.05$, $p > 0.05$) show significant Figure 3 to 9. Suggesting relatively consistent Pb, Cd, As, Cr, Cu, Hg and Zn levels along the tributaries course respectively.

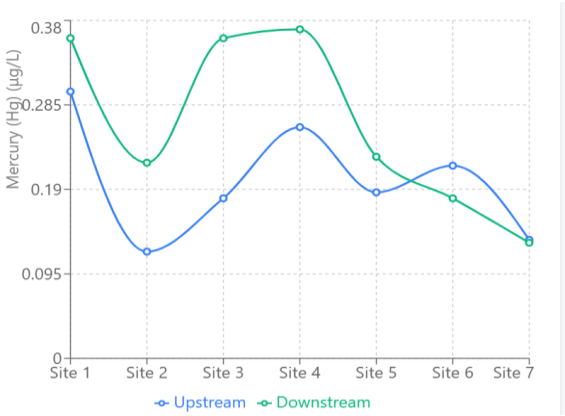

Figure 8: Paired Mercury Upstream-Downstream Contamination trend in Musoma and Tarime.

These increases downstream indicate heavy metal pollution from anthropogenic activities along the tributaries. Urban pollution (batteries, old paint), agricultural pesticides, agricultural activities using copper-based fungicides and livestock supplements, artisanal gold mining may be the main source of high increase of the heavy metals as observed during sampling. Other heavy metal Figure 10 showed decline in value from upstream at downstream indicating binding of heavy metals to suspended sediments or particulate organic matter (Gorny *et al.*, 2016).

3.7 Spatial Distribution Patterns and Correlations Heavy Metals and Physical Parameters

In Tarime, the Mori River exhibited the highest lead (0.0765–0.0791 mg/L) Cadmium (0.00095–0.0097 mg/L) concentrations, coinciding with extreme turbidity (1780–2098 NTU), indicating particulate-bound contaminants from mining activities, consistent with (Mataba *et al.*, 2016). Conversely, Nyandurumo Dam upstream showed minimal contamination (Pb: 0.0039 mg/L) due to sedimentation processes (Nkinda *et al.*, 2021). In Musoma, MUWASA wastewater facilities displayed elevated lead (0.08671 mg/L) with high conductivity (3900 µS/cm) and TDS (2360 mg/L), reflecting anthropogenic inputs similar to (Tang *et al.*, 2023) findings. Lake bay sites showed

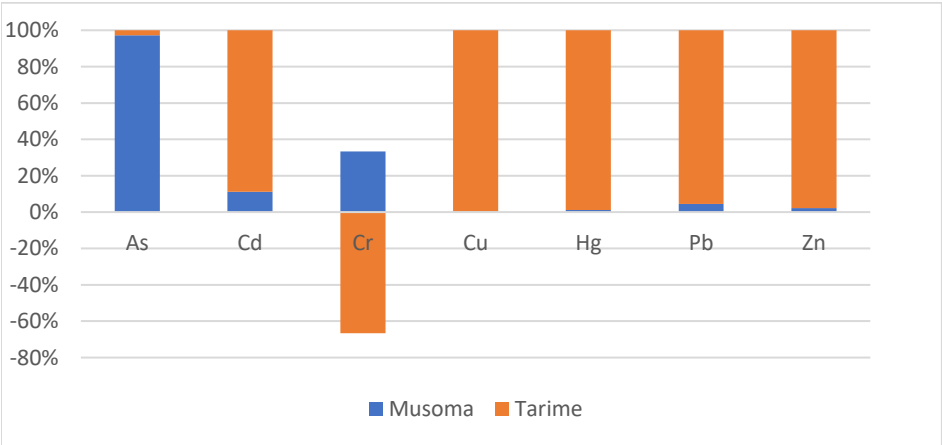

Figure 10: Average Percentage increase Upstream to Downstream at Musoma and Tarime Towns.

lower metal concentrations but higher pH (8.46–9.28), reducing metal solubility through precipitation and

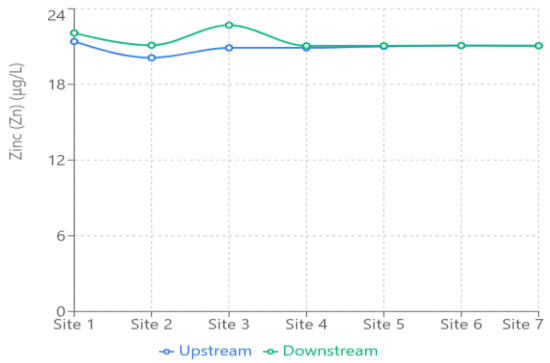

Figure 9: Paired Zinc Upstream-Downstream Contamination trend in Musoma and Tarime

adsorption (Mohamed *et al.*, 2016) emphasizing physicochemical parameters' influence on metal distribution.

4.0 Conclusion

This study revealed critical heavy metal contamination in the Mara River Basin, with lead exceeding WHO limits in 80.7% of samples and cadmium in 92.3% of samples. These findings have urgent implications. Detected levels pose severe risks including neurological damage, kidney disease, and cancer. Immediate public health advisories and community screening programs are essential. The upstream-downstream lead gradient indicates point-source pollution from mining and industrial activities requiring targeted source control, phytoremediation, and continuous monitoring networks. The strengthened national water quality regulations, mandatory EIAs for basin development projects, transboundary cooperation with Kenya, and substantial investment in water treatment infrastructure is required. Without urgent action, communities face irreversible health impacts and long-term economic consequences. This research provides the evidence base for declaring affected areas as environmental emergency zones and mobilizing resources for remediation. Clean water is a fundamental right that must be protected through coordinated policy, management, and community action.

5.0 Recommendation

The study recommends the from;

- Regular Water Quality Monitoring program by The Lake Victoria Basin Water Board for heavy metals and key physicochemical parameters in all tributaries of Musoma and Tarime to detect changes and trends over time in all source of water bodies used by the communities around the region.
- Educate local communities on the risks associated with consuming untreated water, especially highlighting the vulnerability of children to heavy metal exposure. Public awareness should be emphases to small gold mining artisan on protection of their health and protect water pollution from using toxic chemicals like mercury and Arsenic in gold extraction.
- Water Treatment and Remediation during planning and design should consider to employ technology for heavy metals treatment by promote the use of effective water treatment technologies, such as filtration or adsorption methods, to reduce heavy metal concentrations in drinking water sources.
- Encourage local and regional authorities to develop and enforce policies aimed at sustainable water resource management, pollution control, and mitigation of heavy metal exposure. The authorities should enforce policies on solid waste management as were observed in many areas during the study which when not managed may cause sources of water pollution.
- The study recommends periodic studies to track changes in heavy metal concentrations and to assess the effectiveness of intervention

measures over time in all season during rain and dry season around tributaries.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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