

Spatio-temporal Variations and Potential Health Risks of Heavy Metals in Water from River Manafwa, Uganda

Mark Opolot¹, Timothy Omara^{2,3,*} , Christopher Adaku¹, Emmanuel Ntambi¹

¹ Department of Chemistry, Faculty of Science, Mbarara University of Science and Technology, P.O. Box 1410, Mbarara, Uganda; mopolot56@gmail.com (M.O.); cadaku@must.ac.ug (C.A.); emmantambi@must.ac.ug (E.N.);

² Institute of Chemistry of Renewable Resources, Department of Chemistry, University of Natural Resources and Life Sciences, Vienna (BOKU), Konrad-Lorenz-Straße 24, 3430 Tulln an der Donau, Austria

³ Chemistry Division, Testing Department (Food Safety Laboratories), Standards Directorate, Uganda National Bureau of Standards, Bweyogerere Industrial and Business Park, P.O. Box 6329, Kampala, Uganda

* Correspondence: prof.timo2018@gmail.com, timothy.omara@boku.ac.at;

Scopus Author ID 57211523754

Received: 31.10.2022; Accepted: 5.01.2023; Published: 13.08.2023

Abstract: The epicenter of flash flood inundations and landslides in Uganda has been areas around Mt. Elgon. By implication, it has led to the loss of lives and food and water insecurity. This study assessed the seasonal variations in physiochemical parameters and heavy metals (HMs) water content from River Manafwa (R. Manafwa), the major water source used around Mt. Elgon. Potential insidious human health risks associated with consumption and dermal contact with water from the river were assessed using target hazard quotient and incremental lifetime cancer risk methods. Results of atomic absorption spectrometry analysis showed that the concentrations of the HMs in the wet and dry seasons ranged from below the detection limit to 1.407 ± 0.001 mg/L, which were below WHO limits. Health risk assessments indicated that there are discernable non-carcinogenic health risks from the ingestion of water from R. Manafwa, as the total target hazard quotients were above 1 for some of the samples. Cancer risk values indicated that there are no potential cancer risks from ingestion of water from the river. This study recommends that regulatory authorities should intervene to mitigate the pollution of R. Manafwa by strengthening restrictions on sand mining and dumping of wastes into the river.

Keywords: water quality; Manafwa watershed; Bududa; carcinogenic risk; target hazard quotient; trace metals.

© 2023 by the authors. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Rapid economic growth, industrialization, and urbanization with inadequate regulatory structures have infringed on the pristine environment, raising many sustainability challenges [1]. A case in point is developing countries such as China and India, where pollution levels have surpassed regulatory limits and have been the subject of obsessive research [2, 3]. Of immediate concern has been the pollution of water resources with contaminants that make them unsafe for drinking, thereby impeding the realization of some Sustainable Development Goals such as SDG 6 and SDG 14 [4]. Over the years, the scope of water contaminants has widened to include heavy metals (HMs), endocrine-disrupting chemicals, flame retardants, polycyclic aromatic hydrocarbons, current use pesticides, preservatives, personal care products [5-7], and other contaminants of emerging concern such as macro-, micro- and nanoplastics, algal toxins, and active pharmaceutical ingredients [7]. Within this frame of reference, HMs remain the most

ubiquitous contaminants in water resources due to their diverse occurrence and inclusion in appliances, consumer goods, industrial machinery and processes [8].

Heavy metals (HMs) are chemical elements with relatively high densities and are potentially toxic at concentrations above their established threshold limits [9]. They form part of the earth's crust in negligible concentrations but can continuously get enriched due to indiscriminate human activities (that alters their geochemical cycles and biochemical balance) and natural processes such as volcanic activity, metal corrosion, and metal evaporation from soil, water, and sediments [8, 10]. Examples of HMs include typical metals and metalloids such as vanadium, tin, strontium, mercury, arsenic, lead, zinc, nickel, cadmium, chromium, cobalt, copper, iron, molybdenum, and titanium [9, 11]. Some of the HMs are important co-enzymes in reactions that drive living cells but are bioaccumulative and toxic to living organisms at elevated concentrations [12, 13]. For terrestrial and aquatic organisms, exposure to HMs occurs through direct ingestion in water, food, medicine, direct deposition from the atmosphere, dermal adsorption, or inhalation from occupational sources [8, 14-16]. Ingestion of HMs in drinking water is the most common route of exposure, morbidities, and mortalities from HMs [17]. Despite this, routine monitoring of HMs contamination and remediation in water resources of developing countries are limited.

There are various water resources in the East African community, a region of seven developing countries in Eastern Africa. Nevertheless, there are still high incidences of water scarcity in the region [18, 19]. For example, Uganda, the study's focus area, has over 21 million (51%) of its population without access to safe drinking water. This is in part due to the contamination of the available water resources by various anthropogenic activities. Around Mt. Elgon (Manafwa watershed) in Eastern Uganda, there have been several incidences of torrential rains, perennial (flash) floods, and landslides, which have led to an intolerable death toll, food, and water insecurity [20, 21]. The floods have spotlighted the country's climate change crisis, emphasizing the need for more research in this watershed [22].

To date, no study has examined the HMs content as well as health risks that could emanate from ingestion and dermal contact with contaminated water from River Manafwa (also known as Manafwa River; R. Manafwa henceforth) especially following torrential rains and the attendant floods and landslides. Therefore, this contribution assessed the seasonal variations in some selected physiochemical parameters and assessed the health risks associated with ingestion and dermal contact with HMs in water from R. Manafwa, the major water source used across Bududa, Manafwa, Butaleja, and Mbale districts of Eastern Uganda.

2. Materials and Methods

2.1. Description of the study area.

The study was undertaken on water samples from R. Manafwa (0.9420°N 33.920°E), the longest river that flows through the Mbale and Butaleja districts of Uganda. The river is fed by various tributaries (such as Sala, Liisi, Wukha, Tsutsu, Pasa, Kufu, Nambale, and Makhuba) and small streams from the transboundary Mt. Elgon (an extinct volcanic agglomerate of Miocene age that rises to 4321 m above sea level)[23]. River Manafwa is about 14.63 kilometers long and is the main water source for the nearby communities. Still, economic activities (such as sand mining, agriculture, and welding works) and frequent floods have anecdotally been implicated in the deterioration of the water quality of R. Manafwa that forms part of the Manafwa River Basin traversing Bududa, Manafwa, Butaleja, and Mbale districts

of Eastern Uganda (Figure 1) [24]. Rivers and streams from Mt. Elgon densely dissect the Manafwa River Basin, explaining the rugged topography characterizing the steep slopes in this area. Hydrologically, R. Manafwa joins the Mpologoma River and drains into Lake Kyoga, a mesotrophic lake connected to Lake Victoria, and forms part of the River Nile that flows up to Egypt and empties into the Mediterranean Sea [25].

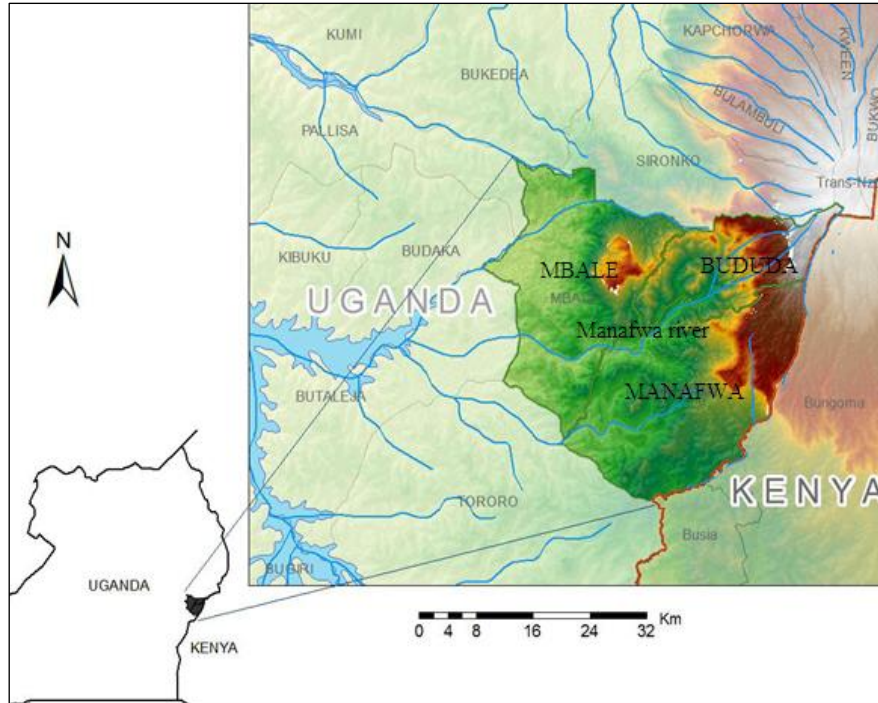


Figure 1. Map showing the location of River Manafwa in Eastern Uganda.

River Manafwa is the major river in the Elgon sub-region. It is the major water source for Manafwa waterworks that supplies water for domestic use to Mbale municipality, Butaleja town, and Kamonkoli town in Budaka district. Its water is also used by the local community for agriculture along the river banks, fish farming and rice growing in the Doho irrigation scheme, Butaleja district. This study considered R. Manafwa stretching from Bulucheke in Bududa district up to slightly beyond Manafwa Water Works, Mbale district (Figure 1). This covered a total distance of about 58 km. The river was divided into two sections, namely, the upper course and the lower course. The upper course stretched from Bulucheke to Manafwa town. This part of the river was further subdivided into two segments, A and B (Table 1). Segment A was from Bulucheke to Bududa, and this was an area where landslides normally occur. Segment B was from Bududa Town up to Manafwa Town, an area characterized by great human settlements and activity in the river catchment area. The lower course of the river was from Manafwa town up to slightly beyond Manafwa Water Works (Figure 2); with the greatest human activities including stone quarrying, sand mining, agriculture, automobile washing, and vehicular movement and sewage treatment. Besides, this part of the river also receives road runoff from Mbale Municipality and Manafwa Town, where many metals work activities and leachates from solid waste heaps occur.

Table 1. Summary of sampling sites and the potential sources of heavy metal contaminants along R. Manafwa.

| Sampling Site | Sample code | Activities/establishments |
|-------------------------|-------------|--|
| Bulucheke area | A1, A2 | Landslide affected site, residential area, school science laboratories |
| Bukigai market area | B1 | Market activities, garages, residential cultivation |
| Bududa Town | B2 | Metal welding and fabrication, Bududa Hospital, car washing bay |
| Manafwa Town downstream | M1 | Metal welding, garages, horticulture cultivation, slum and residential |

| Sampling Site | Sample code | Activities/establishments |
|---------------------------|-------------|---|
| Manafwa Bridge upstream | M2 | Sand mining, vegetable growing, motorcycle washing, stone quarrying |
| Manafwa Bridge Downstream | M3 | Vehicular traffic |
| Manafwa Water Works Area | M4 | Water treatment, sand mining, horticulture |



Figure 2. Overview of R. Manafwa (a) river water choked with high levels of sand and silt; (b) staff at Manafwa Water Works trying to clean water clarifiers to avoid them from silting up, (c) one of the sand mining site operations that is speeding up river bank erosion and sedimentation, and (d) section of the river where flooding swept away a bridge.

2.2. Sample collection.

The water samples were collected at a depth of 10-15 cm below the water surface, using clean 500 mL plastic bottles. Sampling was done at 8.00 am, 12.00 pm, and 4.00 pm (East African Standard Time) to cater for variations that could have occurred in the river water due to temperature changes and the different human activities occurring during the day. Sampling was done thrice each season (September, October, and November 2018 for the wet season, and December 2018, January 2019, and February 2019 for the dry season).

All three water samples collected from each sampling site were mixed to obtain a composite water sample. One liter of the composite water sample was measured and transferred into a cleaned plastic bottle, sealed and labeled to easily identify the sampling site. Four composite water samples were taken from each of the two river sections during each sampling in the major seasons (dry and wet seasons) to account for seasonal variations. In the river's upper course, two composite water samples were taken from each segments A and B and labeled A1, A2, and B1, B2, respectively. In the river's lower course, two water samples were taken from two selected sites within the area just before the Manafwa water works and were labeled M1 and M2. Two other water samples were taken from sites just after the bridge and beyond Manafwa water, labeled M3 and M4. The eight sampling points were chosen to capture the stretch where the landslides normally occur and the major anthropogenic activities carried

out along the river banks (Table 1). Water samples were then transported to the laboratory in ice boxes within 24 hours from the time of collection.

2.3. Sample preparation and analyses.

During the sampling of water, non-conservable parameters (electrical conductivity and pH) were measured on-site using calibrated Jenway pH/mV/Temperature and Conductivity meters (Jenway Gransmore Green, England). The other parameter (total hardness) was determined by EDTA complexometric titration method [26].

Each water sample was filtered through Whatmann No. 42 filter paper to remove suspended solids. They were then acidified with 1 ml of concentrated nitric acid to preserve ions in solution in preparation for elemental analyses. The acidified water samples (250 mL) were evaporated into 25 mL volumes. The concentrates were transferred into 50 mL volumetric flasks and diluted to the mark with diluents (0.1% of lanthanum chloride and 1% of concentrated nitric acid in distilled water). These were then transferred into clean sample bottles and analyzed for the HMs using atomic absorption spectrophotometer (AAS, Perkin Elmer Analyst 100) to determine the concentration of the eight selected HMs: copper (Cu), nickel (Ni), manganese (Mn), zinc (Zn), lead (Pb), cadmium (Cd), chromium (Cr) and iron (Fe).

Working standards prepared from the dilution of 1000 ppm stock solution of the nitrate and chloride salts of the HMs were used to construct calibration curves. The concentration of the HMs in the sample digestates was determined from the calibration curves in mg/L. Quality control was performed by analyzing blanks and spiked samples according to the same procedure. Recoveries obtained ranged from 96% to 101%. Analytical precision (expressed as Relative Standard Deviation) varied between 3% and 4%. The method detection limits (LODs) were computed as Blank + 3 × Standard Deviations for four samples analyzed in triplicate.

2.4. Assessment of human health risks.

Health risk assessments establish the link between the environment and human health that can be expressed quantitatively in terms of hazard degree. This study calculated the carcinogenic and non-carcinogenic health risks separately for adults as the general population and children as a sensitive group.

2.4.1. Non-carcinogenic health risks

The average daily doses were estimated to discern human exposure through direct ingestion ($ADD_{\text{ingestion}}$; mg/kg/day) and dermal contact ($ADD_{\text{dermal contact}}$; mg/kg/day) with water (Equations 1 and 2)[15, 27, 28]. Dermal contact is expected to stem from sand mining in this river, exposing the mining communities to HMs in the contaminated water.

$$ADD_{\text{ingestion}} = \frac{C \times W_{\text{ir}} \times E_f \times E_d}{W_{\text{ab}} \times T_{\text{aet}}} \quad (1)$$

$$ADD_{\text{dermal contact}} = \frac{C \times SAF \times DAF \times AF \times E_f \times E_d}{W_{\text{ab}} \times T_{\text{aet}}} \times 10^{-6} \quad (2)$$

From which C is the heavy metal concentration (mg/L), W_{ir} is the water ingestion rate = 1.8 L/day and 21.0 L/day for children and adults, E_f = exposure frequency (365 days/year), E_d = exposure duration, the average lifetime (58.65 years for an adult Ugandan)[15, 29], W_{ab}

= average body weight (considered to be 15 kg for children and 60 kg for adults), T_{aet} is the average exposure time for non-carcinogens = $E_f \times E_d$ [30], SAF is the exposed surface area = 2,800 cm² for children and 24,350 cm² for adults [28], DAF is the dermal absorption factor = 0.01 for carcinogenic HMs and 0.001 for non-carcinogenic HMs [31], AF is the skin adherence factor in mg/cm²/day = 0.2 and 0.7 for children and adults [32].

Similarly, the target hazard quotient (THQ) was calculated for both direct ingestion and dermal contact with water (Equations 3 and 4). Practically, $THQ \leq 1$ is indicative that the exposure is unlikely to elicit adverse health effects on an individual. Otherwise, $THQ > 1$ attests to the potential of non-carcinogenic effects being experienced [32]. Because such effects are augmentative in the context of contaminants like HMs, the cumulative risk or total THQ was computed as the arithmetic sum of the THQ of the HMs. As per US EPA [33], the health risk calculations assume that the ingested and adsorbed doses are equal to the dose absorbed into the body.

$$THQ = \frac{ADD_{ingestion}}{RfD_{oral}} \quad (3)$$

$$THQ = \frac{ADD_{dermal\ contact}}{RfD_{dermal}} \quad (4)$$

where RfD_{oral} is the oral reference dose. Its values are 4.0×10^{-2} , 3.0×10^{-4} , 3.0×10^{-2} , 3.0×10^{-2} , 4.0×10^{-3} , 1.0×10^{-3} , 1.5×10^0 , and 7×10^{-1} mg/kg/day for Cu, Ni, Mn, Zn, Pb, Cd, Cr, and Fe, respectively. The RfD_{dermal} is the dermal reference dose, with values of 1.0×10^{-2} , 5.40×10^{-3} , 9.6×10^{-1} , 6.0×10^{-4} , 5.25×10^{-4} , 6.0×10^{-5} , 6.0×10^{-5} , and 1.4×10^2 mg/kg/day for Cu, Ni, Mn, Zn, Pb, Cd, Cr and Fe, respectively [33]. A reference dose is defined as the highest amount of a heavy metal ingested through a given pathway which may not result in risk of developing deleterious health effects in an individual in their lifetime [34]. Thus, if the average daily dose ($ADD_{ingestion}$ or $ADD_{dermal\ contact}$) is lower than the respective reference dose, the $THQ < 1$ and adverse health effects are unlikely. Otherwise, an average daily dose greater than the reference dose is indicative that $THQ > 1$ and adverse health effects may occur.

2.4.2. Cancer risk assessment.

The carcinogenic health risk (CR) estimated as the incremental lifetime cancer risk for the carcinogenic HMs (Pb, Cd, Cr, and As) was calculated as the product of $ADD_{ingestion}$ and the ingestion cancer slope factor (CSF) using Equation 5. The total cancer risk (TCR) was calculated using Equation 6, used in previous studies [31, 35].

$$CR = ADD_{ingestion} \times CSF \quad (5)$$

$$TCR = \sum_{i=1}^n CR \quad (6)$$

The CSF for Pb, Cr, and Cd are 8.5×10^{-6} , 5.0×10^{-4} , and 3.8×10^{-4} mg/kg/day, respectively. The CSF is defined as the risk generated by an average lifetime amount of one mg/kg/day of carcinogen chemical and is contaminant specific. The US EPA permissible limits lie between 10^{-6} and $< 10^{-4}$ for a single carcinogenic element and multi-element carcinogens [31].

2.5. Statistical analysis.

Quantitative data from triplicate analyses were entered into Excel, where they were averaged. Significant differences in the spatial variations in water quality among the sampling sites along the river were evaluated using the One Way Analysis of Variance (One Way ANOVA) with Tukey posthoc test. Pearson's bivariate correlation and Principal Component Analysis (PCA) were used to explore the inter-relationships between metal concentrations and the examined physicochemical parameters of R. Manafwa water. The analyses were executed at 95% confidence interval employing GraphPad Prism for Windows (v9.3.1, GraphPad Software, San Diego, CA, USA).

3. Results and Discussion

3.1. Variations in physicochemical parameters of R. Manafwa water.

Table 2 shows the results of pH, conductivity, and total hardness of water from the different sections of R. Manafwa during the wet and dry seasons. The parameters did not differ significantly among the study stations ($p > 0.05$) and seasons ($p > 0.05$). The pH (a measure of hydrogen ions) ranged from 7.46 ± 0.05 in the wet season to 8.19 ± 0.06 in the dry season and were within the acceptable limits of the World Health Organization (WHO) for drinking water [36]. These values were comparable to 7.96-8.22, 6.2-8.0, 6.6-7.5, 5.85-7.60, and 8.05-8.30 reported for water from Nyabugogo and Nyabarongo rivers, Rwanda [35], Mohokare River (Lesotho)[37], River Aturukuku [38], River Nyamugasani [39] and River Rwimi of Uganda [39, 40], but higher than 5.60-6.32 and 5.58-6.80 for River Nyamwamba and River Mubuku of Uganda [40]. Though the pH values obtained lie within acceptable limits, it has been indicated that even slightly high or low water pH is unpleasant. For example, high alkalinity confers a slippery feel to water, making it taste like baking soda, while at highly acidic pH, water possesses a bitter and/or metallic taste and induces corrosion [41]. At very low and high pH levels, the solubility of toxic HMs in water tends to increase and can cause serious human health effects in humans and aquatic organisms [42, 43].

Electrical conductivity (EC) was measured to establish the total dissolved ions in the water samples. It ranged from $88.7 \pm 0.24 \mu\text{S}/\text{cm}$ in the dry season to $122.2 \pm 0.91 \mu\text{S}/\text{cm}$ in the wet season, which was within the WHO guidelines for drinking water. The values obtained in this study are comparable to 80.44, 63.15 and 12-119, 43-103, and 99.91 $\mu\text{S}/\text{cm}$ for water in Ugandan rivers: Lhubiriha, Mobuku, Rwimi, and Nyamwamba but lower than 460.51, 946.08, 118.57, 81-220 and 140.82 $\mu\text{S}/\text{cm}$ in River Lubigi, River Nyamugasani, River Sio, River Rwimi and River Victoria Nile reported by Bwire et al. [44] and, Busulwa and Bailey [39]. Turinayo [45] reported EC of 108-1524 $\mu\text{S}/\text{cm}$ for water from River Musamya in Uganda. In Nyabugogo and Nyabarongo rivers in Rwanda, EC of 74.3-102.0 were reported [35]. Another investigation in Mohokare River water (Lesotho) [37] reported EC of 2000-3800 $\mu\text{S}/\text{cm}$, which is far higher than obtained in this study. In Nigeria, Butu et al. [46] found the EC of River Rido to range from 79 to 146.3 $\mu\text{S}/\text{cm}$ [46], which is close to the ones obtained in this study. The EC of water estimates the total amount of solids dissolved in water (its total dissolved solids) and is directly proportional to the water's temperature. It is directly related to the concentration of ions in the water, and this is supported by the low levels of HMs reported in this study. High EC of water samples indicates the presence of a higher content of different salts and organic and inorganic materials such as alkalis, chlorides, sulfides, and carbonates. As a measure of

water quality, significant changes in EC are indicators of discharges or some other source of pollution entering the river.

Table 2. Physicochemical parameters of water samples from R. Manafwa, Eastern Uganda.

| Sampling site | Wet season | | | Dry season | | |
|---------------------|------------|----------------------|-----------------------|------------|----------------------|-----------------------|
| | pH | Conductivity (µS/cm) | Total hardness (mg/L) | pH | Conductivity (µS/cm) | Total hardness (mg/L) |
| A ₁ | 7.95±0.02 | 107.6±0.12 | 104.2±0.14 | 8.10±0.01 | 100.3±0.05 | 100.5±0.19 |
| A ₂ | 8.14±0.04 | 119.6±0.43 | 112.2±0.67 | 8.19±0.06 | 112.0±0.11 | 108.7±0.40 |
| B ₁ | 7.84±0.01 | 98.3±0.23 | 103.2±0.28 | 7.99±0.01 | 88.7±0.24 | 101.5±0.01 |
| B ₂ | 7.82±0.07 | 101.2±0.15 | 103.0±0.56 | 7.80±0.05 | 94.9±0.10 | 103.0±0.00 |
| M ₁ | 7.74±0.01 | 101.9±0.45 | 115.9±0.76 | 7.79±0.01 | 89.5±0.22 | 106.1±0.52 |
| M ₂ | 7.46±0.05 | 106.3±0.76 | 103.4±0.27 | 7.50±0.03 | 97.8±0.09 | 95.9±0.10 |
| M ₃ | 7.73±0.04 | 122.2±0.91 | 101.8±0.11 | 7.77±0.00 | 115.0±0.14 | 93.6±0.24 |
| M ₄ | 8.09±0.01 | 119.2±0.17 | 89.4±0.13 | 8.00±0.02 | 101.6±0.10 | 80.8±0.11 |
| WHO guidelines [36] | 6.5-8.5 | 250.0 | 200.0 | 6.5-8.5 | 250.0 | 200.0 |

Values are means ± standard deviations of analyses performed in triplicate.

The total hardness of the water samples ranged from 80.8±0.11 mg/L in the dry season to 115.9±0.76 mg/L in the wet season. Based on available criteria, hardness ranging from 80 to 100 mg/L is deemed to be optimal, while those more than 300 mg/L are potentially hard. Overall, water having a hardness of 75 mg/L or less is soft. Water exceeding 200 mg/L is considered poor, whereas those with hardness exceeding 500 mg/L are unacceptable for domestic purposes [47]. Highly hard water is chemically rich in dissolved minerals, especially calcium and magnesium ions which, for aesthetic reasons, may have an unpleasant taste [48]. Both low and high values of hardness may be harmful to the human body. Low levels of hardness may activate colon carcinogens or trigger rectal cancer and cardiovascular diseases [49, 50] because calcium and magnesium ions are capable of binding bile acids and fatty acids, thus affecting the creation of colon mucosa [51]. Higher hardness values may lead to the development of kidney stones and dermal diseases [52]. In addition to these health risks, hard water is a nuisance as it causes mineral buildup on fixtures (hence corrosion) and poor soap or detergent performance due to scum formation.

3.2. Spatio-temporal variations in heavy metal content of River Manafwa water.

3.2.1. Copper.

The seasonal fluctuations in Cu content of R. Manafwa water are shown in Figure 3. The concentrations of Cu ranged from 0.023±0.003 mg/L to 0.06±0.01 mg/L during the wet season and 0.0030 ± 0.01 mg/L to 0.0045 ± 0.01 mg/L in the dry season. The mean values were 0.0382 mg/L and 0.0034 mg/L for the wet and dry seasons. The concentration of Cu generally increased from the upper course of the river downstream in both seasons (p<0.05), but none of the values exceeded the WHO guidelines of 0.5 mg/L in drinking water [36]. The increasing concentration of Cu downstream could be due to runoff from Manafwa town and Mbale municipal motor garages, metal fabrication, road construction, and leachates from dumped domestic biodegradable wastes. The concentration of Cu was higher during the wet season, with 0.06 ± 0.01 mg/L at sampling point M4. This elevated concentration of Cu is probably due to road construction works that were going on during sampling at the Manafwa bridge and leaching from Mbale municipal sewage pipes. Such Cu leaching is accelerated by water characteristics such as high acidity and temperature, and low hardness [53].

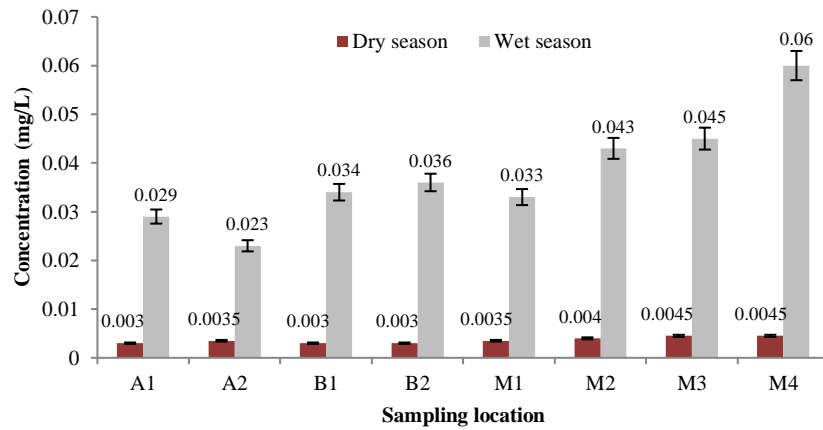


Figure 3. The concentration of copper in water from River Manafwa in the wet and dry seasons. Values are means of analyses performed in triplicate (n = 16 composite samples).

In comparison to previous studies (Table 3), the concentrations of Cu reported in this study are quite lower. Though it is an essential trace metal, ingesting Cu at high concentrations leads to Cu poisoning, a condition characterized by hematemesis and gastrointestinal distress. Similar effects and neurological disorders such as Wilson's, Menkes', Alzheimer's, and Parkinson's diseases have been reported by individuals with dysregulation of the redox-active metal [53, 54].

Table 3. Comparison of the results of heavy metal water contamination (mg/L) from R. Manafwa with previous studies.

| River (Country) | Cu | Ni | Mn | Zn | Pb | Cd | Cr | Fe | References |
|--|------------------------|----------------|---------------|-----------------|-----------------|-----------------|-----------------|-------------|------------|
| River Manafwa (Uganda) | 0.003–0.060 | 0.0015–0.0095 | 0.011–0.262 | 0.0015–0.029 | 0.002–0.010 | 0.001–0.002 | 0.003–0.011 | 0.196–1.407 | This study |
| Marimba River (Zimbabwe) | 0.13–0.14 | — | — | ND | 0.213–0.544 | — | — | 5.6–6.9 | [55] |
| Madanzhe, Dzindi and Mvudi rivers (South Africa) | 0.002–0.003 | — | — | 0.0021–0.0025 | 0.0105–0.0201 | 0.0016–0.0093 | — | — | [56] |
| River Sosiani (Kenya) | 0.001–0.275 | — | — | 0.07–0.57 | 0.02–1.89 | — | 0.003–0.050 | 0.011–3.789 | [57] |
| River Nyamwamba (Uganda) | 1.90–61.0 | 0.67–12.0 | 23.1–100.0 | ND ¹ | 0.27–0.40 | — | — | 185.0–265.0 | [58] |
| River Rwimi (Uganda) | 0.740 | — | — | 0.076 | 0.047 | — | — | — | [40] |
| River Mubuku (Uganda) | 0.010 | — | — | 0.010 | 0.067 | — | — | — | |
| River Mubuku (Uganda) | 0.025 | — | — | 0.010 | 0.053 | — | — | — | [35, 59] |
| Nyabarongo river (Rwanda) | BMDL–0.24 ₁ | — | 0.02–0.53 | BMDL–0.09 | 0.05–0.75 | BMDL–0.106 | BDL–0.06 | 0.63–1.61 | |
| Rongna River (China) | 0.00189–0.806 | 0.00745–0.0601 | 0.0431–2.041 | 0.013–0.415 | 0.00049–0.00241 | 0.00012–0.00064 | 0.00156–0.00637 | — | [60] |
| Bolong river (China) | 0.00542–0.00737 | 0.0107–0.0182 | 0.0378–0.0519 | 0.0398–0.567 | 0.00034–0.00064 | 0.00011–0.00054 | 0.00174–0.00308 | — | |

¹ BDML = Below method detection limit.

3.2.2. Nickel.

The concentration of Ni ranged from 0.0015 ± 0.001 mg/L to 0.0095 ± 0.005 mg/L during the wet season and 0.001 ± 0.010 mg/L to 0.005 ± 0.010 mg/L in the dry season (Figure 4). Like in the case of Cu, the concentration of Ni was higher (p>0.05) during the wet season, and samples were taken within Bududa and Manafwa towns (sampling sites B2, M1, and M2). The major sources could be the use of nickel-cadmium batteries, hydrogenated oils such as margarine, stainless steel, nickel-plated metallic items, and the combustion of petroleum fuels in Bududa and Manafwa towns. Sample A2, taken near Bukigai markets, had a higher concentration of Ni within the upper course of R. Manafwa. This could be due to market waste

and vehicular emissions due to heavy traffic flow during market days. In both the wet and dry seasons, the concentration of Ni in the water samples never surpassed the WHO maximum permissible limit of 0.05 mg/L for Ni in drinking water [36]. Previous studies in River Nyamwamba (Uganda) [58], Rongna, and Bolong rivers (China) [60] detected Ni at concentrations that are higher than was obtained in this study.

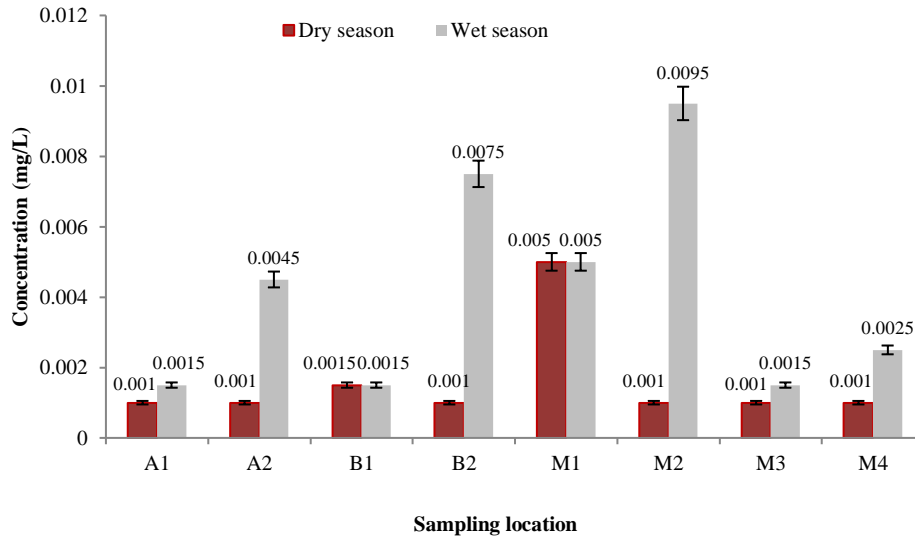


Figure 4. The concentration of nickel in water from R. Manafwa in the wet and dry seasons. Values are means of analyses performed in triplicate (n = 16 composite samples).

3.2.3. Manganese.

In this study, Mn concentrations varied between 0.011 ± 0.05 mg/L and 0.164 ± 0.01 mg/L during the wet season and 0.053 ± 0.007 mg/L and 0.262 ± 0.03 mg/L during the dry season (Figure 5). In the wet season, the concentration of Mn was generally lower ($p < 0.05$) and showed an increase downstream, which could result from discharge from increasing human settlement at the banks of the river. Sample M4 taken downstream of Manafwa Water Works and Mbale-Tororo highway had elevated concentrations of Mn. Intense sand mining and construction repairs on Manafwa Bridge could be the cause. Evident metallic materials like spades and hoes used in sand mining and the combustion of petrol in motor cars could be the sources of Mn in the river water.

In the dry season, the concentration of Mn increased from the upper course of the river downstream and was higher than in the wet season ($p < 0.05$). The source of Mn could be metallic materials like spades and hoes used in sand mining. Samples from sites M3 and M4 taken downstream of Manafwa Water Works with more intense sand mining showed the highest Mn concentrations. The concentration of Mn in the wet season was below the WHO maximum acceptable limit of 0.1 mg/L at all the study sites except site M4. In the dry season, it was above the maximum acceptable limits in all the sites except A1 and B2. These values were comparable to 0.02 mg/L to 0.53 mg/L reported in the Nyabugogo and Nyabarongo rivers, Rwanda [35, 59] but lower than 10.28 mg/L and 11.58 mg/L for water samples from Rwanzekuma and Ruganwa rivers of Rwanda [61].

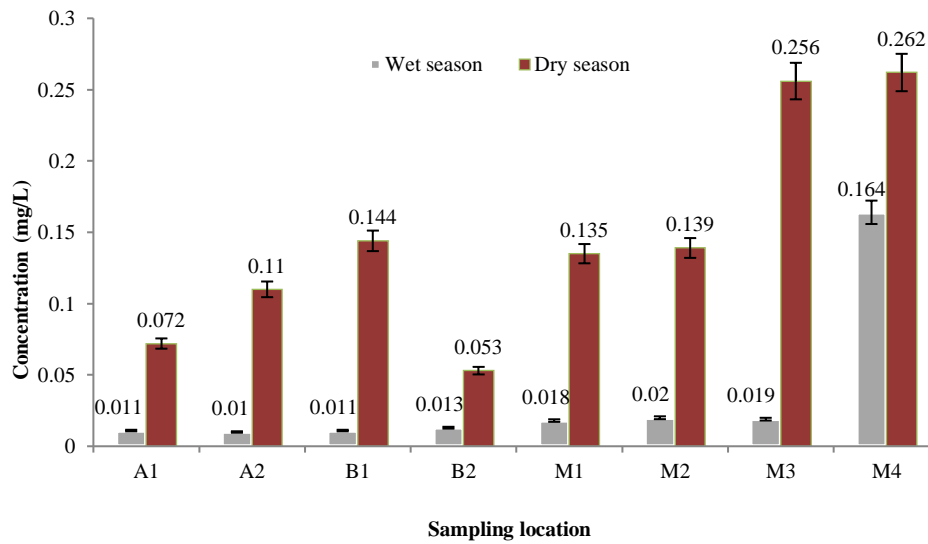


Figure 5. The concentration of manganese in water from R. Manafwa in the wet and dry seasons. Values are means of analyses performed in triplicate (n = 16 composite samples).

3.2.4. Zinc.

On the other hand, Zn was found in levels of 0.008 ± 0.040 mg/L to 0.029 ± 0.001 mg/L in water samples collected during the wet season and 0.0015 ± 0.010 mg/L to 0.0045 ± 0.000 mg/L during the dry season (Figure 6). The highest concentration of 0.029 ± 0.001 mg/L was for samples from M4 in the wet season. The concentration of Zn in the wet season was higher than that in the dry season at all the sampling points ($p < 0.05$). This could be due to the mobilization of the soluble forms of the metal from anthropogenic activities by runoff rainwater. In the wet season, water samples from A2 near the Bukigai market showed a higher concentration of Zn than those from sites A1, B1, B2, and M1. This could be attributed to the leachates from piles of biodegradable wastes generated from the market since Zn is one of the major micronutrients and vehicular emissions. None of the samples, however, contained Zn in levels surpassing the WHO limit of 3 mg/L in drinking water.

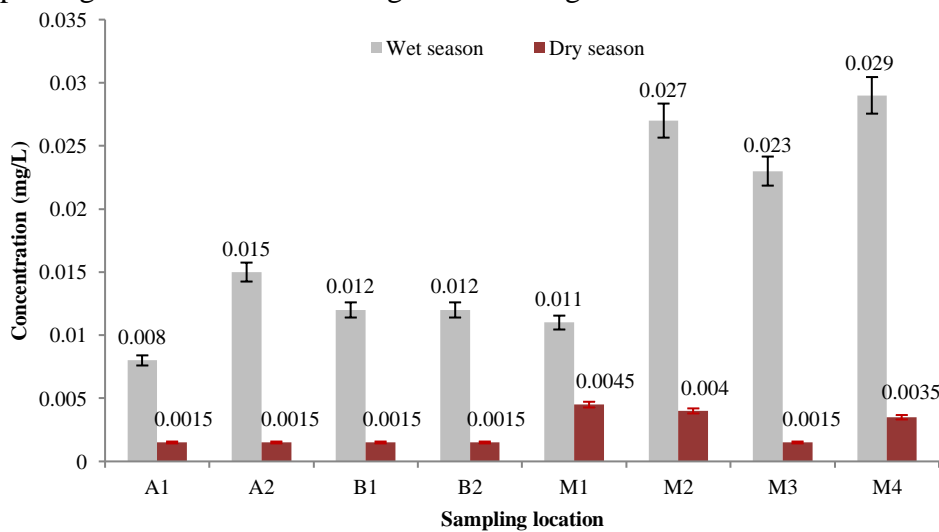


Figure 6. The concentration of zinc in R. Manafwa water samples collected during the wet and dry seasons. Values are means of analyses performed in triplicate (n = 16 composite samples).

3.2.5. Lead.

The seasonal fluctuations in Pb concentrations were more pronounced. The concentrations were from 0.002 ± 0.040 mg/L to 0.01 ± 0.005 mg/L in the wet season and 0.005 ± 0.02 to 0.0085 ± 0.010 mg/L in the dry season (Figure 7). The concentration of Pb decreased from the upper course of the river downstream to Bududa town in both the wet and dry seasons. This indicates the existence of a mild point source of Pb in the upper course of the river. Since there are hardly any settlements or economic activity evidenced at the uppermost course of R. Manafwa, the higher concentration of Pb at this section of the river could be due to natural sources such as landslides or hydro-geochemical reactions occurring rather than anthropogenic sources. The decrease in the concentration of Pb towards Bududa town is attributed to increased distance away from the source of pollution due to possible sedimentation and precipitation. From Bududa town (site B2) downstream up to slightly beyond Manafwa Bridge along Mbale-Tororo highway (site M4), the concentration of Pb increased. This could be due to vehicular emissions, metal welding and fabrication works, disposal of Pb acid battery contents, use of leaded gasoline [62, 63], and sewage leakages from Manafwa and Mbale towns.

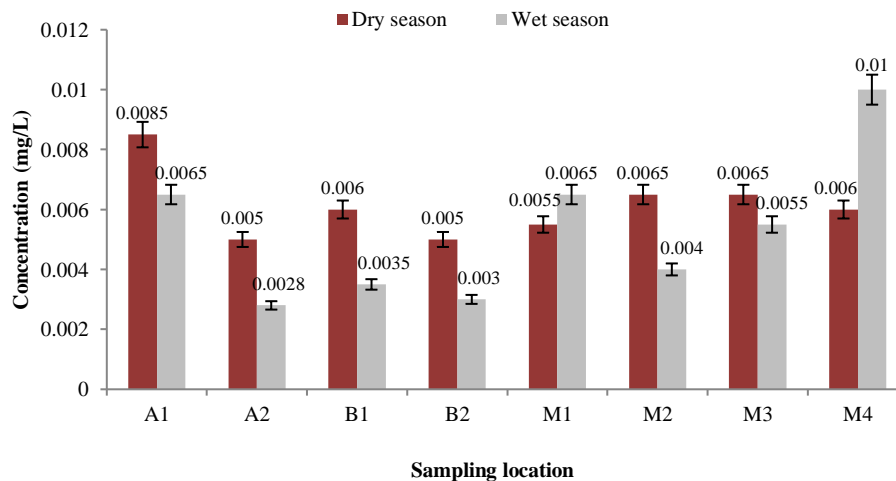


Figure 7. The concentration of lead in R. Manafwa water samples. Values are means of analyses performed in triplicate (n = 16 composite samples).

The concentration of Pb reported in this study did not exceed the WHO maximum limit of 0.01 mg/L. Similar results have been documented for other rivers on the African continent. For example, Okonkwo and Mothiba [56] reported concentrations of 0.010 mg/L to 0.012 mg/L for Pb in water from Dzindi, Madanzhe, and Mvudi rivers, South Africa. Other studies, such as Amadi [57] in Sosiani River, Kenya, and Mvungi et al. [55] in Marimba River (Zimbabwe), reported higher Pb contents than those reported in this study (Table 3). Pb is toxic and a non-essential trace metal. Its chronic ingestion or occupational exposure has been associated with renal failure and liver degradation [64]. In infants, Pb retards interactive, survival, growth, development, and metabolic processes in addition to increasing mucus synthesis and triggering nervous system disorders [65].

3.2.6. Cadmium.

Cadmium was detected at relatively lower concentrations (0.001 ± 0.04 to 0.002 ± 0.00 mg/L) during the wet season but was not detected in the dry season (Figure 8). The highest

concentration of 0.002 mg/L was recorded in the water sample from M4. These results suggest that the Cd found in water samples for the wet season could have been mobilized by runoff water from metal fabrication works, disposed nickel-cadmium batteries, sewage, and other sources related to man's use of metals. The absence of Cd in the dry season could also be due to sedimentation/precipitation of the insoluble forms of Cd into sediments. In all the water samples, the cadmium concentration was below the WHO permissible limit of 0.03 mg/L.

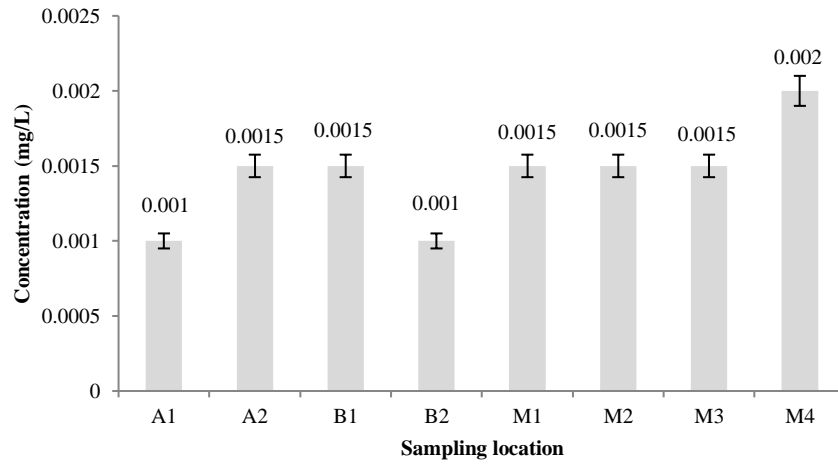


Figure 8. The concentration of cadmium in water samples from R. Manafwa, Uganda, during the wet season. Values are means of analyses performed in triplicate (n = 8 composite samples). Dry season samples had no detectable Cd.

3.2.7. Chromium.

Unlike Cd, Cr was detected during the dry season at site M₄ at a concentration of 0.00093 ± 0.01 mg/L (Figure 9). For wet season samples, the concentration of Cr ranged from 0.003 ± 0.05 mg/L to 0.011 ± 0.01 mg/L for samples obtained near Manafwa water works (site M₄). The relatively higher concentration of Cr at this sampling point could be due to releases from the heavy traffic flow along the Mbale-Tororo highway and leaching from the sewer pipes of Manafwa Water Works. By implication, the observed concentration of Cr during the wet season should be due to its mobilization from anthropogenic and geologic sources by rainwater.

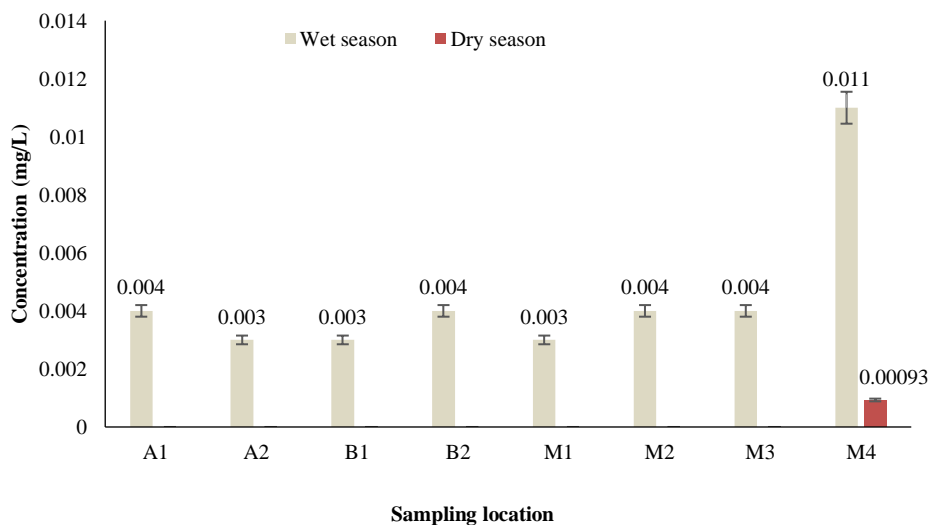


Figure 9. The concentration of chromium in R. Manafwa water samples. Values are means of analyses performed in triplicate (n = 16 composite samples).

3.2.8. Iron.

In comparison to other HMs, Fe was found to be higher in the river water during both seasons, ranging from 0.967 ± 0.06 and 1.407 ± 0.001 mg/L in the dry season and between 0.196 ± 0.01 and 0.909 ± 0.03 mg/L in the wet season (Figure 10). The dry season had higher concentrations of Fe, possibly due to an increase in sand mining within the river when the water levels have reduced as a result of using metallic spades and hoes.

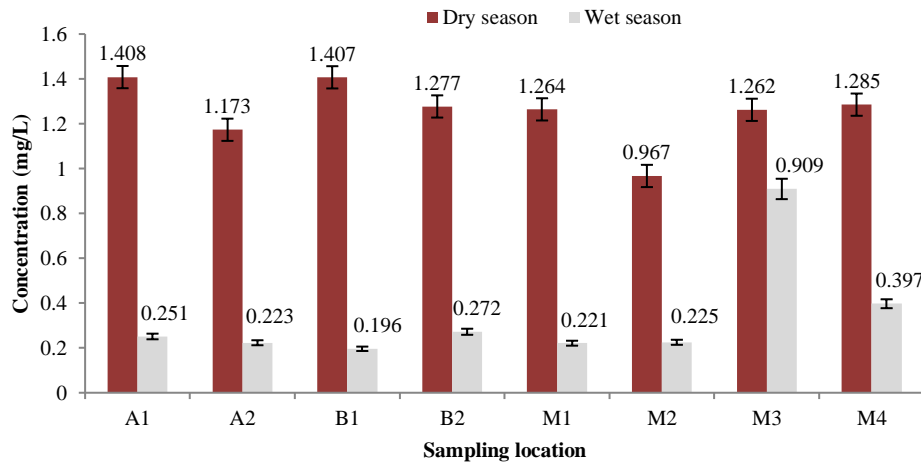


Figure 10. The concentration of iron in R. Manafwa water samples. Values are means of analyses performed in triplicate (n = 16 composite samples).

Inorganic Fe (principally Fe^{2+}) is naturally present in water resources at concentrations up to 50 mg/L [66]. For example, Amadi [57], Eliku, and Leta [67] found Fe (0.011 to 2.897 mg/L, and 1.11 to 4.12 mg/L) in water from River Sosiani (Kenya) and Awash River (Ethiopia) which are comparable to the values obtained in this study. However, the levels found in water in this study are lower than previously detected in some rivers. Nhapi et al. [61] reported elevated Fe levels (8.76 and 6.85 mg/L) in water from the Rusine and Marengé rivers of Rwanda, whereas Kihampa and Wenaty [68] detected Fe in Mara river water (Tanzania) at levels (12.6 to 15.51 mg/L) which are several folds higher than found in this study.

Taken together, the differences in HMs concentration reported in water from rivers across the globe and the present study could plausibly be due to disparities in the geological formation of the rivers, their physicochemical conditions, and the sources of contamination in their vicinities [60, 61].

3.3. Multivariate statistical analysis results.

To discern the pollution sources for the HMs, Pearson's correlation analysis and PCA were performed. In the wet season, there were positive correlations between Cu and Mn ($p = 0.013$), Cu and Zn ($p = 0.012$), Cr and Cu ($p = 0.009$), Pb and Mn ($p = 0.015$), Zn and Mn ($p = 0.088$), Cd and Mn ($p = 0.040$), and Cr and Mn ($p = 0.000$). The total hardness had strong and significant negative correlations with Cu ($p = 0.011$), Mn ($p = 0.028$), and Cr ($p = 0.010$) (Table 4). These observations agreed with PCA results (Figure 11). The strong correlation between the metal pairs suggests that they entered the river from anthropogenic sources or marked similarities in their chemistry [16, 69, 70]. For the negative correlations, it indicates the presence of the respective ions exerts a negative effect on hardness [71].

Table 4. Pearson's correlation matrix for the physicochemical parameters and HMs content in water from R. Manafwa during the wet season.

| | Cu | Ni | Mn | Zn | Pb | Cd | Cr | Fe | pH | Conductivity | Total hardness |
|----------------|---------|--------|---------|--------|--------|--------|--------|--------|--------|--------------|----------------|
| Ni | -0.041 | 1 | | | | | | | | | |
| Mn | 0.820* | -0.195 | 1 | | | | | | | | |
| Zn | 0.823* | 0.190 | 0.639 | 1 | | | | | | | |
| Pb | 0.674 | -0.410 | 0.808* | 0.382 | 1 | | | | | | |
| Cd | 0.643 | -0.170 | 0.729* | 0.726* | 0.525 | 1 | | | | | |
| Cr | 0.837* | -0.181 | 0.985* | 0.643 | 0.798* | 0.626 | 1 | | | | |
| Fe | 0.446 | -0.387 | 0.135 | 0.428 | 0.242 | 0.196 | 0.177 | 1 | | | |
| pH | -0.122 | -0.540 | 0.394 | -0.193 | 0.259 | 0.170 | 0.375 | -0.099 | 1 | | |
| Conductivity | 0.334 | -0.313 | 0.420 | 0.567 | 0.342 | 0.471 | 0.433 | 0.646 | 0.417 | 1 | |
| Total hardness | -0.831* | 0.228 | -0.761* | -0.626 | -0.528 | -0.389 | -0.834 | -0.322 | -0.157 | -0.306 | 1 |

*Significant at the 0.05 level (2-tailed).

For the dry season, Pearson's bivariate correlation coefficients (Table 5) indicated a positive correlation between Cu and Mn ($p = 0.03$), Fe and pH ($p = 0.10$), and significant negative correlations between Cu and total hardness ($p = 0.038$), and Mn and total hardness ($p = 0.027$). The positive correlation indicates that Cu and Mn entered the river through the same anthropogenic routes, and their concentrations would increase or decrease proportionately [16, 72]. Fe is associated with pH because its solubility in aqueous matrices is pH-dependent [73]. These results were also in agreement with PCA results (Figure 12). Overall, multivariate statistical analyses indicated that the comparatively higher pollution levels experienced in R. Manafwa during the wet season are due to anthropogenic contributions.

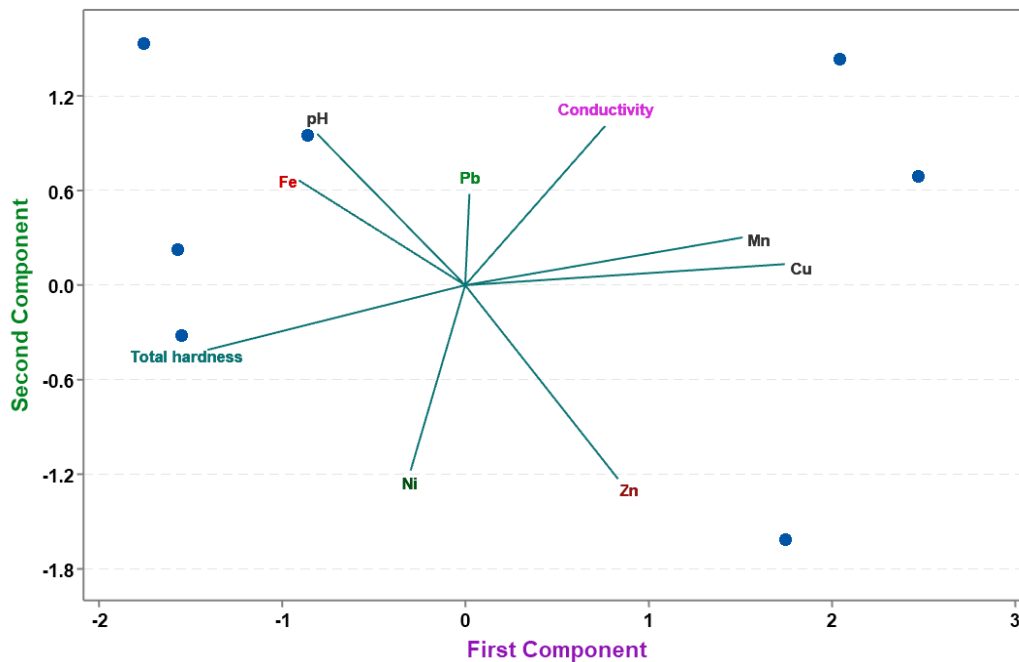


Figure 11. Principal Component Analysis plot showing the effect of three components influencing the variation of HMs in water from R. Manafwa during the wet season.

Table 5. Pearson's correlation matrix for the physicochemical parameters and HMs content in water from R. Manafwa during the dry season.

| | Cu | Ni | Mn | Zn | Pb | Fe | pH | Conductivity | Total hardness |
|----|--------|--------|--------|--------|-------|----|----|--------------|----------------|
| Cu | 1 | | | | | | | | |
| Ni | -0.129 | 1 | | | | | | | |
| Mn | 0.891* | -0.062 | 1 | | | | | | |
| Zn | 0.390 | 0.601 | 0.252 | 1 | | | | | |
| Pb | -0.025 | -0.232 | 0.001 | -0.114 | 1 | | | | |
| Fe | -0.431 | 0.080 | -0.061 | -0.490 | 0.269 | 1 | | | |

| | Cu | Ni | Mn | Zn | Pb | Fe | pH | Conductivity | Total hardness |
|----------------|---------------------|--------|---------|--------|--------|--------|-------|--------------|----------------|
| pH | -0.321 | -0.167 | -0.125 | -0.526 | 0.062 | 0.622 | 1 | | |
| Conductivity | 0.549 | -0.507 | 0.391 | -0.380 | 0.073 | -0.221 | 0.222 | 1 | |
| Total hardness | -0.735 ¹ | 0.357 | -0.764* | -0.260 | -0.253 | 0.032 | 0.167 | -0.187 | 1 |

* Significant at the 0.05 level (2-tailed). Cd and Cr were below detection limits in the dry season.

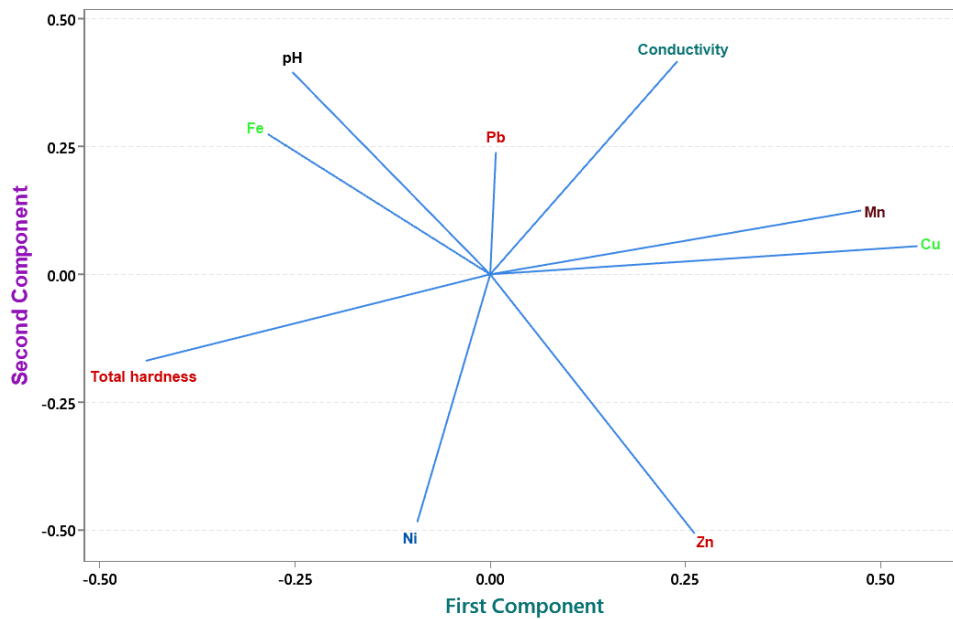


Figure 12. Principal Component Analysis plot showing the effect of three components influencing the variation of HMs in water from R. Manafwa during the dry season.

3.4. Health risks assessment results.

In the wet season, the average daily doses through ingestion of contaminated water ranged from 0.120×10^{-3} mg/kg/day (for Cd ingested by children at A₁, A₂, B₁, and B₂) to 138.95×10^{-3} mg/kg/day for Fe ingested in water from site M₄ by adults (Table S1). The daily doses through dermal contact ranged from 0.0010×10^{-8} mg/kg/day for adults exposed to Cd at B₂ to 258.2318×10^{-8} mg/kg/day for adults exposed to Fe at M₄. In the dry season, the average daily doses through ingestion of contaminated water span from 0.006×10^{-3} mg/kg/day (for Zn ingested by children at A₁, A₂, and B₁) to 154.200×10^{-3} mg/kg/day (for Cu ingested in water from site M₄ by children). On the other hand, the estimated daily doses through dermal contact varied between 0.0037×10^{-8} mg/kg/day (for Cr adsorbed by the skin of children at M₄) to 399.99×10^{-8} mg/kg/day for Fe adsorbed onto adult's skin at A₁. The THQ through ingestion of the HMs, and hence the total THQ for the foregoing HMs exceeded 1 during the wet season at B₂ and M₁ for Ni ingested by children and at all sites for Ni ingested by adults. Similarly, the THQ for ingesting the HMs during the dry season, and hence the total THQ for the HMs exceeded 1 for Ni and Cu ingested by children at A₂, M₁, and M₄, respectively (Table S1). All the THQ from dermal contact were less than 1, and varied between 0.0005×10^{-6} (for Fe at B₁ adsorbed by the skin of children) and 137.3067×10^{-6} (for Zn at M₄ adsorbed by the skin of adults) for the wet season, and 0.0003×10^{-6} (for Mn at A₁ adsorbed by the skin of children) to 21.3067×10^{-6} (for Zn at M₁ adsorbed by the skin of adults) for the dry season. Since some of the average daily doses for Ni and Cu were higher than the corresponding reference doses for ingestion of contaminated water (THQ >1), non-carcinogenic health risks may result from water consumption from the sampled stations of R. Manafwa.

For carcinogenic health risks, the cancer risk values ranged from 4.4625×10^{-10} to 2.22075×10^{-6} , with lower cancer risk values in the dry season than wet season (Table S2). For carcinogenic health risks, the borderline given by US EPA is 1×10^{-4} to 1×10^{-6} and is considered unacceptable where the risk surpasses 1×10^{-4} . The cancer risk values (and the total cancer risk values) obtained for the HMs per sampling site in this study did not surpass 1×10^{-4} , suggesting that no potential cancer risks could arise from water consumption from R. Manafwa, Uganda.

Overall, the health risks assessment performed in this study was based on the HMs analyzed. It is recommended that risk characterizations should be cumulative to account for aggregate exposures to multiple compounds or mixtures causing similar toxicological effects [74]. This is achieved using Adversity Specific Hazard Index for Cumulative risk assessment suitable for toxicants with multiple residues that exert similar toxicological effects, such as pesticides and polychlorinated biphenyls.

4. Conclusions

This study showed that R. Manafwa in Eastern Uganda is contaminated with HMs at concentrations well below the maximum WHO guidelines for drinking water. However, there are discernable non-carcinogenic health risks that may arise from ingesting water from the river. Children are at higher cancer risks than adults, and in all cases, the contribution of Ni (in both seasons) and Cu (during the dry season) towards the target hazard quotient was significant. The heavy metal Cr is the main driver of potential carcinogenicity in the incremental lifetime cancer risk assessment results for the wet season, while Pb is the sole driver in the dry season. Thus, regulatory authorities should intervene and reduce the pollution of R. Manafwa by strengthening restrictions on sand mining and the dumping of waste into the river. Further studies should examine the spatial variations in the concentrations of the HMs in sediments and biota.

Funding

This research received no external funding.

Acknowledgments

Timothy Omara is grateful for the doctoral scholarship supported by the Austrian Partnership Programme in Higher Education and Research (APPEAR) under APPEAR Project 249: Environmental Chemistry for Sustainable Development (ECSDevelop) which made this collaborative research possible. APPEAR is an Austrian Development Cooperation (ADC) program implemented by Austria's Agency for Education and Internationalization (OeAD-GmbH), OEZA Project No. 0894-01/2020.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Hossain, M.A.; Huggins, R. The Environmental and Social Impacts of Unplanned and Rapid Industrialization in Suburban Areas: The Case of the Greater Dhaka Region, Bangladesh. *Environ Urban Asia* **2021**, *12*, 73–89, <https://doi.org/10.1177/0975425321990319>.
2. Li, C.; McLinden, C.; Fioletov, V.; Krotkov, N.; Carn, S.; Joiner, J.; et al. India Is Overtaking China as the World's Largest Emitter of Anthropogenic Sulfur Dioxide. *Sci Rep.* **2017**, *7*, 14304, <https://doi.org/10.1038/s41598-017-14639-8>.
3. Abdul Jabbar, S.; Tul Qadar, L.; Ghafoor, S.; Rasheed, L.; Sarfraz, Z.; Sarfraz, A.; Sarfraz, M.; et al. Air Quality, Pollution and Sustainability Trends in South Asia: A Population-Based Study. *Int. J. Environ. Res. Public Health*. **2022**, *19*, 7534, <https://doi.org/10.3390/ijerph19127534>.
4. Wang, M.; Janssen, A.B.G.; Bazin, J.; Stokal, M.; Ma, L.; Kroeze, C. Accounting for interactions between Sustainable Development Goals is essential for water pollution control in China. *Nat. Commun.* **2022**, *13*, 730, <https://doi.org/10.1038/s41467-022-28351-3>.
5. Nur-E-Alam, M.; Salam, M.A.; Dewanjee, S.; Hasan, M.F.; Rahman, H.; Rak, A.E.; Islam, A.R.M.T.; Miah, M.Y. Distribution, Concentration, and Ecological Risk Assessment of Trace Metals in Surface Sediment of a Tropical Bangladeshi Urban River. *Sustainability* **2022**, *14*, 5033, <https://doi.org/10.3390/su14095033>.
6. Hassaan, M.A.; El Nemr, A. Pesticides pollution: Classifications, human health impact, extraction and treatment techniques. *Egypt. J. Aquat. Res.* **2020**, *46*, 207-220, <https://doi.org/10.1016/j.ejar.2020.08.007>.
7. Shehu, Z.; Nyakairu, G. W. A.; Tebandeke, E.; Odume, O. N. Overview of African water resources contamination by contaminants of emerging concern. *Sci. Total Environ.* **2022**, *852*, 158303, <https://doi.org/10.1016/j.scitotenv.2022.158303>.
8. Briffa, J.; Sinagra, E.; Blundell, R. Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon* **2020**, *6*, e04691, <https://doi.org/10.1016/j.heliyon.2020.e04691>.
9. Ali, H.; Khan, E.; Ilahi, I. Environmental Chemistry and Ecotoxicology of Hazardous Heavy Metals: Environmental Persistence, Toxicity, and Bioaccumulation. *J. Chem.* **2019**, *2019*, 6730305, <https://doi.org/10.1155/2019/6730305>.
10. Singh, R.; Gautam, N.; Mishra, A.; Gupta, R. Heavy metals and living systems: An overview. *Indian J. Pharmacol.* **2011**, *43*, 246–253, <https://doi.org/10.4103%2F0253-7613.81505>.
11. Edelstein, M.; Ben-Hur, M. Heavy metals and metalloids: Sources, risks and strategies to reduce their accumulation in horticultural crops. *Scientia Horticulturae* **2018**, *234*, 431-444, <https://doi.org/10.1016/j.scienta.2017.12.039>.
12. Lall, S.P.; Kaushik, S.J. Nutrition and Metabolism of Minerals in Fish. *Animals* **2021**, *11*, 2711, <https://doi.org/10.3390/ani11092711>.
13. Soetan, K.O.; Olaiya, C.O.; Oyewole, O.E. The importance of mineral elements for humans, domestic animals and plants: A review. *Afri J Food Sci.* **2010**, *4*, 200-222, https://academicjournals.org/article/article1380713863_Soetan%20et%20al.pdf.
14. Balali-Mood, M.; Naseri, K.; Tahergorabi, Z.; Khazdair, M. R.; Sadeghi, M. Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic. *Front Pharmacol* **2021**, *12*, 643972, <https://doi.org/10.3389%2Ffphar.2021.643972>.
15. Omara, T.; Karungi, S.; Kalukusu, R.; Nakabuye, B.; Kagoya, S.; Musau, B. Mercuric pollution of surface water, superficial sediments, Nile tilapia (*Oreochromis nilotica* Linnaeus 1758 [Cichlidae]) and yams (*Dioscorea alata*) in auriferous areas of Namukombe stream, Syanyonja, Busia, Uganda. *PeerJ* **2019**, *7*, e7919, <https://doi.org/10.7717/peerj.7919>.
16. Baguma, G.; Musasizi, A.; Twinomuhwezi, H.; Gonzaga, A.; Nakiguli, C.K.; Onen, P.; Angiro, C.; Okwir, A.; Opio, B.; Otema, T.; Ocira, D.; Byaruhanga, I.; Nirigiyimana, E.; Omara, T. Heavy Metal Contamination of Sediments from an Exoreic African Great Lakes' Shores (Port Bell, Lake Victoria), Uganda. *Pollutants* **2022**, *2*, 407-421, <https://doi.org/10.3390/pollutants2040027>.
17. Witkowska, D.; Słowik, J.; Chilicka, K. Heavy Metals and Human Health: Possible Exposure Pathways and the Competition for Protein Binding Sites. *Molecules* **2021**, *26*, 6060, <https://doi.org/10.3390/molecules26196060>.
18. Loewenson, R. Trends in water resources in east and southern Africa. Training and Research Support Centre in the Regional Network for Equity in Health in East and Southern Africa (EQUINET). 2020. <https://equinetafrica.org/sites/default/files/uploads/documents/EQ%20ESA%20Trends%20in%20water%20resources%20May2020.pdf> (accessed on 15 Sept 2022).

19. Matchawe, C.; Bonny, P.; Yandang, G.; Mafo, H. C. Y.; Nsawir, B. J. Water Shortages: Cause of Water Safety in Sub-Saharan Africa. In: Eyvaz, M.; Albahnasawi, A.; Tekbaş, M.; Gürbulak, E. (Eds.), Drought - Impacts and Management. IntechOpen. **2022**. <https://doi.org/10.5772/intechopen.103927>.
20. Atuyambe, L.M.; Ediau, M.; Orach, C. G.; Musenero, M.; Bazeyo, W. Land slide disaster in eastern Uganda: rapid assessment of water, sanitation and hygiene situation in Bulucheke camp, Bududa district. *Environ. Health* **2011**, *10*, 38, <https://doi.org/10.1186/1476-069X-10-38>.
21. Broeckx, J.; Maertens, M.; Isabirye, M.; Vanmaercke, M.; Namazzi, B.; Deckers, J.; et al. Landslide susceptibility and mobilization rates in the Mount Elgon region, Uganda. *Landslides* **2019**, *16*, 571–584, <https://doi.org/10.1007/s10346-018-1085-y>.
22. Opedes, H.; Múcher, S.; Baartman, J.E.M.; Nedala, S.; Mugagga, F. Land Cover Change Detection and Subsistence Farming Dynamics in the Fringes of Mount Elgon National Park, Uganda from 1978–2020. *Remote Sens.* **2022**, *14*, 2423, <https://doi.org/10.3390/rs14102423>
23. Love Uganda Safaris. River Manafwa. 2022. <https://www.loveugandasafaris.com/river-manafwa.html/>.
24. Cecinati, F. Precipitation Analysis for a Flood Early Warning System in the Manafwa River Basin, Uganda. *Masters Thesis, Massachusetts Institute of Technology*. **2013**. <http://dspace.mit.edu/handle/1721.1/82807>.
25. Obubu, J.P.; Mengistou, S.; Odong, R.; Fetahi, T.; Alamirew, T. Determination of the Connectedness of Land Use, Land Cover Change to Water Quality Status of a Shallow Lake: A Case of Lake Kyoga Basin, Uganda. *Sustainability* **2022**, *14*, 372, <https://doi.org/10.3390/su14010372>.
26. Pal, A.; Pal, M.; Mukherjee, P.; Bagchi, A.; Raha, A. Determination of the hardness of drinking packaged water of Kalyani area, West Bengal. *Asian J. Pharm. Pharmacol.* **2018**, *4*, 203-206, <https://doi.org/10.31024/ajpp.2018.4.2.17>.
27. Nowell, L.; Moran, P.; Gilliom, R.; Calhoun, D.; Ingersoll, C.; Kemble, N.; et al. Contaminants in stream sediments from seven United States metropolitan areas: Part I: distribution in relation to urbanization. *Archiv Environ Contam Toxicol* **2013**, *64*, 32–51, <https://doi.org/10.1007/s00244-012-9813-0>.
28. Ordonez, A.; Alvarez, R.; Charlesworth, S.; De Miguel, E.; Loreda, J. Risk assessment of soils contaminated by mercury mining, Northern Spain. *J. Environ. Monit.* **2011**, *13*, 128, <https://doi.org/10.1039/c0em00132e>.
29. Opolot, M.; Omara, T.; Adaku, C.; Ntambi, E. Pollution Status, Source Apportionment, Ecological and Human Health Risks of Potentially (Eco)toxic Element-Laden Dusts from Urban Roads, Highways and Pedestrian Bridges in Uganda. *Pollutants* **2023**, *3*, 74-88. <https://doi.org/10.3390/pollutants3010007>.
30. Saha, N.; Zaman, M. Evaluation of possible health risks of heavy metals by consumption of foodstuffs available in the central market of Rajshahi City, Bangladesh. *Environ. Monit. Assess.* **2012**, *185*, 3867–78, <https://doi.org/10.1007/s10661-012-2835-2>.
31. Alidadi, H.; Tavakoly Sany, S. B.; Zarif Garaati Oftadeh, B.; Mohamad, T.; Shamszade, H.; Fakhari, M. Health risk assessments of arsenic and toxic heavy metal exposure in drinking water in northeast Iran. *Environ. Health Prevent Med.* **2019**, *24*, 59, <https://doi.org/10.1186/s12199-019-0812-x>.
32. Wojciechowska, E.; Nawrot, N.; Walkusz-Miotk, J.; Matej-Łukowicz, K.; Pazdro, K. Heavy Metals in Sediments of Urban Streams: Contamination and Health Risk Assessment of Influencing Factors. *Sustainability* **2019**, *11*, 563, <https://doi.org/10.3390/su11030563>.
33. US EPA. Risk-based concentration table. United States Environmental Protection Agency: Washington, DC. **2009**. Available online: <https://archive.epa.gov/region9/superfund/web/html/index-23.html>.
34. Qing, X.; Yutong, Z.; Shenggao, L. Assessment of heavy metal pollution and human health risk in urban soils of steel industrial city (Anshan), Liaoning, Northeast China. *Ecotoxicol Environ Saf* **2015**, *120*, 377–85, <https://doi.org/10.1016/j.ecoenv.2015.06.019>.
35. Omara, T.; Nteziyaremye, P.; Akaganyira, S.; Opio, D. W.; Karanja, L. N.; Nyangena, D. M.; et al. Physicochemical quality of water and health risks associated with consumption of African lung fish (*Protopterus annectens*) from Nyabarongo and Nyabugogo rivers, Rwanda. *BMC Res Notes* **2020**, *13*, 66, <https://doi.org/10.1186%2Fs13104-020-4939-z>.
36. WHO. Guidelines for drinking-water quality, 4th edition, incorporating the 1st addendum. World Health Organization. **2017**, <https://www.who.int/publications-detail-redirect/9789241549950>.
37. Chatanga, P., Ntuli, V.; Mugomeri, E.; Keketsi, T.; Chikowore, N.V.T. Situational analysis of physico-chemical, biochemical and microbiological quality of water along Mohokare River, Lesotho. *Egypt J. Aquat. Res.* **2019**, *45*, 45–51, <https://doi.org/10.1016/j.ejar.2018.12.002>.
38. Ochieng, H.; Odong, R.; Okot-Okumu, J. Comparison of temperate and tropical versions of Biological Monitoring Working Party (BMWP) index for assessing water quality of River Aturukuku in Eastern Uganda. *Global Ecol. Conserv.* **2020**, *23*, e01183, <https://doi.org/10.1016/j.gecco.2020.e01183>.

39. Busulwa, H.S.; Bailey, R.G. Aspects of the physico-chemical environment of the Rwenzori rivers, Uganda. *Afr J Ecol.* **2004**, *42*, 87–92, <https://doi.org/10.1111/j.1365-2028.2004.00467.x>.
40. Mukisa, W.; Yatuha, J.; Andama, M.; Aventino, K. Heavy metal pollution in the main rivers of Rwenzori region, Kasese district South-western Uganda. *Octa J Environ Res.* **2020**, *8*, 078-090. http://sciencebeingjournal.com/sites/default/files/02_0803_MW01.pdf.
41. Omara, T.; Nassazi, W.; Adokorach, M.; Kagoya, S. Physicochemical and Microbiological Quality of Springs in Kyambogo University Propinquity. *OALib J.* **2019**, *6*, e5100, <https://doi.org/10.4236/oalib.1105100>.
42. Chuan, M.; Shu, G.; Liu, J. Solubility of heavy metals in a contaminated soil: effects of redox potential and pH. *Water Air Soil Poll.* **1996**, *90*, 543–556, <https://doi.org/10.1007/BF00282668>.
43. Tang, Z.; Hong, S.; Xiao, W.; Taylor, J. Impacts of blending ground, surface, and saline waters on lead release in drinking water distribution systems. *Water Res.* **2006**, *40*, 943–950, <https://doi.org/10.1016/j.watres.2005.12.028>.
44. Bwire, G.; Sack, D. A.; Kagirita, A.; Obala, T.; Debes, A. K.; Ram, M.; Komakech, H.; George, C. M.; Orach, C. G. The quality of drinking and domestic water from the surface water sources (lakes, rivers, irrigation canals and ponds) and springs in cholera prone communities of Uganda: an analysis of vital physicochemical parameters. *BMC Publ. Health.* **2020**, *20*, 1128, <https://doi.org/10.1186/s12889-020-09186-3>.
45. Turinayo, Y. K. Physicochemical Properties of Sugar Industry and Molasses Based Distillery Effluent and its Effect on Water Quality of River Musamya in Uganda. *Int. J. Environ. Agric. Biotechnol.* **2017**, *2*, 1064-1069, <https://dx.doi.org/10.22161/ijeab/2.3.8>.
46. Butu, A.W.; Emeribe, C. N.; Muoka, I. O.; Emeribe, O. F.; Ogbomida, E. T. Downstream Effects of Industrial Effluents Discharge on Some Physicochemical Parameters and Water Quality Index of River Rido, Kaduna State, Nigeria. *Trop. Aqua. Soil Pollut.* **2022**, *2*, 90–108, <https://doi.org/10.53623/tasp.v2i2.100>.
47. Omer, N.H. Water Quality Parameters. In (Ed.), *Water Quality - Science, Assessments and Policy. IntechOpen.* 2019. <https://doi.org/10.5772/intechopen.89657>.
48. Water Stewardship Information Series. Hardness in Groundwater. 2007. <https://www.rdn.bc.ca/cms/wpattachments/wpID2284atID3802.pdf>.
49. Crawford, M.D. Hardness of drinking-water and cardiovascular disease. *Proc. Nutr. Soc.* **1972**, *31*, 347–353, <https://doi.org/10.1079/PNS19720062>.
50. Bernardi, D.; Dini, F. L.; Azzarelli, A.; Giaconi, A.; Volterrani, C.; Lunardi, M. Sudden cardiac death rate in an area characterized by high incidence of coronary artery disease and low hardness of drinking water. *Angiol.* **1995**, *46*, 145–149, <https://doi.org/10.1177/000331979504600208>.
51. Di Vincenzo, F.; Puca, P.; Lopetuso, L. R.; Petito, V.; Masi, L.; Bartocci, B.; Murgiano, M.; De Felice, M.; Petronio, L.; Gasbarrini, A.; Scaldaferrri, F. Bile Acid-Related Regulation of Mucosal Inflammation and Intestinal Motility: From Pathogenesis to Therapeutic Application in IBD and Microscopic Colitis. *Nutrients* **2022**, *14*, 2664, <https://doi.org/10.3390%2Fnu14132664>.
52. WHO. World Health Organization. Hardness in Drinking-Water: Background Document for Development of WHO Guidelines for Drinking-Water Quality. World Health Organization. 2010.
53. Bashir, F.; Irfan, M.; Ahmad, T.; Iqbal, J.; Butt, M. T.; Sadeq, Y.; Umbreen, M.; Shaikh, I. A.; Moniruzzaman, M. Efficient utilization of low cost agro materials for incorporation of copper nanoparticles to scrutinize their antibacterial properties in drinking water. *Environ. Technol. Innov.* **2021**, *21*, 101228, <https://doi.org/10.1016/j.eti.2020.101228>.
54. Lung, S.; Li, H.; Bondy, S. C.; Campbell, A. Low concentrations of copper in drinking water increase AP-1 binding in the brain. *Toxicol. Indust. Health.* **2015**, *31*, 1178-1184, <https://doi.org/10.1177/0748233713491805>.
55. Mvungi, A.; Hranova, R. K.; Love, D. Impact of home industries on water quality in a tributary of the Marimba River, Harare: implications for urban water management. *Phys. Chem. Earth.* **2003**, *28*, 1131-1137, <https://doi.org/10.1016/j.pce.2003.08.034>.
56. Okonkwo, J. O.; Mothiba, M. Physico-chemical characteristics and pollution levels of heavy metals in the rivers in Thohoyandou, South Africa. *J. Hydrol.* **2005**, *308*, 122-127, <https://doi.org/10.1016/j.jhydrol.2004.10.025>.
57. Amadi, E. K. Nutrient loads and heavy metals assessment along Sosiani River, Kenya. *Chem. Mat. Res.* **2013**, *3*, 14–20, <https://iiste.org/Journals/index.php/CMR/article/view/8654/8849>.
58. Mwesigye, A. R.; Tumwebaze, S. B. Water contamination with heavy metals and trace elements from Kilembe copper mine and tailing sites in Western Uganda; implications for domestic water quality. *Chemosphere.* **2017**, *169*, 281–287, <https://doi.org/10.1016/j.chemosphere.2016.11.077>.

60. Nteziyaremye, P.; Omara, T. Bioaccumulation of priority trace metals in edible muscles of West African lungfish (*Protopterus annectens* Owen, 1839) from Nyabarongo River, Rwanda. *Cogent Environ. Sci.* **2020**, *6*, 1779557, <https://doi.org/10.1080/23311843.2020.1779557>.
61. Luo, Y.; Rao, J.; Jia, Q. Heavy metal pollution and environmental risks in the water of Rongna River caused by natural AMD around Tiegelongnan copper deposit, Northern Tibet, China. *PLoS ONE* **2022**, *17*, e0266700, <https://doi.org/10.1371/journal.pone.0266700>.
62. Nhapi, I.; Wali, U.G.; Uwankunda, B. K.; Nsengimana, H.; Banadda N, Kimwaga R. Assessment of water pollution levels in the Nyabugogo catchment, Rwanda. *Open Environ Eng J.* **2011**, *4*, 40–53, <http://dx.doi.org/10.2174/1874829501104010040>.
63. Huang, X.; Luo, D.; Zhao, D.; Li, N.; Xiao, T.; Liu, J.; et al. Distribution, Source and Risk Assessment of Heavy Metal (oid)s in Water, Sediments, and Corbicula Fluminea of Xijiang River, China. *Int J Environ Res Public Health* **2019**, *16*, 1823, <https://doi.org/10.3390%2Fijerph16101823>.
64. Algül, F.; Beyhan, M. Concentrations and sources of heavy metals in shallow sediments in Lake Bafa, Turkey. *Sci. Rep.* **2020**, *10*, 11782, <https://doi.org/10.1038/s41598-020-68833-2>.
65. Salem, H.M.; Eweida, E.A.; Farag, A. Heavy metals in drinking water and their environmental impact on human health. In: *The International Conference for Environmental Hazard Mitigation ICEHM 2000*, 9–12 September 2000, Cairo University, Cairo, Egypt, **2000**, http://www.virtualacademia.com/pdf/health542_556.pdf.
66. Eisler, R. Lead hazards to fish, wildlife and invertebrates: A synoptic review. In: *Contaminant Hazard Reviews, Report 14; Biological Report 85(1.14)*. U.S. Department of the Interior, Fish and Wildlife Service. **1988**, pp. 1–14, <https://pubs.er.usgs.gov/publication/5200021>.
67. WHO. Guidelines for drinking-water quality, Third edition, incorporating first addendum (third edition). World Health Organization. **2004**, Available online: <https://apps.who.int/iris/bitstream/handle/10665/42852/9241546387.pdf;jsessionid=74359F49065804B3FD9ED2693B9447DE?sequence=1>.
68. Eliku, T.; Leta, S. Spatial and seasonal variation in physicochemical parameters and heavy metals in Awash River, Ethiopia. *Appl. Water Sci.* **2018**, *8*, 177, <https://doi.org/10.1007/s13201-018-0803-x>.
69. Kihampa, C.; Wenaty, A. Impact of mining and farming activities on water and sediment quality of the Mara river basin, Tanzania. *Res. J. Chem. Sci.* **2013**, *3*, 15–24, <http://www.isca.in/rjcs/Archives/v3/i7/3.ISCA-RJCS-2013-060.php>.
70. Ibrahim, M.I.A.; Mohamed, L.A.; Mahmoud, M.G.; Shaban, K.S.; Fahmy, M.A.; Ebeid, M.H. Potential ecological hazards assessment and prediction of sediment heavy metals pollution along the Gulf of Suez, Egypt. *Egypt J Aquat Res* **2019**, *45*, 329–335, <https://doi.org/10.1016/j.ejar.2019.12.003>.
71. Gebresilasie, K.G.; Berhe, G. G.; Tesfay, A. H.; Gebre, S. E. Assessment of Some Physicochemical Parameters and Heavy Metals in Hand-Dug Well Water Samples of Kafta Humera Woreda, Tigray, Ethiopia. *Int. J. Anal. Chem.* **2021**, *2021*, 8867507, <https://doi.org/10.1155/2021/8867507>.
72. Khan, T.A. Trace Elements in the Drinking Water and Their Possible Health Effects in Aligarh City, India. *J Water Resour Protect.* **2011**, *3*, 522–530, <http://dx.doi.org/10.4236/jwarp.2011.37062>.
73. Zhu, K.; Hopwood, M. J.; Groenenberg, J. E.; Engel, A.; Achterberg, E. P.; Gledhill, M. Influence of pH and Dissolved Organic Matter on Iron Speciation and Apparent Iron Solubility in the Peruvian Shelf and Slope Region. *Environ. Sci. Technol.* **2021**, *55*, 9372–9383, <https://doi.org/10.1021/acs.est.1c02477>.
74. Taghizadeha, S. F.; Goumenou, M.; Rezaee, R.; Alegakis, T.; Kokaraki, V.; Anestif, O.; Sarigiannise, D. A.; Tsatsakis, A.; Karimi, G. Cumulative risk assessment of pesticide residues in different Iranian pistachio cultivars: Applying the source specific HQS and adversity specific HIA approaches in Real Life Risk Simulations (RLRS). *Toxicol. Lett.* **2019**, *313*, 91–100, <https://doi.org/10.1016/j.toxlet.2019.05.019>.

Supplementary materials

Table S1. Estimated daily doses and hazard quotients through dermal contact and ingestion of water from River Manafwa, Uganda.

| Season | Group | Site | Metal | ADD _{Ingestion} ($\times 10^{-3}$ mg/kg/day) | THQ _{Ingestion} | ADD _{Dermal contact} ($\times 10^{-8}$ mg/kg/day) | THQ _{Dermal contact} ($\times 10^{-6}$) |
|----------------|----------------|----------------|---------------|--|--------------------------|---|--|
| Wet season | Children | A ₁ | Cu | 3.480 | 0.0870 | 1.0827 | 1.0827 |
| | | | Ni | 0.180 | 0.600 | 0.0560 | 1.0370 |
| | | | Mn | 1.320 | 0.0044 | 0.4107 | 0.0042 |
| | | | Zn | 0.960 | 0.0320 | 0.0299 | 0.0498 |
| | | | Pb | 0.780 | 0.0195 | 0.0243 | 0.4629 |
| | | | Cd | 0.120 | 0.1200 | 0.0037 | 0.6167 |
| | | | Cr | 0.480 | 0.3200 | 0.00149 | 0.2483 |
| | | | Fe | 30.120 | 0.0430 | 9.37070 | 0.0067 |
| | | A ₂ | Cu | 2.760 | 0.0690 | 0.85870 | 0.42935 |
| | | | Ni | 0.540 | 0.1800 | 0.0168 | 0.03111 |
| | | | Mn | 1.200 | 0.0040 | 0.3733 | 0.00389 |
| | | | Zn | 1.800 | 0.0600 | 0.5600 | 9.33334 |
| | | | Pb | 0.336 | 0.0840 | 0.01045 | 0.19905 |
| | | | Cd | 0.180 | 0.1800 | 0.05600 | 9.33334 |
| | | | Cr | 0.360 | 0.00025 | 0.01120 | 1.86667 |
| | | | Fe | 26.760 | 0.0383 | 8.3253 | 0.00059 |
| | | B ₁ | Cu | 4.080 | 0.1020 | 0.12693 | 0.12693 |
| | | | Ni | 0.180 | 0.0600 | 0.05970 | 0.11056 |
| | | | Mn | 1.320 | 0.0044 | 0.4107 | 0.00428 |
| | | | Zn | 1.440 | 0.0480 | 0.4480 | 8.12334 |
| | | | Pb | 0.420 | 0.1050 | 0.0131 | 0.24952 |
| | | | Cd | 0.120 | 0.1200 | 0.0411 | 6.8500 |
| | | | Cr | 0.360 | 0.00024 | 0.0112 | 1.8667 |
| | | | Fe | 23.520 | 0.0336 | 7.3173 | 0.0005 |
| | B ₂ | Cu | 4.320 | 0.1080 | 2.4192 | 2.4192 | |
| | | Ni | 0.900 | 3.0000 | 0.5040 | 0.9334 | |
| | | Mn | 1.560 | 0.0052 | 0.8736 | 0.0091 | |
| | | Zn | 1.440 | 0.0480 | 0.8064 | 13.440 | |
| | | Pb | 0.360 | 0.0900 | 0.02016 | 0.3840 | |
| | | Cd | 0.120 | 0.1200 | 0.00672 | 1.1200 | |
| | | Cr | 0.480 | 0.00032 | 0.00269 | 0.4483 | |
| | | Fe | 32.640 | 0.04663 | 18.2784 | 0.0013 | |
| | M ₁ | Cu | 3.960 | 0.0990 | 2.2176 | 2.2176 | |
| | | Ni | 0.600 | 2.0000 | 0.3360 | 0.6223 | |
| | | Mn | 2.160 | 0.0072 | 1.2096 | 0.0126 | |
| | | Zn | 1.320 | 0.0440 | 0.7392 | 12.320 | |
| | | Pb | 0.780 | 0.1950 | 0.04368 | 0.8320 | |
| | | Cd | 0.180 | 0.1800 | 0.01008 | 1.6800 | |
| | | Cr | 0.360 | 0.00024 | 0.02016 | 3.3600 | |
| | | Fe | 26.520 | 0.03789 | 14.8512 | 0.0011 | |
| | M ₂ | Cu | 5.160 | 0.1290 | 0.28896 | 0.28896 | |
| | | Ni | 1.140 | 0.3800 | 0.63840 | 1.1823 | |
| | | Mn | 2.400 | 0.0080 | 1.3440 | 0.0140 | |
| | | Zn | 3.240 | 0.1080 | 1.8144 | 30.240 | |
| | | Pb | 0.480 | 0.1200 | 0.02688 | 0.5120 | |
| | | Cd | 0.180 | 0.1800 | 0.01008 | 1.6800 | |
| | | Cr | 0.480 | 0.0003 | 0.02688 | 4.4800 | |
| | | Fe | 27.00 | 0.0386 | 15.1200 | 0.0011 | |
| M ₃ | Cu | 5.400 | 0.1350 | 1.6800 | 1.6800 | | |
| | Ni | 0.180 | 0.0600 | 0.0560 | 0.1037 | | |
| | Mn | 2.280 | 0.0760 | 0.7093 | 0.0074 | | |
| | Zn | 2.760 | 0.0920 | 0.8587 | 14.3117 | | |
| | Pb | 0.660 | 0.1650 | 0.0205 | 0.3905 | | |
| | Cd | 0.180 | 0.1800 | 0.0056 | 0.9334 | | |
| | Cr | 0.480 | 0.0003 | 0.0149 | 2.4834 | | |
| | Fe | 109.08 | 0.1558 | 33.936 | 0.0024 | | |
| M ₄ | Cu | 7.200 | 0.1800 | 2.2400 | 2.2400 | | |
| | Ni | 0.300 | 1.0000 | 0.0933 | 0.1728 | | |
| | Mn | 0.164 | 0.0006 | 6.1227 | 0.0638 | | |
| | Zn | 19.680 | 0.6560 | 1.0827 | 18.0450 | | |
| | Pb | 1.200 | 0.3000 | 0.0373 | 0.7105 | | |
| | Cd | 0.240 | 0.2400 | 0.0075 | 1.2500 | | |

| Season | Group | Site | Metal | ADD Ingestion ($\times 10^{-3}$ mg/kg/day) | THQ Ingestion | ADD Dermal contact ($\times 10^{-8}$ mg/kg/day) | THQ Dermal contact ($\times 10^{-6}$) |
|------------|--------------|----------------|----------|---|----------------|---|---|
| Dry season | Children | A ₁ | Cr | 1.320 | 0.0009 | 0.0411 | 6.8500 |
| | | | Fe | 47.640 | 0.0681 | 14.821 | 0.0011 |
| | | | Cu | 10.150 | 0.2538 | 8.2380 | 8.2380 |
| | | | Ni | 0.525 | 1.7500 | 0.4261 | 0.0079 |
| | | | Mn | 3.850 | 0.1283 | 3.1249 | 0.0326 |
| | | | Zn | 2.800 | 0.0933 | 2.2727 | 37.8784 |
| | | | Pb | 2.275 | 0.5688 | 0.1847 | 3.5181 |
| | | | Cd | 0.350 | 0.3500 | 0.0284 | 4.7334 |
| | | | Cr | 1.400 | 0.0009 | 0.1136 | 18.9334 |
| | | | Fe | 87.850 | 0.1255 | 71.305 | 0.0051 |
| | | | Cu | 8.050 | 0.2013 | 0.6534 | 0.6534 |
| | | | Ni | 1.575 | 5.2500 | 1.2784 | 2.3674 |
| | | | Mn | 3.500 | 0.0117 | 2.8408 | 0.0295 |
| | | | Zn | 5.250 | 0.1750 | 4.2613 | 71.0217 |
| | | | Pb | 0.980 | 0.2450 | 0.0795 | 1.5143 |
| | | | Cd | 0.525 | 0.5250 | 0.0426 | 7.1000 |
| | | | Cr | 0.105 | 0.0700 | 0.08523 | 14.2050 |
| | | | Fe | 81.550 | 0.1165 | 63.3506 | 0.00453 |
| | | | Cu | 11.900 | 0.2975 | 9.6588 | 9.6588 |
| | | | Ni | 0.525 | 1.7500 | 0.42613 | 0.7891 |
| | | | Mn | 3.850 | 0.0128 | 3.1249 | 0.0326 |
| | | | Zn | 4.200 | 0.1400 | 3.4090 | 56.8167 |
| | | | Pb | 1.225 | 0.3063 | 0.0994 | 1.8934 |
| | | | Cd | 0.350 | 0.3500 | 0.0284 | 4.7334 |
| | | | Cr | 1.050 | 0.0007 | 0.0852 | 14.200 |
| | | | Fe | 68.60 | 0.0980 | 55.680 | 0.0397 |
| | | | Cu | 12.600 | 0.3150 | 10.227 | 10.227 |
| | | | Ni | 2.625 | 8.7500 | 2.1306 | 3.9456 |
| | | | Mn | 4.550 | 0.0152 | 3.6931 | 0.0385 |
| | | | Zn | 4.200 | 0.1400 | 3.4090 | 56.8167 |
| | | | Pb | 1.050 | 0.2625 | 0.0853 | 1.6248 |
| | | | Cd | 0.350 | 0.3500 | 0.0010 | 0.1667 |
| | | | Cr | 1.400 | 0.00093 | 0.0284 | 4.7334 |
| | | | Fe | 95.200 | 0.13600 | 77.271 | 0.0055 |
| | | | Cu | 11.550 | 0.28875 | 9.3748 | 9.3748 |
| | | | Ni | 1.750 | 5.83333 | 1.4204 | 2.6304 |
| | | | Mn | 2.160 | 0.0072 | 5.1135 | 0.0533 |
| | | | Zn | 6.300 | 0.2100 | 3.1249 | 52.0817 |
| | | | Pb | 2.275 | 0.56875 | 0.1847 | 3.5181 |
| | | | Cd | 0.525 | 0.52500 | 0.0426 | 7.1000 |
| | | | Cr | 1.050 | 0.00070 | 0.0852 | 14.200 |
| | | | Fe | 77.350 | 0.1105 | 62.782 | 0.0045 |
| | | | Cu | 15.050 | 0.37625 | 12.216 | 12.2160 |
| | | | Ni | 3.325 | 11.0833 | 2.6988 | 4.9978 |
| | | | Mn | 7.00 | 0.02333 | 5.6817 | 0.0592 |
| | | | Zn | 3.240 | 0.10800 | 7.6703 | 127.8334 |
| | | | Pb | 1.400 | 0.35000 | 0.1136 | 2.1638 |
| | | | Cd | 0.525 | 0.52500 | 0.0426 | 7.1000 |
| Cr | 1.400 | 0.00093 | 0.1136 | 18.9334 | | | |
| Fe | 78.750 | 0.11250 | 63.919 | 0.0046 | | | |
| Cu | 15.750 | 0.39375 | 12.784 | 12.784 | | | |
| Ni | 0.525 | 1.31250 | 0.4261 | 7.8907 | | | |
| Mn | 6.650 | 0.02117 | 5.3975 | 0.0562 | | | |
| Zn | 8.050 | 0.26833 | 6.5339 | 108.8984 | | | |
| Pb | 1.925 | 0.48125 | 0.1562 | 2.9750 | | | |
| Cd | 0.525 | 0.52500 | 0.0426 | 7.1000 | | | |
| Cr | 1.400 | 0.00093 | 0.1136 | 18.9334 | | | |
| Fe | 318.50 | 0.45500 | 258.2318 | 0.0184 | | | |
| Cu | 21.00 | 0.52500 | 17.0450 | 17.0450 | | | |
| Ni | 0.875 | 2.91667 | 0.7102 | 1.3152 | | | |
| Mn | 57.400 | 0.19133 | 465.897 | 4.8531 | | | |
| Zn | 10.150 | 0.38333 | 8.2384 | 137.3067 | | | |
| Pb | 3.500 | 0.87500 | 0.2841 | 5.4114 | | | |
| Cd | 0.700 | 0.7000 | 0.0568 | 9.4667 | | | |
| Cr | 3.850 | 0.00233 | 0.3125 | 52.0834 | | | |
| Fe | 138.95 | 0.19850 | 112.7811 | 0.0081 | | | |
| Cu | 0.3600 | 0.0900 | 0.1120 | 0.1120 | | | |

| Season | Group | Site | Metal | ADD Ingestion ($\times 10^{-3}$ mg/kg/day) | THQ Ingestion | ADD Dermal contact ($\times 10^{-8}$ mg/kg/day) | THQ Dermal contact ($\times 10^{-6}$) |
|--------|--------|----------------|-------|---|---------------|---|--|
| | | | Ni | 0.1200 | 0.4000 | 0.0373 | 0.0691 |
| | | | Mn | 8.6400 | 0.0288 | 0.0269 | 0.0003 |
| | | | Zn | 0.1800 | 0.0060 | 0.0560 | 0.9334 |
| | | | Pb | 1.020 | 0.2550 | 0.0317 | 0.6038 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 168.96 | 0.2414 | 52.565 | 0.0038 |
| | | | Cu | 3.500 | 0.0875 | 0.1307 | 0.1307 |
| | | | Ni | 0.420 | 1.4000 | 0.0373 | 0.0691 |
| | | | Mn | 13.200 | 0.0440 | 4.1067 | 0.0428 |
| | | A ₂ | Zn | 0.1800 | 0.0060 | 0.0560 | 0.9334 |
| | | | Pb | 0.6000 | 0.1500 | 0.0187 | 0.3562 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 140.76 | 0.20109 | 43.792 | 0.0031 |
| | | | Cu | 0.36 | 0.0090 | 0.0120 | 0.0120 |
| | | | Ni | 0.18 | 0.6000 | 0.0560 | 0.1037 |
| | | | Mn | 17.28 | 0.0576 | 5.3760 | 0.0560 |
| | | B ₁ | Zn | 0.18 | 0.0060 | 0.0560 | 0.9334 |
| | | | Pb | 0.72 | 0.1800 | 0.0224 | 0.4267 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 168.84 | 0.2412 | 52.527 | 0.00375 |
| | | | Cu | 0.360 | 0.0090 | 0.0112 | 0.0112 |
| | | | Ni | 0.120 | 0.4000 | 0.0373 | 0.0691 |
| | | | Mn | 6.360 | 0.0212 | 1.9787 | 0.0206 |
| | | B ₂ | Zn | 0.180 | 0.0060 | 0.0560 | 0.9334 |
| | | | Pb | 0.600 | 0.1500 | 0.0187 | 0.3562 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 153.24 | 0.2189 | 47.675 | 0.0034 |
| | | | Cu | 0.4200 | 0.0105 | 0.1307 | 0.1307 |
| | | | Ni | 0.6000 | 2.0000 | 0.1867 | 0.3457 |
| | | | Mn | 16.200 | 0.0540 | 5.0400 | 0.0525 |
| | | M ₁ | Zn | 0.5400 | 0.0180 | 0.1680 | 2.800 |
| | | | Pb | 0.6600 | 0.1650 | 0.0205 | 0.3905 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 151.680 | 0.2167 | 47.1893 | 0.0034 |
| | | | Cu | 0.4800 | 0.0120 | 0.1493 | 0.1493 |
| | | | Ni | 0.1200 | 0.4000 | 0.0373 | 0.0691 |
| | | | Mn | 16.680 | 0.0556 | 5.1893 | 0.0541 |
| | | M ₂ | Zn | 0.1800 | 0.0060 | 0.0560 | 0.9334 |
| | | | Pb | 0.7800 | 0.1950 | 0.0243 | 0.4629 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 151.44 | 0.2163 | 47.1147 | 0.0034 |
| | | | Cu | 0.5400 | 0.0135 | 0.1680 | 0.1680 |
| | | | Ni | 0.1200 | 0.4000 | 0.0373 | 0.0691 |
| | | | Mn | 30.720 | 0.1024 | 9.5570 | 0.0996 |
| | | M ₃ | Zn | 0.4200 | 0.0140 | 0.1307 | 2.1784 |
| | | | Pb | 0.7200 | 0.1800 | 0.0224 | 0.4267 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 1.285 | 0.00184 | 47.9733 | 0.0034 |
| | | | Cu | 154.200 | 3.8550 | 0.1680 | 0.1680 |
| | | | Ni | 0.1200 | 0.4000 | 0.0373 | 0.0691 |
| | | | Mn | 31.440 | 0.1408 | 9.7813 | 0.1019 |
| | | M ₄ | Zn | 0.4200 | 0.0140 | 0.1307 | 2.1700 |
| | | | Pb | 0.7200 | 0.1800 | 0.0224 | 0.4267 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | 0.1200 | 0.00008 | 0.0037 | 0.6167 |
| | | | Fe | 154.20 | 0.2203 | 47.973 | 0.0034 |
| | | | Cu | 0.1050 | 0.00263 | 0.8523 | 0.8523 |
| | Adults | A ₁ | Ni | 0.0350 | 0.11667 | 0.2841 | 0.5261 |
| | | | Mn | 2.5200 | 0.00840 | 20.454 | 0.2131 |
| | | | Zn | 0.0525 | 0.00175 | 0.4261 | 7.1017 |

| Season | Group | Site | Metal | ADD _{Ingestion} ($\times 10^{-3}$ mg/kg/day) | THQ _{Ingestion} | ADD _{Dermal contact} ($\times 10^{-8}$ mg/kg/day) | THQ _{Dermal contact} ($\times 10^{-6}$) |
|--------|-------|----------------|-------|--|--------------------------|---|---|
| | | | Pb | 0.2975 | 0.07438 | 0.2415 | 4.6000 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 49.280 | 0.0704 | 399.99 | 0.0285 |
| | | | Cu | 1.2250 | 0.0306 | 0.9943 | 0.9943 |
| | | | Ni | 0.0350 | 0.11667 | 0.2841 | 0.5261 |
| | | | Mn | 3.8500 | 0.01283 | 31.249 | 0.3255 |
| | | A ₂ | Zn | 0.0525 | 0.00175 | 0.4261 | 7.1017 |
| | | | Pb | 0.1750 | 0.04375 | 0.1420 | 2.7048 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 41.055 | 0.05865 | 3.3323 | 0.00023 |
| | | | Cu | 0.1050 | 0.00263 | 0.8523 | 0.8523 |
| | | | Ni | 0.0525 | 0.1750 | 0.4261 | 0.7891 |
| | | | Mn | 176.40 | 0.5880 | 40.908 | 0.42613 |
| | | B ₁ | Zn | 1.8375 | 0.06125 | 0.4261 | 7.1017 |
| | | | Pb | 0.2100 | 0.03000 | 0.1705 | 3.2476 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 49.245 | 0.07035 | 399.705 | 0.02855 |
| | | | Cu | 0.1050 | 0.002625 | 0.8523 | 0.8523 |
| | | | Ni | 0.0350 | 0.11667 | 0.2841 | 0.5261 |
| | | | Mn | 1.8550 | 0.00618 | 15.056 | 0.1568 |
| | | B ₂ | Zn | 0.0525 | 0.00175 | 0.4261 | 7.1017 |
| | | | Pb | 0.1750 | 0.04375 | 0.14204 | 2.7055 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 44.695 | 0.06424 | 362.777 | 0.2591 |
| | | | Cu | 0.1225 | 0.00306 | 0.9943 | 0.9943 |
| | | | Ni | 0.1750 | 0.58333 | 1.4204 | 2.6304 |
| | | | Mn | 4.7250 | 0.01575 | 38.350 | 0.3995 |
| | | M ₁ | Zn | 0.1575 | 0.00525 | 1.2784 | 21.3067 |
| | | | Pb | 0.1925 | 0.04813 | 0.1562 | 2.8926 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 44.240 | 0.06320 | 359.081 | 0.0257 |
| | | | Cu | 0.1400 | 0.00350 | 1.1363 | 1.1363 |
| | | | Ni | 0.0350 | 0.11667 | 0.2841 | 0.5261 |
| | | | Mn | 4.8650 | 0.01622 | 39.488 | 0.4114 |
| | | M ₂ | Zn | 0.0015 | 0.00005 | 0.4261 | 7.1017 |
| | | | Pb | 0.0525 | 0.01313 | 0.1847 | 3.5181 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 44.170 | 0.06310 | 358.513 | 0.0256 |
| | | | Cu | 0.1575 | 0.00394 | 1.2784 | 1.2784 |
| | | | Ni | 0.0350 | 0.11667 | 0.2841 | 0.52611 |
| | | | Mn | 8.9600 | 0.029867 | 72.725 | 0.75755 |
| | | M ₃ | Zn | 0.1225 | 0.004083 | 0.9943 | 16.5717 |
| | | | Pb | 0.2100 | 0.05250 | 0.1705 | 3.24762 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | NA | NA | NA | NA |
| | | | Fe | 44.975 | 0.06425 | 365.047 | 0.00267 |
| | | | Cu | 0.1575 | 0.00394 | 1.278 | 1.27800 |
| | | | Ni | 0.0350 | 0.11667 | 0.2841 | 0.52611 |
| | | | Mn | 9.1700 | 0.03057 | 74.430 | 0.77531 |
| | | M ₄ | Zn | 0.1225 | 0.00408 | 0.9943 | 16.5717 |
| | | | Pb | 0.2100 | 0.05250 | 0.1705 | 3.24762 |
| | | | Cd | NA | NA | NA | NA |
| | | | Cr | 0.0350 | 0.000023 | 0.0284 | 4.73334 |
| | | | Fe | 44.975 | 0.064250 | 365.047 | 0.02607 |

Values in **bold** indicate exceedance of reference dose for estimated daily doses (ADD_{Ingestion} or ADD_{Dermal contact}) or unity for target hazard quotient (THQ). NA = Not applicable. The oral reference doses are 4.0×10^{-2} , 3.0×10^{-4} , 3.0×10^{-2} , 3.0×10^{-2} , 4.0×10^{-3} , 1.0×10^{-3} , 1.5×10^0 and 7×10^{-1} mg/kg/day for Cu, Ni, Mn, Zn, Pb, Cd, Cr and Fe, respectively. The corresponding reference doses for Cu, Ni, Mn, Zn, Pb, Cd, Cr and Fe are 1.0×10^{-2} , 5.40×10^{-3} , 9.6×10^{-1} , 6.0×10^{-4} , 5.25×10^{-4} , 6.0×10^{-5} , 6.0×10^{-5} , and 1.4×10^2 mg/kg/day, respectively.

Table S2. Cancer risks through ingestion of water from River Manafwa, Uganda.

| Season | Group | Site | Metal | Cancer risk | Total Cancer Risk |
|----------------|----------------|------------------------|--------------------------|--------------------------|-------------------------|
| Wet season | Children | A ₁ | Pb | 6.63×10^{-9} | 2.8626×10^{-6} |
| | | | Cd | 4.56×10^{-8} | |
| | | | Cr | 2.4×10^{-7} | |
| | | A ₂ | Pb | 2.856×10^{-9} | 8.8536×10^{-8} |
| | | | Cd | 6.84×10^{-8} | |
| | | | Cr | 1.728×10^{-8} | |
| | | B ₁ | Pb | 3.57×10^{-9} | 6.645×10^{-8} |
| | | | Cd | 4.56×10^{-8} | |
| | | | Cr | 1.728×10^{-8} | |
| | | B ₂ | Pb | 3.06×10^{-9} | 7.166×10^{-7} |
| | | | Cd | 4.56×10^{-8} | |
| | | | Cr | 2.304×10^{-8} | |
| | M ₁ | Pb | 6.63×10^{-9} | 2.49063×10^{-7} | |
| | | Cd | 6.84×10^{-8} | | |
| | | Cr | 1.80×10^{-7} | | |
| | M ₂ | Pb | 4.08×10^{-9} | 3.08808×10^{-7} | |
| | | Cd | 6.84×10^{-8} | | |
| | | Cr | 2.40×10^{-7} | | |
| | M ₃ | Pb | 5.61×10^{-9} | 3.08961×10^{-7} | |
| | | Cd | 6.84×10^{-8} | | |
| | | Cr | 2.40×10^{-7} | | |
| | M ₄ | Pb | 5.61×10^{-9} | 7.51761×10^{-7} | |
| | | Cd | 9.12×10^{-8} | | |
| | | Cr | 6.60×10^{-7} | | |
| Adults | A ₁ | Pb | 1.934×10^{-8} | 8.5234×10^{-7} | |
| | | Cd | 1.33×10^{-7} | | |
| | | Cr | 7.0×10^{-7} | | |
| | A ₂ | Pb | 8.33×10^{-9} | 2.8283×10^{-7} | |
| | | Cd | 1.995×10^{-7} | | |
| | | Cr | 7.50×10^{-8} | | |
| | B ₁ | Pb | 1.041×10^{-8} | 6.6841×10^{-7} | |
| | | Cd | 1.33×10^{-7} | | |
| | | Cr | 5.25×10^{-7} | | |
| | B ₂ | Pb | 8.925×10^{-9} | 8.41925×10^{-7} | |
| | | Cd | 1.33×10^{-7} | | |
| | | Cr | 7.00×10^{-7} | | |
| M ₁ | Pb | 1.934×10^{-8} | 7.4384×10^{-7} | | |
| | Cd | 1.995×10^{-7} | | | |
| | Cr | 5.250×10^{-7} | | | |
| M ₂ | Pb | 1.19×10^{-9} | 9.0069×10^{-7} | | |
| | Cd | 1.995×10^{-7} | | | |
| | Cr | 7.00×10^{-7} | | | |
| M ₃ | Pb | 1.636×10^{-8} | 9.1586×10^{-7} | | |
| | Cd | 1.995×10^{-7} | | | |
| | Cr | 7.00×10^{-7} | | | |
| M ₄ | Pb | 2.975×10^{-8} | 2.22075×10^{-6} | | |
| | Cd | 2.66×10^{-7} | | | |
| | Cr | 1.925×10^{-6} | | | |
| Dry season | Children | A ₁ | Pb | 8.67×10^{-9} | 8.67×10^{-9} |
| | | | Cd | NA | |
| | | | Cr | NA | |
| | | A ₂ | Pb | 5.10×10^{-9} | 5.10×10^{-9} |
| | | | Cd | NA | |
| | | | Cr | NA | |
| | | B ₁ | Pb | 6.12×10^{-9} | 6.12×10^{-9} |
| | | | Cd | NA | |
| | | | Cr | NA | |
| | | B ₂ | Pb | 5.10×10^{-9} | 5.10×10^{-9} |
| | | | Cd | NA | |
| | | | Cr | NA | |
| M ₁ | Pb | 5.61×10^{-9} | 5.61×10^{-9} | | |
| | Cd | NA | | | |
| | Cr | NA | | | |
| M ₂ | Pb | 6.63×10^{-9} | 6.63×10^{-9} | | |
| | Cd | NA | | | |

| Season | Group | Site | Metal | Cancer risk | Total Cancer Risk |
|--------|--------|----------------|-------|--------------------------|--------------------------|
| | | | Cr | NA | |
| | | M ₃ | Pb | 6.12×10^{-9} | |
| | | | Cd | NA | 6.12×10^{-9} |
| | | | Cr | NA | |
| | | M ₄ | Pb | 6.12×10^{-9} | |
| | | | Cd | NA | 6.612×10^{-8} |
| | | | Cr | 6.00×10^{-8} | |
| | | A ₁ | Pb | 2.52875×10^{-9} | |
| | | | Cd | NA | 2.52875×10^{-9} |
| | | | Cr | NA | |
| | | A ₂ | Pb | 1.4875×10^{-9} | |
| | | | Cd | NA | 1.4875×10^{-9} |
| | | | Cr | NA | |
| | | B ₁ | Pb | 1.785×10^{-9} | |
| | | | Cd | NA | 1.785×10^{-9} |
| | | | Cr | NA | |
| | Adults | B ₂ | Pb | 1.4875×10^{-9} | |
| | | | Cd | NA | 1.4875×10^{-9} |
| | | | Cr | NA | |
| | | M ₁ | Pb | 1.636×10^{-9} | |
| | | | Cd | NA | 1.636×10^{-9} |
| | | | Cr | NA | |
| | | M ₂ | Pb | 4.4625×10^{-10} | |
| | | | Cd | NA | 4.4625×10^{-10} |
| | | | Cr | NA | |
| | | M ₃ | Pb | 1.785×10^{-9} | |
| | | | Cd | NA | 1.785×10^{-9} |
| | | | Cr | NA | |
| | | M ₄ | Pb | 1.785×10^{-9} | |
| | | | Cd | NA | 1.9285×10^{-8} |
| | | | Cr | 1.750×10^{-8} | |

The ingestion cancer slope factors (mg/kg/day) for Pb, Cr and Cd are 8.5×10^{-6} , 5.0×10^{-4} and 3.8×10^{-4} , respectively.