

## Research

# Occurrence of toxic metals in river Rwizi surface water and efficacy of wastewater stabilization ponds (WSPs) in Mbarara City, Uganda

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## Abstract

Toxic metal concentrations and physical chemical properties of River Rwizi surface water were determined. Aluminium, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, potassium, lead, manganese, molybdenum, nickel, selenium, silver, thallium, thorium, uranium, vanadium, and zinc, were quantified using Inductively coupled plasma optical emission spectroscopy (ICP-OES). Physical chemical parameters were measured in-situ using a HANA meter. Heavy metal pollution index (HMPI), Contamination Degree ( $C_D$ ) and Hazard index (HI) were determined by comparing measured concentrations and reference values. Efficacy of wastewater treatment was evaluated from metal concentrations at the inlet and outlet of the Wastewater Stabilization Ponds (WSP). Selenium (up to 10.35 µg/L), iron (up to 601.74 µg/L) and aluminium (up to 435.44 µg/L), were higher than the World Health Organization (WHO) recommendations of 10 µg/L, 300 µg/L and 100 µg/L respectively. The physical–chemical parameters met the drinking water standard, except for turbidity (up to 89.1 NTU) which was higher than the WHO recommendation of < 5 NTU. HMPI was 19.5–140.7 and  $C_D$  was – 12.0–18.5 showing moderate to very high pollution. The HI was 0.084–0.804 for children and 0.036–0.379 for adults. For chronic exposure, HI was 0.008–0.069 for children and 0.016–0.163 for adults. The risk to human health exceeded the negligible threshold of  $HI \leq 0.1$  for adults. The efficiency of removal of metals by WSPs was low (5.87–57.73%), therefore, better wastewater management methods are desirable for protection of human health.

**Keywords** Toxic metals · River Rwizi · ICP-OES · Wastewater stabilization pond (WSP)

## 1 Introduction

Accumulation of toxic metals in different environmental compartments hinders the environment from performance of its roles in fostering life and causes deleterious effects [1]. While metals occur naturally in the environment, their use in various anthropogenic activities increases their concentration beyond acceptable levels in the atmosphere,

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water, sediment and soil [2] leading to environmental pollution. Toxic metal contamination of surface water threatens human health globally [3] because surface water is the main source of water for various domestic and industrial applications. Metals enter surface water from waste generated during industrial and agricultural activities, municipal waste and surface runoff [1, 4, 5] ultimately polluting water sources.

Globally, about 80% industrial and domestic wastewater is released into the environment without adequate treatment [6] polluting and degrading surface water ecosystems with various pollutants such as toxic metals, persistent organic pollutants, pesticides, chlorination by-products and pharmaceutical products [6, 7]. River systems in developing countries such as China, India and Brazil are affected by severe pollution making their water unsuitable for use [8–10]. Surface water pollution is a growing problem in cities of low and middle income countries (LMICs) where untreated wastewater and other wastes are indiscriminately disposed of [11, 12]; moreover, treatment facilities in LMICs are often inadequate and overloaded [3, 13].

In Uganda, about 15% of the land surface is covered by fresh water however, the distribution is uneven [14]. The sources of water include lakes, rivers, ponds and scoop holes which are generally considered unsafe and difficult to protect. Other sources such as groundwater, boreholes, protected wells and rain water are also used [15]. Access to safe water in Uganda is still a challenge. Thirty eight million out of the forty seven million people (81% of the population) lack access to safe water [16]. Treated piped water is supplied by the National Water and Sewerage Corporation (NWSC) throughout the country. While 85% of the urban areas access NWSC water, only 30% of the rural areas access this piped water [17]. In Mbarara District in western Uganda, safe water coverage has improved from 47.5% [18] to approximately 63% in rural areas and up to 65% in Mbarara City [17]. However, intermittent supplies compel residents to rely on unsafe and untreated water [19] drawn directly from rivers and boreholes which are often contaminated [13].

The quality of drinking water in Uganda was previously evaluated against the World Health Organization (WHO) drinking water standards. For example physical–chemical parameters of water from cholera prone communities did not meet the WHO drinking water standards [20]. Sources in mining areas and urban areas were contaminated with toxic metals [21–23]. Other pollutants detected in surface and groundwater in Uganda include pharmaceuticals [24, 25], microbes [11, 26–28] and microplastics [29]. Densely populated and urban areas are more severely affected [24, 26, 28], showing that untreated water is not suitable for consumption.

In Mbarara City and its surroundings, River Rwizi is the main source of water supporting the livelihoods of about 2.5 million people in western Uganda [30]. River Rwizi is currently threatened by anthropogenic pollution and climate change. Cropland and settlement in its catchment increased by 26.09% and 0.35% respectively and the wetland reduced by 1.62% for the period 1997–2019 [31], lowering the capacity for phytochemical purification of water.

The growing population and corresponding increase in water demand have led to intensified abstraction of water from River Rwizi. In 2020 the annual domestic water demand in the Rwizi catchment was estimated at 17.4 million cubic meters with projections indicating a rise to 28.1 million cubic meters by 2040 [32]. Nonetheless, water levels and quality continue to decline [33] as anthropogenic pollution increases [34], therefore, communities that use untreated water from this river could be at health risk.

Increasing pollution of River Rwizi was reported based on analysis of physical–chemical parameters [35], microbial parameters [11] and toxic metals [36, 37]. Lead (Pb), cadmium (Cd), copper (Cu) and zinc (Zn) in the concentration range of 0.034–2.665 µg/L were reported in the river section traversing Mbarara City [37]. Eleven toxic metals including: arsenic (As), aluminium (Al), gold (Au), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), lead (Pb) and zinc (Zn) were determined from six sites along River Rwizi including two sites in Mbarara City. Although most metal concentrations were within the acceptable range of World Health Organization (WHO) drinking water standards, Fe (up to 67.27 ppm) and Mn (up to 3.75 ppm) exceeded the standards; moreover consumption of *Brycinus sadleri* sourced from river Rwizi posed a potential health risk [36].

The presence of toxic metals in water affects human and aquatic health [5, 12, 38]. Exposure to toxic metals is associated with harmful effects such as neurological disorders, cardiac abnormalities, tremors, weakness, shortness of breath, paralysis and cancers [5, 39, 40] therefore their presence in drinking water raises concern. Available data about River Rwizi was obtained from small sections of the river. The data accounts for the contribution of artisanal gold mining in upper reaches and pollution from Mbarara City. Anthropogenic sources in the middle course of the river which is threatened by sand mining and encroachment of wetlands [33] had not been assessed. A more comprehensive assessment of the river was required to allow for formulation of appropriate mitigation strategies. Data about a wider range of toxic metals, spatial variation, potential sources and potential risk posed along the river can inform such strategies, hence there was a need to assess the river more broadly.

Mbarara City's wastewater is currently discharged into three wastewater stabilization ponds (WSPs) located in the River Rwizi catchment at Katete, Kijungu and Kakoba. WSPs are the most common wastewater treatment methods in developing countries where modern wastewater treatment plants (WWTPs) are limited [41]. They are composed of anaerobic (primary treatment), facultative (secondary treatment), and maturation ponds (tertiary treatment) to achieve effective wastewater treatment. The combined total flow of sewage treated at the three WSP systems located in Mbarara is 540 m<sup>3</sup>/d, with 200 m<sup>3</sup>/d for Katete, 160 m<sup>3</sup>/d for Kijungu and 180 m<sup>3</sup>/d for Kakoba pond systems. This flow is equivalent to about 5% of the total sewage flow generated in Mbarara Municipality [42]. These WSPs are insufficient for treatment of wastewater generated in the city moreover sewage over flows and surface run off are evident at the WSP sites. This can pollute nearby surface water sources with various pollutants including metals. Toxic metal entry to River Rwizi from anthropogenic sources could potentially harm to human health, therefore risk assessment was imperative.

The potential health risks due to drinking or exposure to contaminated water can be identified using a health risk assessment approach [43–45]. Evaluation of overall water quality, usually reported in terms of indices such as water quality index (WQI), chronic daily intake (CDI), hazard quotient (HQ) hazard indices (HI) and heavy metal pollution index (HMPI) provides useful information regarding potential risk to human health. These indices provide a structured method to quantitatively express the link between exposure and human health [36, 39, 43, 45–47].

The objectives of this study therefore were to: (i) determine the concentration and spatial distribution of selected toxic metals in surface water from River Rwizi and wastewater stabilization ponds (WSPs) in Mbarara City; (ii) quantify the extent of pollution; (iii) evaluate the efficiency of WSPs in removing toxic metals; and (iv) assess the potential human risks associated with the presence of these metals. The study's comprehensive approach, which included representative spatial sampling, identification of contaminated zones, and a thorough health risk assessment, established the novelty of this study. The findings will contribute to the development of strategies for safeguarding public health, improving water resource management, and guiding recommendations for wastewater treatment improvements.

## 2 Materials and methods

### 2.1 Study site and hydrogeological characteristics

River Rwizi is located in South Western Uganda between latitudes of 0.21° S to 0.92° S and longitudes of 30.21° E to 32.52° E [31]. It is an important river in the Lake Victoria basin and originates from the hilly terrains of Buhweju (00°21.983' S, E030°26.363'E) and Ntungamo (00°45.151'S, 030°20.139'E) districts [31, 48]. River Rwizi is fed by numerous tributaries from other hills in the Ankole region [31] mostly in Sheema and Mbarara Districts. It eventually discharges into Lake Victoria through the Lake Mburo-Nakivale Ramsar site and other small lakes system consisting of lakes Kachera, Nakivale, and Kijanebarola [35, 49]. River Rwizi is dominated by wetlands and has an average discharge of 19–386 million cubic meters (MCM) of water per year [50].

The Rwizi catchment which covers approximately 8554 square kilometres, is characterized by a rocky topography of a high elevation ranging from 1300 to 2170 m above sea level [35, 48, 51]. The river is about 55 km from the source to its mouth [34] and passes through Mbarara City where wastewater treatment plants (WWTPs) are located in its catchment. In terms of landscape, the upper catchments is hilly and rugged [51–54], the middle is generally flat and the lower reaches, towards Lake Victoria, are mainly marshland [32].

River Rwizi supports livelihoods in twelve districts including Buhweju, Bushenyi, Rubirizi, Sheema Rwampara, Isingiro, Mbarara, Rakai, Kiruhura, Lyantonde, Lwengo and Kyotera [30, 32, 33]. Seventeen (17) sites, spanning from Buhweju through Mbarara City to Lake Mburo, were purposively selected to ensure coverage of more impacted areas in the upper and lower reaches, as well as representative sites in the middle section, as shown in Fig. 1. The geographic coordinates of the sites including those of the WSPs are stated in Table 1.

In terms of geology, the study area is located in the Mesoproterozoic Karagwe-Ankole Belt (KAB) [55–60] which has undergone tectonic shifts associated with the western rift valley [61]. It comprises of the Western domain characterized by green schist and amphibolite rocks; and the Eastern domain characterized by basal conglomerates and metasediments [55, 62]. The major structures in the area are: beddings, faults, folds and joints while the minor ones include: micro-folds, micro-faults, quartz veins, foliation, laminations and mud cracks [55, 56, 62, 63].

The geological map of Buhweju district which is in the upper reaches of River Rwizi was described by Bahiru and Woldai [64]. The underling rock system, also described as the Igara and Buhweju rock system, is a sedimentary rock of the Precambrian age, typical of South-western Uganda [33, 65]. The Igara group consists of paraschist with occasional

**Fig. 1** Map of Uganda showing study sites (A). The geology map (B) indicated a predominantly undivided Precambrian (pCm) base rock, with some Quarternary (Q) and Jurassic through carboniferous (JC) rocks. C and D are expanded images of the sites. KIJUNGU, KAKOBA and KATETE are wastewater stabilization ponds (WSPs)

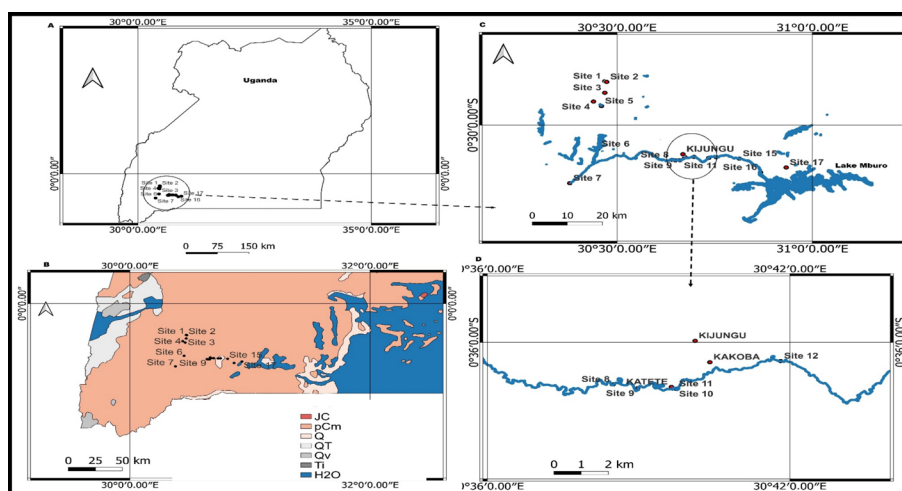


**Table 1** Geographical coordinates and activities of study sites

| Site number: coordinates (latitude, longitude) | Name/Activities in vicinity                                                                                 |
|------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| Site 1: 0° 20' 58.344"S 30° 28' 8.0034"E       | <b>Rwankondo (Karungu1)</b> /Farming (bananas, coffee, beans, vegetables), local distillation               |
| Site 2: 0° 21' 6.732"S 30° 28' 24.7434"E       | <b>Kamajumba (Karungu 1)</b> /Farming (bananas, coffee, beans, vegetables), cattle rearing, school, homes   |
| Site 3: 0° 23' 20.652"S 30° 28' 7.2474"E       | <b>Kanyabukanja</b> /Farming (bananas, coffee, beans, vegetables), cattle rearing                           |
| Site 4: 0° 25' 8.904"S 30° 26' 23.352"E        | <b>Kyenyonyi (Rwengwe Sub county)</b> /Wetland, local distillation                                          |
| Site 5: 0° 26' 4.74"S 30° 27' 36.8274"E        | <b>Nyakambu</b> /Wetland, site next to bridge on marram road                                                |
| Site 6: 0° 34' 54.0114"S 30° 27' 3.6"E         | <b>Kooga (Mbarara- Bushenyi Road)</b> /Farming, site next to highway                                        |
| Site 7: 0° 41' 54.492"S 30° 22' 45.192"E       | <b>Nyeihanga</b> /Wetland, cattle rearing, site next to trading centre                                      |
| Site 8: 0° 37' 6.8514"S 30° 38' 29.76"E        | <b>Nyamitanga (near Bridge)</b> /Next to high way, local fishing                                            |
| Site 9: 0° 37' 12.756"S 30° 38' 58.9554"E      | <b>Kashanyarazi</b> /Residential area (densely populated)                                                   |
| Site 10: 0° 37' 13.8"S 30° 39' 44.028"E        | <b>Kitobero (before WSP)</b> /Residential area (densely populated)                                          |
| Site 11: 0° 37' 13.8"S 30° 39' 44.028"E        | <b>Kitobero (after WSP)</b> /After wastewater stabilization pond                                            |
| Site 12: 0° 36' 29.6994"S 30° 41' 48.984"E     | <b>Bishop Stuart University</b> /Next to the playground, washing of vehicles                                |
| Site 13: 0° 36' 42.732"S 30° 44' 5.244"E       | <b>Kyahi Forest reserve</b> /Washing laundry, motorcycles, cattle drinking, severe plastic bottle pollution |
| Site 14: 0° 36' 33.4794"S 30° 45' 14.796"E     | <b>Rwebicuncu (Kyahi forest reserve)</b> Cattle drinking, farming                                           |
| Site 15: 0° 36' 52.38"S 30° 48' 47.4834"E      | <b>Rwobushuri (Lake Mburo NP)</b> National park                                                             |
| Site 16: 0° 39' 41.3994"S 30° 52' 2.28"        | <b>Bisheshe (lake Mburo NP)</b> National park                                                               |
| Site 17: 0° 38' 41.028"S 30° 55' 59.1594"E     | <b>Rubaare (Lake Mburo NP)</b> National park, fishing site                                                  |
| KAKOBA: 0° 36' 31.608"S 30° 40' 24.8154"E      | <b>Kakoba wastewater stabilization ponds</b> Wastewater stabilization pond (WSP)                            |
| KATETE: 0° 37' 10.8834"S 30° 39' 38.952"E      | <b>Katete wastewater stabilization ponds</b> Wastewater stabilization pond (WSP)                            |
| KIJUNGU: 0° 35' 57.588"S 30° 40' 7.732"E       | <b>Kijungu wastewater stabilization ponds</b> Wastewater stabilization pond (WSP)                           |

The bold words are names of the villages where sample sites are located

quartzite while the Buhweju group has psammitic and pelitic rocks overlying the Igara group [64]. The underlying rock system in middle and lower reaches of River Rwizi is also Karagwe-Ankolean as described by Ryznar et al. and Zi et al. in their geological maps [59, 66]. It is predominantly undivided Precambrian as shown the geological map in Fig. 1. It consists of quartz–mica and mica schists, shale, swamp deposits, alluvium and phyllite [33, 50, 52, 61, 65] with the later most dominant [52]. The map was drawn using QGIS 3.40 (Bratislava) using geological data from <https://www.usgs.gov/centers/central-energy-resources-science-center/science/world-geologic-maps>.

Ground water in the KAB is mostly found in the regolith with limited amounts in the bedrock. The drainage pattern is structurally controlled because the intact rock is impermeable. Structural faults, folds and joints enhance secondary porosity and control aquifer dynamics by guiding recharge, flow, and discharge processes [60, 62, 63, 67, 68]. In the Rwizi

catchment aquifers occur both in the regolith and in the unweathered crystalline rocks [50, 62, 69, 70]. The regolith thickness is low to medium (20–45 m), with low to moderate transmissivities (up to 100 m<sup>2</sup>/d) and aquifer yields of 0.5–4 m<sup>3</sup>/hr [50, 60, 71]. Borehole yields are 0.5–12 m<sup>3</sup>/hr with high yielding wells located in fissured granites and gneisses. The weathered crystalline-rock aquifers have low transmissivities (median 0.8 m<sup>2</sup>/d) with borehole depth and yield of 9–129 m and 0.3–15 m<sup>3</sup>/d respectively [61]. The hydraulic conductivity (K) and specific storage (Ss) values in the KAB fractured domain are  $1.7 \times 10^{-2}$  m/day and  $3.76 \times 10^{-2}$  respectively while in the matrix domain conductivity and storage are  $1.4 \times 10^{-7}$  m/day and  $4.37 \times 10^{-4}$  respectively [50, 69]. Highly productive channels have been reported to yield more than 50 m<sup>3</sup>/hr [60] implying that the aquifers in the study area are weak. Although weathered and fractured bedrock aquifers have low transmissivity, they can be easily recharged [60, 61]. Water recharge into the River Rwizi primarily occurs through rainfall and from tributaries in the catchment. These two main sources replenish the water table [31, 33].

The Rwizi catchment is characterized by a bimodal rainfall pattern; with two wet seasons (February to May and August to December) and two dry seasons (January to February and June to August) [33, 48]. Annual average precipitation ranges from 690 to 1300 mm per year, temperature in the catchment varies between 14 and 33 °C with an average of 23 °C [48, 53, 54]. The river flow regime is dependent on climate and land use changes, including deforestation and agricultural expansion [54, 72].

## 2.2 Sample collection and preservation

Samples were collected during the dry and wet seasons during 2023 and 2024. The river was divided into: the low anthropogenic activity upper reaches (5 sites); the mid reaches, made up of low activity (2 sites) and high activity (5 sites); and finally the lower reaches of the river (5 sites). Twenty-two (22) potentially toxic metals were quantified in water samples from River Rwizi collected during the dry (June–July) and wet seasons (September–November). Physical–chemical parameters of the water including temperature, dissolved oxygen (DO), pH, total dissolved solids (TDS), electrical conductivity (EC), oxidation–reduction potential (ORP) and turbidity were measured in-situ using a HANNA multi-parametric meter (HI9829).

Water samples (1 L) were collected in pre-washed plastic (HDPE) bottles at each sampling site by submerging the container to a depth of 10–30 cm below the surface with the open end against the flow of water [73]. In each season, samples were collected in duplicate from predetermined sites on the river to make a total of thirty-four (34) surface water samples. At the WSP, duplicate samples were collected at the inlet to the WSP, after secondary treatment and after tertiary treatment. Eighteen (18) samples were collected from wastewater stabilization ponds (WSPs). The samples collected were preserved by addition of concentrated nitric acid [74] and then transported on ice in a cool box to the laboratory where they were stored at –20 °C in a refrigerator before further sample preparation.

## 2.3 Sample preparation and analysis

Samples were digested following the method of the American Public Health Organization for examination of water and wastewater [74]. Waters samples (500 mL) were evaporated in an oven at 80–90 °C to reduce the volume to about 10 mL. The reduced sample (~10 mL) was transferred to a crucible and 2 mL of nitric acid (1 + 1) were added followed by 10 mL of HCl (1 + 1). The mixture was digested on a hot plate to reduce the volume to about 5 mL, making certain that the sample did not boil. The sample was later adjusted to 10 mL using distilled water before analysis.

Metals in the digested samples were determined by using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Agilent Technologies, 5800 series instrument USA), equipped with auto-sampler, concentric nebulizer, cyclonic spray chamber and radial torch. A radial geometric torch view, 2-point background correction and three repeats were utilized to generate data. A blank solution made up of nitric acid (environmental grade, 67–70%, thermofisher) was used. A standard metal solution mixture was made by dilution of a 1000 µg/L stock solution containing silver (Ag), aluminium (Al), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), potassium (K), magnesium (Mg), manganese (Mn), molybdenum (Mo), Nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), thorium (Th), thallium (Tl), uranium (U), vanadium (V) and Zinc (Zn) in % nitric acid (Inorganic Ventures).

Calibration solutions were made at concentrations ranging from 0.05 ppm to 1 ppm for the metals except calcium (Ca), iron (Fe) and sodium (Na) which ranged from 5 to 100 ppm. The blank was analysed three times before analysis of samples and standards and that was repeated after every six real samples for quality control. The instrument conditions, emission wavelength lines liberated from spectra impedance for different toxic metals, the detection ranges and coefficients of determination were as shown in Table 2.

## 2.4 Quantification of pollution using heavy metal pollution index (HMPI) and contamination index (CD)

The heavy metal pollution index (HMPI) describes the composite influence of different metals on the total quality of water. It establishes a rating or weightage ( $W_i$ ) between 0 and 1 which is inversely proportional to the standard permissible value ( $S_i$ ) of the corresponding parameter [47, 75, 76]. HMPI was determined using the formula of Mohan et al., [75] as indicated in Eqs. (1–3). The permissible or critical pollution index for drinking water is 100 [75]. The HMPI categorizes pollution levels as low (HMPI < 100), near the threshold (HMPI = 100), or high (critical pollution index) (HMPI > 100) [44].

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

where  $W_i$  is the unit weight of the  $i$ -th parameter and  $n$  is the number of parameters considered.

$Q_i$  is the sub-index of the  $i$ -th parameter

$$Q_i = \sum_{i=1}^n \frac{(M_i(-)I_i)}{(S_i - I_i)} \times 100 \quad (2)$$

$M_i$  is the monitored value of the  $i$ -th parameter,  $I_i$  is the ideal value of the  $i$ -th parameter.  $S_i$  is the standard value of the parameter,  $(-)$  indicates the numerical difference of the two values, ignoring the algebraic sign [44, 75–77].

**Table 2** ICP-OES instrument conditions, toxic metals studied, their emission wavelengths and calibration points

|                       |                 |                                                                                                                                                                                                                                          |                                  |  |
|-----------------------|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|--|
| Instrument conditions |                 | Auxiliary, and nebulizer gas Argon (99.95%)<br>RF power 1200 W<br>plasma gas stream 12 L/min<br>auxiliary gas stream 1 L/min,<br>nebulizer gas stream 0.7 L/min<br>pump speed 12 rpm<br>sample up-take delay and stabilization time 15 s |                                  |  |
| Toxic metal           | Wavelength (nm) | R <sup>2</sup> Value                                                                                                                                                                                                                     | Calibration points (ppm)         |  |
| Ag                    | 328.068         | 0.9998                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Al                    | 396.152         | 0.9998                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| As                    | 188.980         | 0.9997                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Ba                    | 455.403         | 0.9999                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Be                    | 313.042         | 0.9997                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Cd                    | 214.439         | 0.9994                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Co                    | 238.892         | 0.9997                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Cr                    | 267.716         | 0.9998                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Cu                    | 372.395         | 0.9998                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Fe                    | 238.204         | 0.9996                                                                                                                                                                                                                                   | 5.0, 10.0, 15.0, 20.0, 50.0, 100 |  |
| K                     | 766.491         | 1.0                                                                                                                                                                                                                                      | 5.0, 10.0, 15.0, 20.0, 50.0, 100 |  |
| Mn                    | 257.610         | 0.9997                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Mo                    | 202.032         | 0.9999                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Ni                    | 231.604         | 0.9996                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Pb                    | 220.353         | 0.9994                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Sb                    | 206.834         | 0.9994                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Se                    | 196.026         | 0.996                                                                                                                                                                                                                                    | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Th                    | 283.730         | 0.9999                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Tl                    | 190.794         | 0.999                                                                                                                                                                                                                                    | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| U                     | 385.957         | 0.9999                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| V                     | 292.401         | 0.9998                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |
| Zn                    | 213.857         | 0.9998                                                                                                                                                                                                                                   | 0.05, 0.10, 0.15, 0.2, 0.5, 1.0  |  |

$$w_i = \frac{K}{S_i} \quad (3)$$

The contamination index ( $C_D$ ) describes the extent of heavy metal pollution. It is a summation of all contamination factors that exceed the upper permissible values [47, 78] and was determined using the Eqs. (4 and 5). Contamination values ( $C_D$ ) are generally classified into three categories: low ( $C_D < 1$ ), medium ( $C_D 1-3$ ) and high ( $C_D > 3$ ) [47].

$$C_D = \sum_{i=1}^n Cf_i \quad (4)$$

$$Cf_i = \frac{C_{Ai}}{C_{Ni}} \quad (5)$$

where:

$C_{Ai}$  is analytical value of the  $i$ -th component, and  $C_{Ni}$  upper permissible concentration of the  $i$ -th component. The  $C_{Ni}$  value is taken as the same as the drinking water guideline [76, 79].

## 2.5 Human health risk assessment

The risk of exposure to a mixture of metals can be determined by hazard index calculation [80]. The hazard index (HI) is determined from the sum of hazard quotients (HQ) from the different heavy metals as shown in Eq. (6). An  $HI < 1$  implies minimal or no risk of adverse effects. An  $HI > 1$  raises concerns about significant negative health impacts. In terms of chronic exposure,  $HI < 0.1$  implies negligible risk,  $HI \geq 0.1 < 1$  low risk,  $HI \geq 1 < 4$  medium risk and  $HI \geq 4$  implies high risk [81].

$$HI = \sum_{i=1}^n HQ \quad (6)$$

Hazard quotient was calculated using Eqs. (7 and 8)

$$HQ = \frac{CDI}{RfD} \quad (7)$$

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (8)$$

where:

CDI is the chronic daily intake (mg/kg/day); RfD is the reference dose, C is the concentration of the contaminant in water sample (mg/L); IR is the ingestion rate per unit time (1 L/day for a child and 2.2 L/day for an adult) ED is the exposure duration (6 years for a child and 30 years for an adult); EF is the exposure frequency (365 days/year); BW is body weight (15 kg for a child and 70 kg for an adult); AT is the average exposure time (for carcinogens,  $AT = 70 \text{ years} \times 365 \text{ days/year} = 25,550 \text{ days}$  for both children and adults; for non-carcinogens,  $AT = ED \times 365 \text{ days/year} = 2190 \text{ days}$  and 10,950 days for children and adults, respectively) [45, 46, 81–83].

## 2.6 Efficiency of toxic metal removal by wastewater stabilization ponds (WSP)

The metal removal efficiency of the WSP was calculated using Eq. (9) [41, 84]. This method is applicable to the standard rectangular WSP as described in the design by Mara et al. [85]

$$\text{Removal efficiency \%} = \frac{C_i - C_e}{C_i} \times 100 \quad (9)$$

where  $C_i$  is influent concentration and  $C_e$  is effluent concentration.

## 2.7 Data management

Data was presented as means evaluated using Microsoft Excel 2016. Toxic metal concentration data was subjected to principal component analysis (PCA), a multivariate statistical technique used when variables are highly correlated. PCA was used to investigate relationships and potential sources of pollution. It was performed using IBM SSPS statistics 26 software with varimax rotation to minimize the number of variables with high loading on each component to facilitate easier interpretation [31]. Spatial variation in concentration of individual toxic metals was evaluated using QGIS 3.4 (Bratislava). A spatial distribution map was generated for each metal.

## 3 Results and discussion

### 3.1 Physical–chemical properties of River Rwizi water

The River Rwizi surface water pH, DO, temperature, ORP, EC and TDS were in acceptable ranges for drinking water standards [86, 87]. However the measured pH, EC and TDS in our study were higher than that reported previously for River Rwizi water while the DO reduced [35, 37] from the range of 6.73–10.44 mg/L, to a range of 1.4–5.3 mg/L signifying increasing pollution of the water. The pH was comparable to that reported for Lake Victoria on the Kenyan side and River Kapingazi in Kenya [88, 89] but was slightly more alkaline compared to that reported for water sources in Nakivale refugee camp in Uganda [90]; Himalayan tributaries of River Ganga, in India [91] and the more anthropogenic impacted surface water from Mezam River in Bamenda, Cameroon [92].

DO was comparable to that of rivers in Bori, Nigeria [93] and river Kapingazi in Kenya but lower than in Lake Victoria on the Kenyan side [89]. The pH ranges measured can be attributed to nature of the bedrock and anthropogenic effects [33, 94]. EC and TDS in a water body can be attributed to its lithology and anthropogenic activities [95]. The values in our study were comparable to Himalayan tributaries of Ganga River [91] but were lower than in Mezam River [92]; Nakivale sources [90] and the brackish waters in Bori, Nigeria [93] which had more anthropogenic impact.

Turbidity exceeded the World health Organization (WHO) recommended standards [96] of < 5 NTU in all sites except one as shown in Table 3. Turbidity in this study, was higher than that from un impacted rivers in the higher altitudes of Nepal [97] but comparable to what was reported for River Kagera in South western Uganda and Lake Victoria as well as River Kapingazi in Kenya [88, 89, 98]. The value of turbidity however was lower than that reported in higher anthropogenic impact rivers in for Bori in Nigeria [93] and Poland [99]. Generally, turbidity in surface waters is higher than in drinking water due to presence of plant material, soils, silt and clay, and other substances like salts, minerals and metals [100]. Turbidity values obtained in this study were moderate (less than 50 NTU) [101] except for sites 4, 6, 8, 9, 10, 12 and 13 which are near human settlements. The high turbidity at these sites may be attributed to anthropogenic activities such as sand abstraction which increases silting [32], animals drinking, traditional distillation, washing of laundry and vehicles observed in the vicinity of the sites as shown in Fig. 2.

### 3.2 Concentration of trace metals in River Rwizi surface water

Surface water toxic metal composition can be influenced by base rock geology as well as anthropogenic input. In the Karagwe Ankolean belt (KAB), the water chemistry can be influenced by leaching from the underlying Precambrian basement rock. In the River Rwizi catchment, lithological differences are relatively small [52]. The soils consist of acric ferralsols, dystic regosols, eutric regosols, gleyic arenosols, gleysols, histosols and leptosols [31, 33, 53]. Thus the toxic metal composition, if strongly influenced by geogenic input, would reflect an array of the major elements in phyllites, pelites (shales and mudstones), psammite (Quartz and feldspar 80–100% plus mica < 20%) and schists. The water would be expected to have a high concentration of Al, Ca, Fe, K Mg, Na [58, 66, 102, 103] from geogenic sources.

The concentration of toxic metals determined in River Rwizi surface water and in the wastewater stabilization ponds is presented in Table 4. Based on average metal concentrations, the order of abundancy of metals in water was Fe > K > Al > Mn > Ni > U > Zn > Ba > Cr > Cd > Pb > Th > Cu > V > Mo > Co > As > Sb > Tl > Se > Be in surface water as shown in Fig. 3. While most metal concentrations were within the acceptable range as guided by the World Health Organisation (WHO), the average concentrations of Se (up to 10.35 µg/L), Fe (up to 601.74 µg/L) and Al up to 435.44 µg/L) were higher than 10.0 µg/L, 300 µg/L and 200 µg/L respectively which are the maximum standards recommended for drinking water in

**Table 3** Physical–chemical properties of River Rwizi surface water

| Sites and site No.                        | pH | DO ppm            | Temp °C | ORP mV             | EC $\mu\text{S/cm}$                            | TDS ppm              | Turbidity                            |
|-------------------------------------------|----|-------------------|---------|--------------------|------------------------------------------------|----------------------|--------------------------------------|
| Karungu                                   | 1  | 1.55 $\pm$ 0.35   | 24.12   | 87.70 $\pm$ 22.20  | 44.50 $\pm$ 0.71                               | 22.50 $\pm$ 0.71     | 4.60 $\pm$ 2.55                      |
| Kamajumba                                 | 2  | 1.4 $\pm$ 0.26    | 23.58   | 140.70 $\pm$ 71.92 | 52.33 $\pm$ 4.16                               | 26.67 $\pm$ 2.08     | 11.03 $\pm$ 6.46                     |
| Kanyabukanja                              | 3  | 1.6 $\pm$ 0.26    | 21.47   | 154.43 $\pm$ 35.71 | 49 $\pm$ 9.17                                  | 25.00 $\pm$ 4.58     | 23.07 $\pm$ 9.76                     |
| Kyenyonyi                                 | 4  | 1.57 $\pm$ 0.31   | 20.38   | 164.13 $\pm$ 19.31 | 63.67 $\pm$ 4.04                               | 32.00 $\pm$ 2.00     | <b>89.10 <math>\pm</math> 77.48</b>  |
| Nyakambu                                  | 5  | 2.43 $\pm$ 0.91   | 21.47   | 150.13 $\pm$ 29.80 | 71.00 $\pm$ 3.61                               | 35.67 $\pm$ 2.08     | 38.00 $\pm$ 32.26                    |
| Kooga                                     | 6  | 3.0 $\pm$ 1.22    | 27.03   | 141.30 $\pm$ 19.88 | 165.33 $\pm$ 86.38                             | 82.67 $\pm$ 43.66    | <b>66.33 <math>\pm</math> 102.03</b> |
| Nyethanga                                 | 7  | 3.73 $\pm$ 1.22   | 20.33   | 145.33 $\pm$ 28.24 | 53.33 $\pm$ 15.31                              | 26.67 $\pm$ 7.57     | 33.87 $\pm$ 22.0                     |
| Nyamitanga (bridge)                       | 8  | 5.27 $\pm$ 3.95   | 20.68   | 135.17 $\pm$ 37.97 | 106.33 $\pm$ 28.43                             | 53.33 $\pm$ 14.01    | <b>63.37 <math>\pm</math> 56.12</b>  |
| Kashanyarazi                              | 9  | 3.13 $\pm$ 1.17   | 20.77   | 149.13 $\pm$ 38.41 | 207.67 $\pm$ 200.43                            | 54.33 $\pm$ 13.80    | <b>65.17 <math>\pm</math> 60.48</b>  |
| Kitobero 1 (Before WWSP)                  | 10 | 3.23 $\pm$ 1.74   | 21.01   | 153.77 $\pm$ 37.24 | 82.00 $\pm$ 63.21                              | 42.00 $\pm$ 30.05    | <b>86.33 <math>\pm</math> 97.57</b>  |
| Kitobero 2 (After WWSP)                   | 11 | 3.50 $\pm$ 2.12   | ND      | 155.00 $\pm$ 39.60 | 93.50 $\pm$ 7.78                               | 46.50 $\pm$ 3.54     | 31.1 $\pm$ 1.27                      |
| Bishop Stuart University                  | 12 | 2.19 $\pm$ 0.69   | 21.44   | 131.20 $\pm$ 28.78 | 111.67 $\pm$ 27.59                             | 56.00 $\pm$ 14.00    | <b>69.47 <math>\pm</math> 64.63</b>  |
| Kyaahi Forest                             | 13 | 2.05 $\pm$ 0.87   | 22.14   | 163.77 $\pm$ 20.4  | 107.33 $\pm$ 33.95                             | 54.33 $\pm$ 17.24    | <b>64.97 <math>\pm</math> 62.39</b>  |
| Rwebicuncu                                | 14 | 1.81 $\pm$ 1.00   | ND      | 168.00 $\pm$ 45.96 | 98.00 $\pm$ 5.66                               | 49.00 $\pm$ 2.83     | 28.35 $\pm$ 0.64                     |
| <b>Uganda standard for drinking water</b> |    | <b>6.5–8 mg/L</b> |         | 650 mV             | <b>2500 (<math>\mu\text{S/cm}</math>) max</b>  | <b>1500 mg/L max</b> | <b>25 NTU max</b>                    |
| <b>WHO standard for drinking water</b>    |    | <b>6.50–8.50</b>  |         |                    | <b>2500 (<math>\mu\text{S/cm}</math>) max</b>  | <b>300 mg/L</b>      | <b>&lt; 5 NTU</b>                    |
| <b>EPA</b>                                |    | <b>6.50–8.50</b>  |         | 300–500 mV         | <b>&lt; 1000 (<math>\mu\text{S/cm}</math>)</b> | <b>500 mg/L</b>      | <b>&lt; 0.15 NTU</b>                 |

ND—not determined

**Fig. 2** Activities at study sites. **A**- fetching water for domestic use, **B**. Cattle drinking, **C**. A very turbid site, **D**. Local gin brewing. Photo credit: Dr. Irene Aheisibwe



Uganda and by the World Health Organisation (WHO) [86, 87] as shown in Table 4. The concentrations of Cd, Fe, Mn were comparable to those reported previously for the same river; Al was slightly higher while As, Co, Cu and Zn were lower than previously reported [36].

Selenium can be introduced in the environment naturally through geochemical processes and from anthropogenic sources including, industry, electrical and semiconductor devices, additives in pharmaceuticals, fertilizers etc. [40, 104]. The concentration determined in this study was slightly higher than that recorded in Ethiopia [104] and higher than that reported in less impacted Himalayan tributaries of the Ganga river, in India [91]. A high concentration of selenium (10.35  $\mu\text{g/L}$ ) was recorded at site 3, in the upper reaches. This site was located under a bridge in a predominantly agricultural area. The high concentration at site 3 is attributed to agricultural input [40]. Prolonged exposure to a high concentration of selenium may be harmful to humans and the environment [40, 105], exposure to excess selenium can result in selenosis [96] therefore potential risk should be assessed in water sources with a high concentration.

The concentration of Al in this study was higher than low anthropogenic impact regions in the Himalayan tributaries of River Ganga [91] and Pechora river in the Arctic Ocean basin [106]; but comparable to impacted springs in Kampala Uganda [23]. Natural aluminium can be solubilized from the bedrock at pH less than 5.5 [23] however in this study, the lowest pH value was 7.92 therefore geogenic input was limited. The high concentration of Al can be attributed to anthropogenic activities, such as metal wearing off and infiltration of wastewater [23, 107]. The highest concentrations were recorded at sites 8–11 which are located within Mbarara City in the middle reaches of the river. Basooma et al. [36] also reported a high concentration of Al at Rwebikona which is located near site 8 in our study signifying anthropogenic input. Aluminium exposure at high concentrations through drinking water is associated with neurodegeneration [108–110] although more concrete evidence is necessary. In the meantime, adequate removal from drinking water should be ensured to reduce potential risk [110].

Iron determined in this study was lower than that reported in springs in Kampala, Uganda [23]; and in selected rivers in Poland [99] but comparable to that in the Arctic Ocean basin [106] and Himalayan tributaries of the Ganga river [91]. Iron in small quantities is an essential element for human physiology and supports a variety of biochemical processes [5, 111]; excess iron however is toxic and can damage organs. Iron in surface water can come from geogenic sources [23]. The Fe determined in this study was attributed to erosion of acidic ferralsols along its path [33] although activities like sand mining can exacerbate it [35]. Therefore, care should be taken during treatment of drinking water to achieve adequate metal removal.

Sites 13 and 14 had high concentrations of potassium up to 1528.90  $\mu\text{g/L}$  and 1276.34  $\mu\text{g/L}$  respectively. The amounts were lower than the World Health Organization (WHO) drinking water standard of 50,000  $\mu\text{g/L}$ . Higher amounts were detected in streams and springs in Kampala, Uganda [23] and in ground water in Nakivale [69]. Anthropogenic sources of potassium include surface runoff and use of potassium products in personal care products [112]. Comparable potassium concentrations were detected in the populous Dhanbad City in India [113] linking high potassium concentration to human activity. The source of potassium in this study can be attributed to laundry activities observed at the sites as indicated in Table 1 although geogenic contribution cannot be completely ignored.

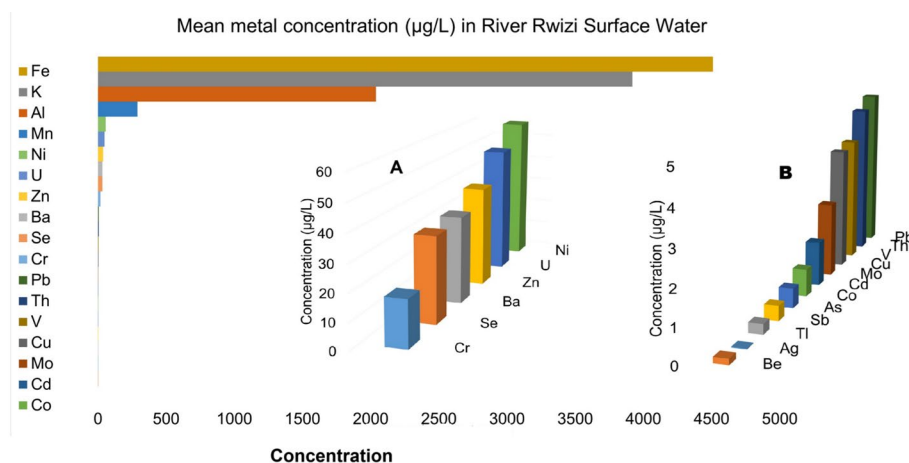
**Table 4** Concentrations of toxic metals determined in River Rwizi surface water, wastewater and WSP effluents

| Metal                                    | Th        | U         | Sb        | Se           | Fe            | Mn         | Mo        | Cr       | Zn          | Ni           | Co        | As        | Al            | Be        | K              | Ti        | V         | Pb        | Cd       | Cu          | Ag         | Ba         |
|------------------------------------------|-----------|-----------|-----------|--------------|---------------|------------|-----------|----------|-------------|--------------|-----------|-----------|---------------|-----------|----------------|-----------|-----------|-----------|----------|-------------|------------|------------|
| <b>Surface water concentrations µg/L</b> |           |           |           |              |               |            |           |          |             |              |           |           |               |           |                |           |           |           |          |             |            |            |
| Site 1                                   | 0.08      | 0.94      | 0.04      | 7.76         | 92.12         | 7.26       | 0.22      | 1.52     | 3.38        | 2.10         | 0.06      | 0.02      | 42.08         | ND        | 153.92         | ND        | 0.04      | 0.30      | ND       | 0.24        | ND         | 3.62       |
| Site 2                                   | 0.06      | 0.68      | 0.02      | 7.32         | 68.24         | 9.62       | 0.10      | 0.80     | 3.12        | 2.62         | 0.02      | 0.02      | 84.2          | ND        | 216.00         | 0.02      | 0.06      | 0.20      | ND       | 0.22        | 0.02       | 2.48       |
| Site 3                                   | 0.48      | 5.52      | 0.04      | <b>10.35</b> | 515           | 29.86      | 0.02      | 0.38     | 3.42        | 12.2         | ND        | 0.08      | 116.18        | ND        | 95.04          | 0.04      | 0.10      | 0.48      | 0.02     | 0.28        | ND         | 2.24       |
| Site 4                                   | 0.38      | 4.56      | 0.02      | 7.33         | <b>436.58</b> | 22.86      | ND        | 0.58     | 2.62        | 0.40         | ND        | 0.04      | 36.82         | ND        | 156.04         | 0.04      | 0.10      | 0.22      | ND       | 0.14        | ND         | 2.10       |
| Site 5                                   | 0.42      | 4.86      | 0.04      | 8.86         | <b>455.26</b> | 26.5       | 0.04      | 0.52     | 4.58        | 4.58         | ND        | 0.06      | 99.42         | ND        | 172.2          | 0.04      | 0.22      | 0.34      | ND       | 0.20        | ND         | 2.62       |
| Site 6                                   | 0.24      | 2.64      | 0.02      | 7.61         | <b>249.74</b> | 32.82      | ND        | 0.34     | 3.96        | 1.3          | 0.02      | 0.02      | 41.7          | ND        | 130.62         | 0.06      | 0.08      | 0.18      | ND       | 0.12        | ND         | 1.88       |
| Site 7                                   | 0.42      | 4.80      | 0.04      | 6.59         | <b>454.22</b> | 31.78      | 0.02      | 0.52     | 5.70        | <b>16.52</b> | 0.02      | 0.06      | 271.3         | ND        | 99.18          | 0.06      | 0.30      | 0.72      | 0.32     | 0.38        | ND         | 2.46       |
| Site 8                                   | 0.54      | 5.40      | 0.04      | 5.92         | <b>508.32</b> | 33.12      | 0.08      | 0.94     | 5.28        | 6.88         | 0.10      | 0.06      | <b>369.62</b> | 0.02      | 193.70         | 0.02      | 0.48      | 1.14      | ND       | 0.46        | ND         | 3.92       |
| Site 9                                   | 0.58      | 5.70      | 0.08      | 7.96         | <b>531.18</b> | 32.62      | 0.42      | 4.12     | 3.66        | 14.38        | 0.14      | 0.08      | <b>435.44</b> | 0.02      | 179.40         | 0.02      | 0.74      | 0.38      | ND       | 0.44        | ND         | 4.12       |
| Site 10                                  | 0.64      | 6.50      | 0.02      | 6.82         | <b>594.42</b> | 38.32      | 0.02      | 0.7      | 4.40        | 9.44         | 0.10      | 0.06      | <b>282.26</b> | 0.02      | 194.44         | 0.04      | 0.56      | 0.38      | ND       | 0.58        | 0.20       | 4.00       |
| Site 11                                  | 0.46      | 5.10      | 0.10      | 8.00         | <b>482.08</b> | 26.46      | 1.88      | 8.96     | 3.64        | 14.4         | 0.16      | 0.04      | <b>249.52</b> | ND        | 101.42         | 0.02      | 0.28      | 0.28      | ND       | 0.54        | ND         | 2.44       |
| Site 12                                  | 0.64      | 6.60      | 0.04      | 7.55         | <b>601.74</b> | 36.22      | 0.02      | 0.62     | 3.80        | 2.74         | 0.08      | 0.08      | 204           | 0.02      | 974.18         | 0.04      | 0.54      | 1.46      | 0.44     | 0.44        | ND         | 3.94       |
| Site 13                                  | 0.58      | 6.16      | 0.08      | 6.15         | <b>563.84</b> | 31.64      | 0.48      | 4.52     | 3.34        | 3.86         | 0.12      | 0.06      | 195.08        | 0.02      | <b>1528.98</b> | 0.02      | 0.50      | 0.30      | ND       | 0.44        | ND         | 3.32       |
| Site 14                                  | 0.44      | 4.94      | 0.04      | 5.45         | <b>461.56</b> | 26.38      | 0.02      | 0.56     | 3.30        | 2.40         | 0.02      | 0.02      | 93.44         | ND        | <b>1276.34</b> | 0.04      | 0.24      | 0.34      | ND       | 0.18        | ND         | 2.52       |
| Site 15                                  | 0.45      | 4.38      | 0.04      | 8.17         | <b>390.91</b> | 21.76      | 0.05      | 0.67     | 1.97        | 0.42         | 0.06      | 0.07      | 170.8         | 0.006     | 180.22         | 0.02      | 0.49      | 0.21      | ND       | 0.35        | ND         | 2.71       |
| Site 16                                  | 0.38      | 3.73      | 0.01      | 5.30         | <b>336.59</b> | 19.26      | 0.03      | 0.46     | 1.97        | 0.28         | 0.05      | 0.07      | 131.48        | 0.003     | 191.28         | 0.02      | 0.39      | 0.25      | ND       | 0.29        | ND         | 2.49       |
| Site 17                                  | 0.05      | 0.64      | 0.003     | 6.10         | 60.14         | 10.72      | 0.02      | 0.22     | 1.08        | 0.13         | ND        | 0.01      | 12.14         | ND        | 227.01         | 0.01      | 0.03      | 0.06      | ND       | 0.07        | ND         | 1.22       |
| Min                                      | 0.05      | 0.64      | 0.003     | 5.30         | 60.14         | 7.26       | 0.02      | 0.22     | 1.08        | 0.13         | 0.02      | 0.01      | 12.14         | 0.003     | 95.04          | 0.01      | 0.03      | 0.06      | 0.02     | 0.07        | 0.02       | 1.22       |
| Max                                      | 0.64      | 6.6       | 0.1       | <b>10.35</b> | <b>601.74</b> | 38.32      | 1.88      | 8.96     | 5.7         | <b>16.52</b> | 0.16      | 0.08      | <b>435.44</b> | 0.02      | 1528.98        | 0.06      | 0.74      | 1.46      | 0.44     | 0.58        | 0.2        | 4.12       |
| Mean                                     | 0.40      | 4.30      | 0.04      | 7.25         | <b>400.11</b> | 25.72      | 0.23      | 1.55     | 3.48        | 5.57         | 0.07      | 0.05      | 166.79        | 0.02      | 357.06         | 0.03      | 0.30      | 0.43      | 0.26     | 0.32        | 0.11       | 2.83       |
| St. dev                                  | 0.19      | 1.95      | 0.03      | 1.29         | 178.96        | 9.36       | 0.48      | 2.28     | 1.17        | 5.63         | 0.05      | 0.02      | 122.26        | 0.01      | 443.51         | 0.02      | 0.22      | 0.36      | 0.23     | 0.15        | 0.13       | 0.84       |
| <b>USL</b>                               | <b>NL</b> | <b>30</b> | <b>50</b> | <b>10</b>    | <b>300</b>    | <b>400</b> | <b>NL</b> | <b>5</b> | <b>5000</b> | <b>20</b>    | <b>NL</b> | <b>10</b> | <b>200</b>    | <b>NL</b> | <b>50,000</b>  | <b>NL</b> | <b>NL</b> | <b>10</b> | <b>3</b> | <b>1000</b> | <b>500</b> | <b>700</b> |
| <b>WHO</b>                               | <b>NL</b> | <b>30</b> | <b>20</b> | <b>10</b>    | <b>300</b>    | <b>500</b> | <b>40</b> | <b>5</b> | <b>3000</b> | <b>70</b>    | <b>NL</b> | <b>10</b> | <b>100</b>    | <b>NL</b> | <b>50,000</b>  | <b>20</b> | <b>5</b>  | <b>10</b> | <b>3</b> | <b>1300</b> | <b>100</b> | <b>700</b> |
| <b>Wastewater concentrations</b>         |           |           |           |              |               |            |           |          |             |              |           |           |               |           |                |           |           |           |          |             |            |            |
| KAKOBA INLET                             | 0.7       | 4.08      | 0.14      | 23.42        | 348.4         | 57.06      | 0.26      | 0.93     | 311.32      | 23.82        | 0.23      | 3.24      | 369.84        | ND        | 9707.59        | 0.21      | 0.76      | 20        | ND       | 216.2       | 0.05       | 6.18       |
| KAKOBA OUTLET 1                          | 0.03      | 1.02      | 0.05      | 28.28        | 66.72         | 104.58     | 0.23      | 0.45     | 8.39        | 1.49         | 0.2       | 0.11      | 50.29         | ND        | 12,900.49      | 0.14      | 0.16      | 0.24      | ND       | 1.38        | 0          | 7.1        |
| KAKOBA OUTLET 2                          | 0.05      | 1.02      | 0.08      | 22.8         | 67.26         | 71.78      | 0.21      | 0.55     | 8.56        | 1.77         | 0.17      | 0.1       | 47.93         | ND        | 12,790.18      | 0.08      | 0.18      | 0.22      | ND       | 1.12        | 0          | 5.27       |
| KUJUNGU INLET                            | 0.18      | 1.02      | 0.12      | 33.12        | 229.8         | 67.31      | 0.45      | 1.3      | 48.98       | 3.65         | 0.14      | 0.08      | 268.36        | ND        | 13,454.4       | 0.05      | 0.38      | 0.67      | ND       | 5.03        | 0.04       | 10.49      |
| KUJUNGU OUTLET 1                         | 0.03      | 1.02      | 0.06      | 18.92        | 46.43         | 76.12      | 0.17      | 0.64     | 5.87        | 3.39         | 0.18      | 0.09      | 68.32         | ND        | 15,244.31      | 0.09      | 0.12      | 0.22      | ND       | 0.77        | 0.07       | 4.07       |
| KUJUNGU OUTLET 2                         | 0.02      | 1.02      | 0.06      | 14.32        | 45.69         | 57.62      | 0.12      | 0.63     | 6.98        | 4.05         | 0.15      | 0.07      | 53.18         | ND        | 12,332.77      | 0.12      | 0.13      | 0.21      | ND       | 0.5         | 0.03       | 2.85       |
| KATETE INLET                             | 0.21      | 1.02      | 0.08      | 21.2         | 260.14        | 53.08      | 0.27      | 1.25     | 26.46       | 7.05         | 0.09      | 0.06      | 380.69        | ND        | 9760.59        | 0.08      | 0.45      | 0.67      | 0.35     | 3.41        | 0.08       | 9.01       |
| KATETE OUTLET 1                          | 0.04      | 1.02      | 0.04      | 6.39         | 55.95         | 53.56      | 0.34      | 0.67     | 10.27       | 9.55         | 0.12      | 0.04      | 66.54         | ND        | 10,880.23      | 0.03      | 0.16      | 0.26      | 0.01     | 0.83        | 0.05       | 3.14       |
| KATETE OUTLET 2                          | 0.13      | 1.02      | 0.1       | 11.17        | 116.94        | 59.83      | 0.17      | 1.4      | 11.79       | 10.58        | 0.14      | 0.1       | 401.73        | ND        | 11,084.98      | 0.12      | 0.86      | 0.64      | ND       | 0.99        | 0.1        | 4.45       |
| Inlet—wastewater inlet from sewer pipe   |           |           |           |              |               |            |           |          |             |              |           |           |               |           |                |           |           |           |          |             |            |            |

**Table 4** (continued)

| Metal                                          | Th | U     | Sb  | Se  | Fe | Mn  | Mo | Cr  | Zn | Ni  | Co  | As  | Al   | Be | K   | Tl   | V   | Pb  | Cd  | Cu | Ag  | Ba |
|------------------------------------------------|----|-------|-----|-----|----|-----|----|-----|----|-----|-----|-----|------|----|-----|------|-----|-----|-----|----|-----|----|
| Outlet 1—effluent from primary treatment tank  |    |       |     |     |    |     |    |     |    |     |     |     |      |    |     |      |     |     |     |    |     |    |
| Outlet 2 effluent from tertiary treatment tank |    |       |     |     |    |     |    |     |    |     |     |     |      |    |     |      |     |     |     |    |     |    |
| <b>%Removal efficiency</b>                     |    |       |     |     |    |     |    |     |    |     |     |     |      |    |     |      |     |     |     |    |     |    |
| KAKOBA                                         | 93 | 77    | 46  | 2.7 | 81 | -26 | 20 | 41  | 97 | 93  | 27  | 97  | 87   |    | -32 | 61   | 76  | 99  | ND  | 99 | 100 | 15 |
| KIJUNGU                                        | 88 | 78.62 | 55  | 57  | 80 | 14  | 74 | 52  | 86 | -11 | -7  | 18  | 80   |    | 8.3 | -127 | 65  | 69  | ND  | 90 | 43  | 73 |
| KATETE                                         | 39 | 53.84 | -18 | 47  | 55 | -13 | 39 | -12 | 55 | -50 | -50 | -52 | -5.5 |    | -14 | -52  | -91 | 4.5 | 100 | 71 | -35 | 51 |
| ND—Not detected                                |    |       |     |     |    |     |    |     |    |     |     |     |      |    |     |      |     |     |     |    |     |    |
| USL- Uganda standard limits                    |    |       |     |     |    |     |    |     |    |     |     |     |      |    |     |      |     |     |     |    |     |    |

**Fig. 3** Abundance of toxic metals in River Rwizi surface water. Inserts are expanded sections of main Figure from Cr to Ni (A) and Be to Pb (B)



The metal concentrations determined during the wet and dry seasons were not statistically different with  $t$  values of  $-0.67$ – $1$  less than  $t_{critical}$  of  $1.72$  at all sites. The metals concentrations in our study were lower than what was reported in groundwater in the Ugandan districts of Mbarara and Kampala [13] and in surface water in areas impacted by mining activities like Kasese and Buhweju [114, 115]. They were lower than those reported in more anthropogenic impact areas such as: spring water in Uganda's capital Kampala [23, 116]; in River Atuwara in Nigeria [117]; in the Hindukush region in Pakistan [118] and in ground mining areas in Cote d'Ivoire [119].

The cadmium and lead concentrations in this study were lower than what was reported in River Kagera in South Western Uganda [98] as well as in ground water in Anambra state in Nigeria [82]. Manganese at  $7.26$ – $38.32$  µg/L was higher than in River Kapingazi in Kenya [88]. The amounts detected were comparable to those reported for Pechora River in the Arctic Ocean basin which has low anthropogenic impact [106].

### 3.3 Source apportionment and spatial variation of toxic metals

In order to further evaluate the relationship between the metal at different sites, principal component analysis (PCA) was done. Spatial distribution studies provided information on sites most impacted. A scatter plot showing four metal concentration clusters and three site clusters is shown in Fig. 4. The clustering implies similarity in sources. Metals enter surface water from natural (geogenic) and anthropogenic input [5, 13, 47]. Lead, copper, arsenic, zinc are associated with paints and dyes [5, 13, 47] implying that their sources are anthropogenic.

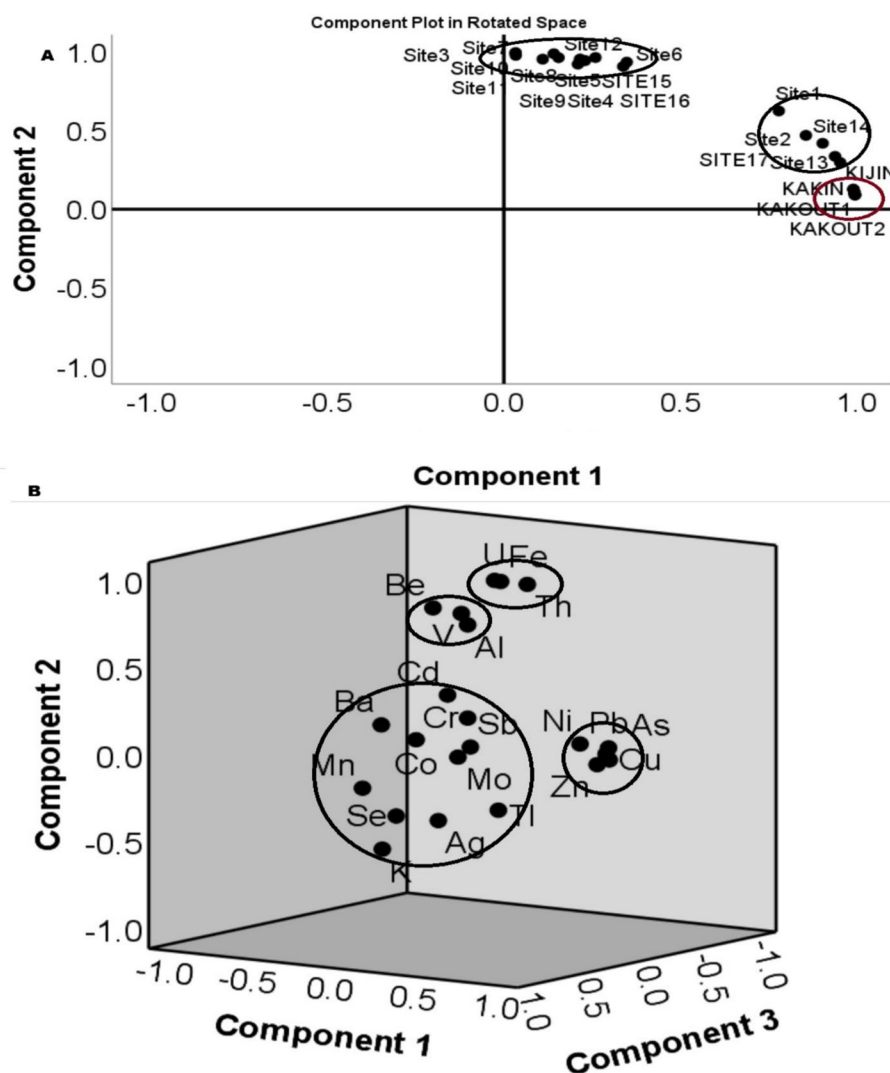
Presence of nickel is associated with disposal of Ni–Cd batteries [12] and zinc can also come from poorly disposed batteries, alloys and paints [5]. The clustering of wastewater sites (Fig. 4a) and that of metals Pb, Ni, As, Zn and Cu (Fig. 4b) is strongly indicative of common anthropogenic sources such as urban runoff (from vehicle wear, paints, and alloys) and industrial/municipal waste. Similarly, the clustering of Be, V, Al next to Fe, Ti and U (Fig. 4b) suggests a geogenic (natural weathering of bedrock) origin, as uranium and beryllium are associated with mining activities [5, 120]. The fourth cluster could imply close to equal contributions from natural and anthropogenic sources, however, further study in source apportionment is necessary to confirm these relationships.

Middle and lower reaches of the river were generally more impacted as shown in Fig. S1 (supplementary data). Sites 8–12 located in Mbarara City, were strongly impacted with toxic metals of anthropogenic origin including Fe, Mn, Mo, Cr, Zn, Ni, Co, Al, Cd and Cu, which were likely carried downstream, impacting sites in the lower reaches of the River Rwizi. Site 3 (in the upper reaches) was impacted by silver as shown in Fig. S1. Silver is associated with mining activities [36, 121], therefore its source is geogenic.

### 3.4 Heavy metal pollution index (HMPI) contamination degree (CD) and hazard index (HI)

The potential human health risk of consumption of river Rwizi water was assessed using the heavy metal pollution index (HMPI), contamination degree ( $C_D$ ) and hazard index (HI). The mean concentrations of toxic metals determined were

**Fig. 4** A PCA scatter plots based on sites (A) and metal concentrations (B)



used to calculate the HMPI. The value of HMPI ranged from 5.3 to 140.7 for surface water as shown in Table 5. This HMPI was lower than that obtained for more polluted surface water from the ground mining areas in Cote d'Ivoire [119]; the industrial region of Gazpur in Bangladesh [43] and the semi-arid region of Daraa in Morocco [78]. Sites 3, 7, 8, 10, 11 and 12 had a high HMPI which can be attributed to the anthropogenic activities. The highest HMPI of 140.7 was at Nyeihanga trading centre (site 7). This high pollution is attributed to anthropogenic activities such as washing of vehicles, cattle grazing and sand abstraction observed at the site. Wastewater had very high values of HMPI (475.1–1668.4). The high HMPI suggests severe environmental pollution which may pose health and environmental risk especially in the urban areas.

The contamination degree ranged from – 12.0 to 18.5. Contamination was less than what was reported for surface water in the industrial Gazipur of Bangladesh [43]; ground water in Nalagarh, India [47] and in the semi-arid region of Daraa in Morocco [78]. The highest values were at site 8 (18.5) > site 11 (16.8) > Site 9 (16.2) > site 13 (10.7). These sites locations are in residential urban areas with high traffic as described in Table 1. Therefore, that contamination can be attributed to anthropogenic activity.

The HI for children was 0.084–0.804 while that for adults was 0.036–0.379. This HI was comparable to water from the unimpacted Pechora River in the Arctic Ocean basin [106]. The HI in our study was lower than that of spring water from Kampala, Uganda's capital [116]; River Atuwara in Anambra state in Nigeria [82, 117] and from ground mining areas in Cote d'Ivoire [119] which experience more anthropogenic pollution.

Most of the sites had HI < 1 implying low risk [81], however sites 7, 8, 9, 10 and 12 had high contamination degrees implying that the water was contaminated. The chronic exposure HI ranged from 0.008 to 0.069 for children and

**Table 5** Evaluation of potential human health risk using heavy metal pollution; metal contamination; hazard and chronic hazard indices

| Site number | Heavy Metal pollution index (HMPI) | Metal contamination index ( $C_D$ ) | Hazard Index (HI) Children | Hazard Index (HI) Adults | Chronic Hazard Index (HI) Children | Chronic Hazard Index (HI) Adults |
|-------------|------------------------------------|-------------------------------------|----------------------------|--------------------------|------------------------------------|----------------------------------|
| Site 1      | 19.500                             | −8.400                              | 0.099                      | 0.047                    | 0.009                              | 0.020                            |
| Site 2      | 18.300                             | −6.800                              | 0.084                      | 0.036                    | 0.008                              | 0.016                            |
| Site 3      | <b>82.700</b>                      | <b>6.810</b>                        | 0.518                      | 0.244                    | 0.045                              | <b>0.105</b>                     |
| Site 4      | 31.800                             | −0.200                              | 0.438                      | 0.207                    | 0.038                              | 0.089                            |
| Site 5      | 50.700                             | 1.900                               | 0.460                      | 0.217                    | 0.040                              | <b>0.093</b>                     |
| Site 6      | 23.400                             | −6.300                              | 0.253                      | 0.120                    | 0.022                              | 0.052                            |
| Site 7      | <b>140.700</b>                     | <b>16.000</b>                       | 0.467                      | 0.220                    | 0.040                              | <b>0.095</b>                     |
| Site 8      | <b>79.200</b>                      | <b>18.500</b>                       | 0.518                      | 0.245                    | 0.045                              | <b>0.105</b>                     |
| Site 9      | 31.100                             | 2.800                               | 0.552                      | 0.260                    | 0.048                              | <b>0.112</b>                     |
| Site 10     | <b>80.000</b>                      | <b>16.200</b>                       | <b>0.608</b>               | 0.287                    | 0.053                              | <b>0.123</b>                     |
| Site 11     | <b>93.700</b>                      | <b>16.800</b>                       | 0.505                      | 0.238                    | 0.044                              | <b>0.102</b>                     |
| Site 12     | <b>131.900</b>                     | <b>10.700</b>                       | <b>0.804</b>               | 0.379                    | <b>0.069</b>                       | <b>0.163</b>                     |
| Site 13     | <b>62.200</b>                      | <b>9.400</b>                        | <b>0.470</b>               | <b>0.222</b>             | <b>0.041</b>                       | <b>0.095</b>                     |
| Site 14     | <b>44.300</b>                      | <b>0.760</b>                        | <b>0.459</b>               | <b>0.217</b>             | <b>0.040</b>                       | <b>0.093</b>                     |
| Site 15     | <b>35.900</b>                      | <b>2.300</b>                        | <b>0.783</b>               | <b>0.369</b>             | <b>0.068</b>                       | <b>0.159</b>                     |
| Site 16     | <b>29.400</b>                      | <b>−0.800</b>                       | <b>0.673</b>               | <b>0.318</b>             | <b>0.058</b>                       | <b>0.138</b>                     |
| Site 17     | <b>5.300</b>                       | <b>−12.000</b>                      | <b>0.124</b>               | <b>0.059</b>             | <b>0.011</b>                       | 0.025                            |
| KAKOBA WSP  | <b>225.900</b>                     | <b>15.950</b>                       | <b>ND</b>                  | <b>ND</b>                | <b>ND</b>                          | ND                               |
| KATETE WSP  | <b>191.500</b>                     | <b>28.200</b>                       | <b>ND</b>                  | <b>ND</b>                | <b>ND</b>                          | ND                               |
| KIJUNGU WSP | <b>160.000</b>                     | <b>8.700</b>                        | <b>ND</b>                  | <b>ND</b>                | <b>ND</b>                          | ND                               |

HMPI < 100 (low pollution), HMPI = 100 (critical threshold), HMPI > 100 (high pollution)

Low degree contamination ( $C_D < 1$ ), medium degree of contamination ( $C_D$  1–3) and high degree of contamination ( $C_D > 3$ )

HI < 1 minimal or no risk of adverse effects, HI > 1 significant negative health impacts. For chronic exposure, HI < 0.1 negligible risk, HI ≥ 0.1 < 1 low risk, HI ≥ 1 < 4 medium risk and HI ≥ 4 high risk

ND–Not determined

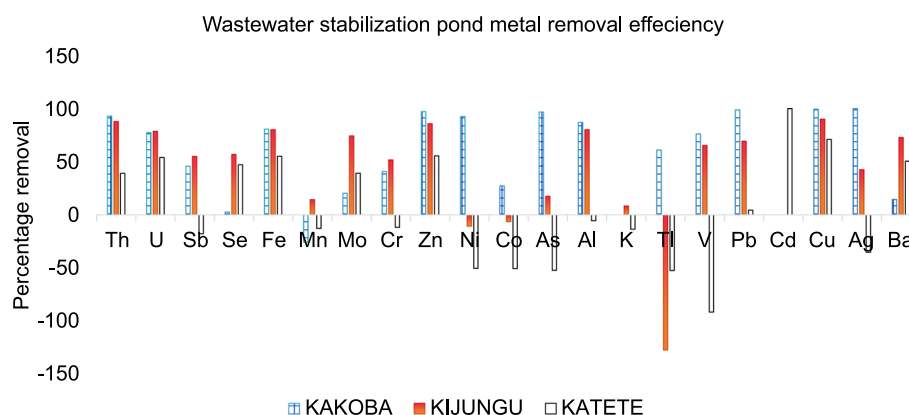
0.016–0.163 for adults (Table 5). While the water may pose low risk to human health ( $H < 1$ ), it exceeded the negligible threshold of  $HI \leq 0.1$  for chronic exposure risk in adults. An HI value above 0.1 indicate a potential for adverse non-carcinogenic health effects upon chronic exposure [81]. An HI > 0.1 as determined in this study, implies possibility of adverse health effects on chronic exposure therefore the consumption of untreated water sourced from River Rwizi is risky. Furthermore, toxic metals in surface water can accumulate in biota or end up in the food chain eventually harming human and animal life.

### 3.5 Metal removal efficiency by wastewater stabilization ponds (WSP)

In wastewater the most prominent toxic metals were  $K > Al > Fe > Zn > Cu > Mn > Ni > Se > Pb$ . This is comparable to findings in Peru [122, 123]. The calculated metal removal efficiency ranged from −91.53 to 100% as shown in Fig. 5. The performance of the WSP was comparable to what was reported in Turkey in regard to Cr, Pb and Mn removal [123] and but WSP in Iran performed better for removal of Pb and Cd [124]. Negative value removal efficiencies in wastewater treatment have been previously reported for pharmaceuticals [125] and zinc [126]. Negative removal can be attributed to repartitioning of the pollutants desorbed from the sludge [41, 127, 128]. In the case of Mbarara city WSPs, the most efficient WSP was Kakoba with an average removal efficiency of 57.73%, followed by Kijungu with 44.3%. Katete WSP had the lowest removal efficiency averaging at 5.87%.

The removal efficiency of lead and cadmium for Kakoba WSP was comparable to literature [123, 124] but Kijungu and Katete performed poorly. The performance of WSP depends on the wastewater characteristics, design, hydraulic retention time (HRT) and environmental factors [41, 84, 123, 128, 129]. The observed sludge accumulation reduces the

**Fig. 5** Removal of toxic metals by wastewater stabilization ponds in Mbarara City



designed hydraulic retention time (HRT), short-circuiting the treatment process. This allows metal loaded effluent to exit the ponds before adequate remediation can occur.

Since the designs of the WSPs in Mbarara City are similar, the poor performance of Kijungu and Katete WSP were due to local factors such as overload/overflow, poor maintenance, sludge accumulation and surface runoff resulting into poor removal efficiency compared to the removal efficiencies in well run facilities [41, 84]. The accumulated sludge due to less frequent dredging usually lowers the HRT, which leads to poor efficiency of the WSP [130], this may have contributed to the poor performance of WSPs at Katete and Kijungu where sludge accumulation was evident at the WSP. Based on this limited metal removal efficiency, wastewater is likely to contaminate the nearby river Rwizi surface water.

### 3.6 Environmental implications of presence of toxic metals in River Rwizi water and pollution management

The presence of toxic metals in River Rwizi surface water poses significant risk to ecological and human health within its catchment spanning over 12 districts in South-Western Uganda. There is a potential human health risk resulting from consumption of contaminated water and direct contact. Toxic metals interfere with antioxidant defence mechanisms, signalling pathways and affect several cellular processes, such as cell growth, proliferation, survival, metabolism, and apoptosis [131]. Chronic exposure to metals is associated with organ damage, neurodegenerative diseases, circulatory diseases and endocrine disruption [132–134]. The reliance on the River Rwizi for water for domestic use risk human health and may result in chronic diseases like neurological disorders and kidney failure through direct ingestion. The intermittent nature of piped supplies may aggravate the risk.

Exposure of aquatic life toxic metals results in their accumulation in tissues and organs like gills, liver kidneys and bones. Trophic transmission in food chains is a public health risk but also threatens food security [135–137]. Their presence in River Rwizi water therefore threatens ecosystem and human health in its catchment. Furthermore, if this contaminated water is used for irrigation, toxic elements accumulate in soil. Here they change the soil chemistry which in turn degrades soil fertility and affects the fungal and bacterial ecosystem leading to more soil erosion [138]. The toxic metals can be absorbed by food crops, entering the human food chain [139] and compromising local food security.

The inefficiency of WSPs in toxic metal removal exacerbates the risk. The WSP inadequacy leads to discharge of contaminated water in the environment which not only introduces toxic metals but can introduce untreated sewage in the water resulting in eutrophication which further degrades the water quality. The failure of the WSPs also highlights a critical gap in infrastructure, which must be addressed to protect public safety and prevent ongoing systemic environmental degradation.

Effective management of pollution of River Rwizi requires preventing water contamination and effective treatment of wastewater generated from anthropogenic sources. Therefore, upgrade and optimization of infrastructure is urgently required. Concurrently, Mbarara City must prioritize expanding the sewage collection network to ensure that wastewater currently entering the river through surface runoff is contained and routed for treatment, thus stabilizing the engineered barrier against pollution.

To ensure long-term environmental protection, management efforts must focus on implementing policy regulations on management of wastewater treatment plants, industrial discharge regulations, and agricultural runoff management.

For example, major dischargers should implement a robust industrial pre-treatment program that mandates them to treat their wastewater before discharge.

## 4 Limitations of the study and future direction

The findings of this study describe the toxic metal concentrations on the basis of a single point in time and space as grab samples were used [140]. In future, a continuous sampling strategy such as passive sampling could be employed to show a weighted time average concentration moreover, a geological map could be used contribute to understanding the contribution of toxic from the bedrock. Assessment of health risk using hazard indices alone may not give a true picture of risk because  $HI < 0.1$  may not describe non carcinogenic risk. Furthermore synergistic or potentiation effects due to presence of a mixture of chemical may not be adequately explained [141]. Therefore, exposure studies can be done to assess the biochemical changes associated with toxic metal for example at the metabolome level. This can contribute to understanding the risk posed by a mixture of toxic metals in the concentration ranges indicated in this study. More work can be done on sediment and aquatic life to fully understand the metal distribution in aquatic ecosystem. Further studies about source apportionment are necessary to establish definitive causal links.

## 5 Conclusions and recommendations

The findings from this study indicated presence of toxic metals of significant environmental implications for ecological health and human safety. Iron, selenium and aluminium were detected in surface water of the River Rwizi at concentrations higher than the World Health Organisation drinking water standards. Sites 3, 7, 8, 10, 11 and 12 which are in urban and residential areas were the most polluted as shown by the high HMPI and contamination degrees. While the HI was  $< 1$ , it was higher than the threshold of 0.1 for adults. There is a need for urgent and comprehensive management strategies.

Anthropogenic pollution can be reduced through appropriate waste management and educational programs in Mbarara City and surrounding areas. This can contribute to potential risk mitigation associated with presence of these metals in River Rwizi water and downstream in protected and Ramsar sites of Lake Mburo National Park. In order to reduce the human risk care must be taken during drinking water treatment to remove these metals.

Based on the limited toxic metal removal by the WSP, there is a need for adequate wastewater management in Mbarara City. A state of the art wastewater treatment facility is required to manage increasing wastewater generated by the increasing population. Finally, a sustainable strategy requires a long-term water quality monitoring network to track metal concentrations and WSP performance over time, coupled with clear public awareness campaigns to inform communities about the health risks of using untreated river water and promoting interim point-of-use treatment methods.

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**Data availability** All data is included in this manuscript and supplementary files uploaded.

## Declarations

**Ethics approval and consent to participate** Not applicable. All authors have read, understood, and have complied as applicable with the statement on ethical responsibilities of authors.

**Consent to participate** Not applicable.

**Competing interests** The authors declare no competing interests.

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