Assessment of Levels, Speciation, and Toxicity of Trace Metal Contaminants in Selected Shallow Groundwater Sources, Surface Runoff, Wastewater, and Surface Water from Designated Streams in Lake Victoria Basin, Uganda

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The levels, speciation of elements, and toxicity of selected trace metals as well as other parameters in selected surface water, shallow groundwater sources, landfill leachate, and associated surface runoff in the Lake Victoria basin, Uganda, were studied. The WHO guidelines, Ugandan standards, Canadian guidelines and Swedish EPA were used for assessment. The shallow groundwater was acidic with pH values below 6.5. The pH, dissolved organic carbon, fluoride, and sulphate levels for all springs were below the guideline values although 52.8% was contaminated with nitrates while 39% was contaminated with chloride ions. Some surface water samples had levels of major elements, such as iron, chromium, aluminium, and manganese, above the guideline values. Speciation studies showed that 74% of the metal ions was bound to dissolved organic matter in surface water, whereas in landfill leachates, the dominant ionic species was metal hydroxides or fulvic acid bound. Risk analysis based on the Swedish EPA showed varied risks of negative effects in 30%–76% of the sample sites ranging from high to increased risk in surface water, whereas the results from modelling sorption data using the Bio-met tool showed potential risk to toxicity effects of Cu2+, Ni2+, Zn2+, and Pb2+ in 15.3%–30.8% surface water samples and 8.3%–62.5% groundwater samples.

1. Introduction

The presence of heavy metals and other pollutants in the aquatic systems has become a serious problem for environmental scientists in many developing countries and also for agencies engaged in environmental production [1]. Freshwater resources constitute only about 2.5% of the total volume of water on Earth (~1.4 million km³), and only about 0.01% (200,000 km³) of all the water on Earth is usable freshwater for ecosystems and humans [2]. While the freshwater volume remains generally constant, the population using the water continues to rise, stressing this supply more critically each year [3]. Freshwater is therefore a meagre resource whose quality is very difficult and costly to reverse to pristine and usable condition when it deteriorates [4]. Uganda is a developing country that is home to the source of the River Nile which is the longest river in the world that moves 6,850 km to the Mediterranean Sea from Lake Victoria. Lake Victoria is the second largest freshwater lake in the world with a surface area of 68,800 km² and a volume of 2,760 km³ [5]. The Nile river basin covers almost 10% of the total area of the African continent with an area of 3,100 km² [6]. There are eleven countries that make up the Nile River drainage basin, namely, Rwanda, Burundi, Democratic Republic of Congo, Uganda, South Sudan, Sudan, Kenya, Tanzania, Ethiopia, Eritrea, and Egypt. Some of those riparian countries only have a small part of their area within the basin while others are located virtually entirely within the basin [5]. Nile River drainage basin serves the domestic, industrial, and agricultural needs over
150 million people. The Lake Victoria basin, Uganda, forms a bigger part of the upper Nile basin that covers much of Uganda where it serves over 36 million people. There are socioeconomic as well as industrial activities of the urbanizing region with consequential unprecedented anthropogenic contamination of the basin’s surface water system which may eventually irreversibly impact the shallow aquifers. The extent of anthropogenic environmental pollution in the developing world is well documented [7]. Geologically, Uganda is dominated by crystalline rocks which are covered by regolith, a layer of the weathered material that varies from rock fragments to well-weathered soil and hardened laterite at the ground surface [8]. The British Geological Survey [8] reported that groundwater is abstracted from both the fractured bedrocks and the weathered regolith. According to Taylor and Howard [9], the regolith aquifer is a reusable resource due to its promising yields and lower cost of development than the deeper groundwater from the basement. However, the commonest groundwater sources in Kampala abstract water from shallow aquifers through protected and unprotected springs. Spring waters are the least mineralised with compositions approaching those of the surface waters [10] which indicate that groundwater in shallow aquifers discharges fast with minimum chemical interactions with aquifer minerals. The shallow aquifers are prone to contamination from anthropogenic sources due to unorthodox handling and management practices for domestic, municipal, and industrial wastes and wastewater. For instance, the unlined landfills for the urban wastes are located in wetlands and pollute the aqueous environment with noxious gases and leachate. Muwanga and Balifaijo [11] revealed that industrial effluents were one of the main sources of pollution in the Lake Victoria basin, Uganda. Kulabako et al. [12] indicated that the quality of the shallow groundwater in periurban areas is a potentially major environmental health problem, and Howard et al. [13] observed that the consumption of contaminated drinking water in the densely populated periurban areas is one of the most significant causes of ill-health. Relatively little data are available on the extent of environmental pollution because there are no agencies charged with the routine monitoring and protection of the environment [14]. Therefore, the assessment of levels and speciation of toxic trace metal contaminants in shallow groundwater, surface runoff, and surface water from selected waterways would reveal the state of environmental health of the shallow aquifers associated with them.

Trace metals are always present in trace amounts in fresh waters from terrigenous sources such as weathering of rocks resulting in geochemical recycling of heavy metal elements in these ecosystems [15, 16], but Sekabira et al. [17] observed that heavy metal pollution of aquatic ecosystems is becoming a potential global problem. Inadequate waste handling and management systems as well as the release of untreated dumpsite leachate and industrial effluent to the environment have significantly contaminated wetlands, surface water, and groundwater which affect the proper functioning of the aquatic ecosystems and endanger aquatic life especially when the pH is low. Studies on an urban open drain Nakivubo Channel have indicated high concentration of toxic trace metals in water and the soils in the near-stream zone that are flooded with contaminated water [18, 19]. Moulodi and Thorsell [20] observed that infiltration is however taking place by localized recharge of different types of wastewater in the periurban areas, which has a clear negative impact on the quality of water resources. The contamination of land and surface water ecosystems with trace metals will continuously threaten the aquifers and shallow groundwater resources for a long time. The environmental health effects of trace metal contaminants are manifested after chronic exposure to low levels or acute exposure to high doses of trace metals. Trace metals are grouped into essential and nonessential trace metals depending on their biological importance. The essential trace metals are those that have known biological roles in living organisms, whereas the nonessential trace metals interfere with the uptake of the essential ones and have known toxicity to life processes. Trace metals such as cadmium, mercury, lead, copper, and zinc are regarded as serious pollutants of aquatic ecosystems due to their environmental persistence, toxicity, and ability to be incorporated into food chains [21]. Essential trace metals such as zinc show toxicity effects when ingested in excess of the optimal levels or in insufficient amounts to bodily needs, whereas nonessential trace metals such as lead and cadmium express toxicity effects when taken in above the tolerable levels.

The major anthropogenic sources of trace metals are combustion of fossil fuels, sewage sludge, and waste dumpsite leachates as well as the wearing of car tyres, brake pads, bearings, radiators [22], mining, smelting, and processing industries. The high concentrations of trace metals are attributed to wastes and industrial effluent deposited in the environment which may result from wearing of machines, smith workshop waste, motor service centres, surface runoff, and industrial chemicals. The main recipient of these metals is the soil, and their fate depends on the chemical and physical properties of the metal or its compounds, soil type, and its organic matter content. Adsorption onto soil particles and soil organic matter causes retention of trace metals and reduces their transmission to the soil water, but when the soil is overladen or when the soil pH is lowered, trace metals’ vertical mobility increases and contamination of groundwater occurs through the soil solution. Consequently, the trace metal contaminants may show toxicity effects on fauna since the flora are more tolerant to high levels of trace metals.

The aim of this study was to assess the levels of major and trace elements and establish the speciation of selected trace elements in the aqueous environment of selected shallow groundwater, surface runoff, surface water, landfill leachate, and wastewater in several subcatchment areas in Lake Victoria basin, Uganda. The other objective of the study was to risk assessment for selected trace elements in designated surface water and shallow groundwater sources to inform policy and action on remediation and protection of environmental health. The speciation of trace elements in the aqueous environment will show the distribution of the
different metal species amongst metal ions bound to organic species, free metal ions, and inorganic metal ions which would have different effects on environmental mobility, distribution, and life support systems.

2. Materials and Methods

2.1. Study Area and Sampling Sites. The study area is the Lake Victoria basin, Uganda, with sampling points on streams (Figure 1) and protected springs (Figure 2). Some of the coordinates of the sampling points mapped in Figures 1 and 2 are shown in Table 1. The streams, protected springs, and landfill leachate that were sampled and studied are within in the catchment areas associated with Lake Victoria basin and are located in Kampala Capital City (Figure 2) which is the country’s most industrialized business district. The choice of the sampling points in the study area was based on the resident population density and anthropogenic activities in the area, dependence of the population on the shallow groundwater, and surface water sources as well as logistics and time limitations.

2.2. Water Sampling. The shallow groundwater from protected springs was drawn as it discharged from shallow aquifers. The sampling of shallow groundwater was done four times, once each year from March 2012 to February 2015. Surface runoff that flowed and settled in the catchment areas associated with the protected springs was trapped in shallow patches from which grab samples were picked thirty minutes after the onset of heavy downpours of the wet season, from September to October 2013. Three grab samples were picked and homogenised before a representative sample was taken for analysis. The surface runoff was sampled because there is a risk of intrusion to the shallow aquifers since during wet seasons the water table rises and increases probabilities of surface water and shallow groundwater mixing. The surface runoff assessment is therefore a basic and meaningful part of hydrological studies. The surface water samples from urban and rural waterways as well as leachate samples from unlined landfills were picked at points 1 m from the peripheral at depths within 0.5 m of the surface. The water samples were collected from the sample sites in 500 mL plastic bottles that had been prewashed thrice using sample water prior to collection. Water samples were filtered through 0.45 \( \mu \)m nonpyrogenic syringe filters and stored in 30 mL polypropylene vials. The pH, temperature, and electrical conductivity were measured at the point of collection of samples. The samples were placed in cooler boxes and transferred to the analytical laboratory.

For streams, the sampling was done twice in June 2014 and February 2015. The plastic bottles used for collection of water samples were cleaned and rinsed twice with the water to be sampled before use. Field measurements of pH, temperature, and electrical conductivity (EC) were measured using a pH Ion meter. The water samples for determination of DOC were filtered into sample bottles using 0.45 \( \mu \)m filters and cooled before being transferred to the laboratory. The water samples were subsampled twice; one sample was filtered and cooled, while the sample for trace metals analysis was filtered and acidified with concentrated nitric acid before being transferred to the analytical laboratory at room temperature (25°C).

2.3. Metals, Anions, and DOC Analyses. The acidified water samples were subsequently analysed for trace and major elements using an inductively coupled plasma-mass spectrometer (ICP-MS) (2007, Model: PerkinElmer Elan 9000) with an instrument limit of detection of 0.002 ppm for cadmium and 0.009 ppm for lead, whereas the samples for DOC and anions analysis were evaluated using the Shimadzu TOC-5000 without acidification. The leachate samples were digested using the wet acid digestion procedure. Pretreatment of 50 mL of leachate was done with 2 mL nitric acid, and 5 drops of 30% hydrogen peroxide were added in a closed bottle and placed in a constant temperature water
bath at 60°C for 1 hour. The clear supernatant was filtered through 0.45 µm filters into plastic sample bottles and analysed for cations, whereas the samples for DOC and anions analysis were only filtered before analysis. The analyses were done over a period of three years, and mean values of the measurements have been reported. The major anions Cl\(^-\), NO\(_3\)\(^-\), and SO\(_4\)\(^{2-}\) were analysed at KTH, Stockholm, using a Dionex DX-120 ion chromatograph.

### 2.4. Speciation and Toxicity Studies.

The chemical species distribution in organic and inorganic phases would impact on the sorption process since the metal ions in the free ionic state and inorganic state would be available for sorption onto biosorbents and would also be important for toxicity studies. The speciation of selected trace metals was performed with Visual MINTEQ 3.1, and risk assessment of trace metals to aquatic fauna was done by comparison with the Swedish environmental guidelines for selected shallow groundwater and surface water samples. Pb\(^{2+}\) and Cd\(^{2+}\) ions speciation in selected contaminated surface water and leachate at various conditions of DOC and pH was performed with Visual MINTEQ 3.1 which was originally coded by the U.S. Environmental Protection Agency (EPA) and has been further developed by Gustafsson [23, 24]. For the speciation studies of the metal ions in selected surface water, the Stockholm Humic Model (SHM) was used. The assumption used by the US EPA in setting the Water Quality Criteria in which all DOC in natural waters was considered to be active and organic matter consisted of 90% fulvic acid and 10% humic acid was adopted in these studies. Toxicity studies were done by assessing the environmental risks due to trace elements through modelling using the Bio-met software tool. The Bio-met software tool version 4 is based on calculations from Biotic Ligand Models (BLM) to estimate the potential risk to the aquatic environment posed by copper, nickel, zinc, and lead after considering bioavailability. The basis of biotic ligand modelling is that metal accumulation at the "biotic ligand" is proportional to toxicity and that this accumulation can be predicted by solving the appropriate simultaneous equilibria among the biotic ligand(s) and the dissolved components (aqueous ligands and competing cations) in the exposure water [25]. Data analysis for environmental risks due to trace metals was done using the Swedish environmental protection agency criteria and the bioavailability-based approach through simulations using the biotic ligand model and the Bio-met software tool.

In Figure 3, a modified schematic diagram of the biotic ligand model (BLM) has been presented that explains the assumptions and interactions between the inorganic, organic, and biotic ligands in the aqueous media. These

| Sample site | Latitude (N) | Longitude (E) |
|-------------|--------------|---------------|
| Units       |   ' (degrees) |   ' (minutes) |   ' (seconds) |   ' (degrees) |   ' (minutes) |   ' (seconds) |
| Katarina    |            00 |            20 |             58 |            32 |             37 |             48 |
| Nabuze      |            00 |            20 |             38 |            32 |             38 |             28 |
| Buwooya     |            00 |            21 |             30 |            32 |             38 |             0  |
| Bukoto 1    |            00 |            21 |             29 |            32 |             36 |             0  |
| Bukoto 2    |            00 |            21 |             10 |            32 |             35 |             3  |
| Nabukalu    |            00 |            21 |             30 |            32 |             33 |             4  |
| Abdu        |            00 |            21 |             0  |            32 |             33 |             0  |
| SP4306K     |            00 |            20 |             5  |            32 |             33 |             0  |
| Kikoni      |            00 |            19 |             53 |            32 |             33 |             3  |
| SP11414R    |            00 |            20 |             44 |            32 |             32 |             0  |
| Sentamu     |            00 |            20 |             40 |            32 |             32 |             0  |
| Kunnya      |            00 |            20 |             10 |            32 |             32 |             0  |
| SP5003C     |            00 |            19 |             26 |            32 |             34 |             3  |
| SP1212R     |            00 |            20 |             0  |            32 |             32 |             0  |
| Kibumbiro   |            00 |            19 |             10 |            32 |             31 |             2  |
| Kabaale     |            00 |            18 |             40 |            32 |             31 |             0  |
| Nababirye   |            00 |            19 |             36 |            32 |             32 |             10 |
| SP11010R    |            00 |            20 |             37 |            32 |             33 |             24 |
| Kapeke      |            00 |            17 |             47 |            32 |             34 |             5  |
| Yusuf       |            00 |            18 |             10 |            32 |             34 |             5  |
| Kasanvu     |            00 |            18 |             25 |            32 |             36 |             45 |
| Nsambya     |            00 |            18 |             29 |            32 |             36 |             45 |
| Nabagereka  |            00 |            18 |             40 |            32 |             34 |             9  |
| Barracks    |            00 |            19 |             11 |            32 |             34 |             10 |
| Lubigi      |            00 |            21 |             01 |            32 |             33 |             56 |
| Mulago      |            00 |            20 |             44 |            32 |             34 |             11 |
| Nakivubo    |            00 |            18 |             56 |            32 |             35 |             43 |
| Lugogo      |            00 |            19 |             19 |            32 |             36 |             34 |
| Bugoloobi   |            00 |            19 |             07 |            32 |             37 |             0  |
| Kiteezi     |            00 |            24 |             49 |            32 |             34 |             37 |
interactions are shown in Figure 3 with the free metal ion, $M^{2+}$, and naturally occurring competitive cations, $Na^+$, $H^+$, $Mg^{2+}$, and $Ca^{2+}$, and abiotic ligands by DOC, $CO_3^{2-}$, $HCO_3^-$, $OH^-$, and $Cl^-$, whereas the site toxic action is represented by the biotic ligand or test organism under study. According to the conceptual framework of the BLM, the accumulation of the metal ions at the biotic ligand or greater than a critical threshold concentration of metal ions onto the biotic ligand leads to toxicity effects. BLMs allow chemical and biological interactions to be taken into account and relate, through water chemistry, metal toxicity to a dissolved concentration which can be used in the compliance assessment [27].

3. Results and Discussion

The levels of major elements in shallow groundwater, surface runoff, landfill leachate, wastewater, and surface water were analysed and studied with the guidance of WHO guideline values, Ugandan standards, and the Swedish Environmental Protection Agency guideline values [28–30]. According to the WHO guidelines, the results for selected protected springs in Kampala which are shown in Tables 2 and 3 indicate that 58% of the sampled protected springs are contaminated with Fe which exceeds 0.3 mg/l in the range 0.34–1.86 mg/l. This exceedance of the guideline value can be attributed to weathering, and a clear testimony is observed with surface water in the corresponding wetlands having a rusty flimsy layer in slow and stagnant waters. The results for Fe are in agreement with the report by BGS [8] where it was stated that iron was one of the main inorganic groundwater quality problems. Iron is mainly transported in groundwater in the reduced form as $Fe^{2+}$. Therefore, the main source of Fe contamination appears to be background levels in the soils where acidic and redox conditions enhance release of Fe and Mn into soil water. There were only 4% of the springs that had Cr levels above the 0.05 mg/l level.

The protected springs with the elevated Cr levels are located in Nakawa division, and their contamination may be attributed to the existence of paint manufacturing industries in the spring catchment zone. However, 8% of the samples had high levels of Al (0.299–0.360 mg/l) exceeding the 0.2 mg/l level. The contamination of the environment with aluminium may be due to anthropogenic activities besides wear and tear of motor parts since the contaminated sampling points were located in a built environment with paved roads but near a car parking lot. On the contrary, the soils in Kampala were reported to be acidic by Moulodi and Thorsell [20], whereas under acidic conditions, the natural sources of metals may contribute to high levels of aluminium since it is mobilised and solubilized from bedrock and soil into soil water at pH $<5.5$. The springs that had levels of K above the guideline value, 10 mg/l, were 33% and had values between 15 and 17 mg/l, whereas 29% had Mn levels above the 0.4 mg/l mark with values ranging between 0.58 and 1.20 mg/l. The BGS [8] report indicates that high concentrations of manganese are a common problem in Ugandan groundwater. The high iron and manganese occurrences have been attributed to the shallow clayey regolith that restrict aeration of underlying aquifers leading to anaerobic conditions to which the high iron and manganese are related [8]. These results for iron and manganese concur with other studies in Uganda by GIBB [31] where iron levels were reported as 0.3–4.9 mg/l; moreover, Taylor and Howard [32] reported iron concentrations up to 45 mg/l and the Mn levels up to 2 mg/l. The water samples that had Ca levels below the required levels for drinking water (20 mg/l) were 95.5%, and with the low pH, it may be a health risk. According to the Ugandan standards, the levels of contamination of the groundwater samples were 20% for Al, 4.2% for Cr, 66.7% for Mn, and 58.3% for Fe, whereas the other major elements were within the Ugandan urban drinking water standards.

Tables 4 and 5 show levels of trace elements in protected springs and percentage springs with levels above and below the guideline values, respectively. For the case of Ugandan standards, all the elements were below the guidelines, whereas for the WHO guideline values, 8.3% of the protected springs had barium levels above the guideline value, and all the other elements were below the guideline values. For Canadian guideline values, 8.3% of the springs had antimony levels above the guideline value. The contaminated protected springs were located on the peripheral of a busy urban market, car washing bay, and motorcycle service workshop which were suspected to be the sources of contamination.

The protected springs that had elevated levels of trace elements were characterised by nearness to motorways and residential areas where wearing of car parts, surface runoff, and domestic wastewater are assumed to impact the metal levels. The mobility of trace metals increases under acidic conditions with high dissolved organic matter content, but contamination of the acidic shallow groundwater was not alarming due to low dissolved organic matter content. The
sampled shallow groundwater from Kampala had elevated levels of trace metals and was not contaminated; nevertheless, groundwater quality monitoring will ensure adherence to the WHO guidelines to inhibit water contamination and imminent trace metal poisoning.

Tables 6 and 7 show the other parameters of water that were studied. The temperature of the water varied but was within the guideline value 25°C; moreover, the pH values were all below the guideline values range of 6.5–8.5. The shallow groundwater is therefore generally acidic with pH < 7.0, whereas acidic water increases the weathering of rocks and release of metals from soil surfaces into soil water.

Acidic water is aggressive to surfaces and has a high capacity to corrode ferrous materials which explain why surface water in the catchment areas exhibits a flimsy rusty layer. On the contrary, Olade [14] stated that groundwater tapped from weathered regolith is acidic which may promote oxidation and corrosion of steel casings and screens. The DOC levels were all below the contamination level (2.0 mg/l). Mobility of trace metals is known to be dependent on the dissolved organic matter content and pH although re-distribution of trace metals in groundwater may be affected by other factors such as redox conditions.

The electrical conductivity (EC) values were high and exceeded the guideline value of 1000 μS/cm in almost 13.5% of the shallow groundwater case studies and 21.6% of the surface runoff samples studied which indicated that inorganic species occurred mainly in the ionic form especially in the high population density periurban areas where those particular protected springs were located. Only 5.4% of the
Table 4: Levels of trace elements (µg/L) in water from selected protected springs in Kampala city in comparison to WHO guideline values [30, 33, 34].

| Sample site | Ba | Cd | Cu | Ni | Sb | Zn |
|-------------|----|----|----|----|----|----|
| WHO guidelines | 2400 | 20 | 70 | 2000 | 3000 | 3 |
| Ugandan standards | — | — | — | — | — | 10 |
| Canadian guidelines | 5000 | 6 | — | 1000 | 5000 | 5 |

Table 5: A summary of the percentage of selected protected springs in Kampala city with levels of trace elements in water above and below the WHO guidelines, Canadian guidelines, and Ugandan standards.

| Element | B | Sb | Ni | Cu | Zn | Cd | Ba | Pb |
|---------|----|----|----|----|----|----|----|----|
| Springs above Ugandan guidelines | — | — | — | 0 | 0 | 0 | 0 | 0 |
| Springs below Ugandan guidelines | — | — | — | 100 | 100 | 100 | 100 | 100 |
| Springs above WHO guidelines | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Springs below WHO guidelines | 100 | 100 | 100 | 100 | 100 | 100 | 91.7 | 100 |
| Springs above Canadian guidelines | 0 | 8.3 | — | — | 0 | 0 | 0 | 0 |
| Springs below Canadian guidelines | 100 | 91.7 | — | 100 | 100 | 100 | 100 | 100 |

sampled spring water had nitrate levels below the Ugandan standard of 10 mg/L, and the rest was highly polluted with 11–125 mg/L which implied that there was enrichment of the shallow groundwater with nutrients from urbanisation and industrialisation activities. Of the sampled shallow groundwater, 52.8% had nitrate levels above the drinking water guideline value of 50 mg/L and 21.6% of them had elevated levels. The Canadian guideline value of 45 mg/L was exceeded by 73% of all sampled springs. These results were in agreement with studies by Taylor and Howard [32], where nitrate levels of 26 mg/L were reported in groundwater, and in another study by Kulabako et al. [35], the mean nitrate values reported in shallow groundwater were 67 mg/L. These high nitrate levels are indicative of nutrient loading of the shallow aquifers which could be attributed to anthropogenic sources such as onsite sanitation, domestic sewage disposal habits, waste dumpsites, and others in the spring catchment areas. All the chloride levels in the spring water samples were below the guideline values although they were elevated and indicated increasing salinity probably due to weathering since the groundwater is acidic; however, these results were similar to the high salinity reported by Kulabako et al. [35] which was 59 mg/L, whereas Moulodi and Thorsell [20] reported 4.6–54.6 mg/L of chloride levels in shallow
Table 6: Mean values of other parameters of shallow groundwater and associated surface runoff from periurban Kampala compared to Guidelines for Canadian Drinking Water Quality and Ugandan Standards.

| Spring name   | Analysis of spring water | Surface runoff analysis |
|---------------|--------------------------|-------------------------|
|               | T (°C) | pH | DOC (mg/L) | EC (µS/cm) | NO₃⁻ (mg/L) | Cl⁻ (mg/L) | F⁻ (mg/L) | EC (µS/cm) | Cd²⁺ (µg/L) | Pb²⁺ (µg/L) |
| Canadian guidelines | —     | 6.5–8.5 | — | 45 | — | 0.5 | — | — | 5 | 10 |
| Ugandan standards | 6.0–8.5 | — | 1000 | 10 | 250 | 1.0 | — | 1000 | 10 | 50 |
| Nakawa division |       |      |          |            |            |          |        |      |      |      |
| Nabuze       | 25.0 | 5.46 | 1.0 | 665 | 34.1 | 11.9 | 0.1 | 750 | 1.18 | 178 |
| Katarina     | 24.0 | 5.36 | 1.0 | 372 | 19.9 | 6.9 | 0.1 | 450 | 1.30 | 81 |
| Buwooya      | 25.0 | 5.45 | 1.0 | 211 | 10.4 | 3.8 | 0.2 | 350 | 2.62 | 560 |
| Bukoto 1     | 26.0 | 5.07 | 1.0 | 226 | 27.0 | 13.3 | 0.3 | 300 | 2.52 | 915 |
| Bukoto 2     | 25.0 | 4.80 | 2.0 | 470 | 64.3 | 24.2 | 0.2 | 520 | 3.10 | 905 |
| Kiddumu      | 25.0 | 5.72 | 1.0 | 862 | 44.8 | 16.8 | 0.1 | 1208 | 0.32 | 108 |
| Kawempe division |      |      |          |            |            |          |        |      |      |      |
| Nabukalu     | 25.0 | 4.93 | 2.0 | 873 | 78.7 | 30.3 | 0.1 | 980 | 2.39 | 129 |
| Abdu         | 26.0 | 4.74 | 1.0 | 2650 | 78.5 | 46.5 | 0.1 | 3050 | 2.64 | 1294 |
| SP3430K      | 25.0 | 4.98 | 1.0 | 786 | 38.6 | 16.6 | 0.1 | 824 | 1.35 | 95.8 |
| Kikoni       | 26.0 | 5.35 | 1.0 | 497 | 42.5 | 18.2 | 0.1 | 532 | 8.00 | 519 |
| Bukuku       | 26.0 | 5.86 | 2.0 | 643 | 65.4 | 31.2 | 0.1 | 835 | 1.19 | 92.1 |
| Ruhaga division |      |      |          |            |            |          |        |      |      |      |
| SP1414R      | 26.0 | 4.93 | 1.0 | 774 | 63.6 | 27.0 | 0.1 | 812 | 1.82 | 121 |
| Sentamu      | 25.0 | 4.98 | 1.0 | 722 | 74.6 | 32.3 | 0.1 | 820 | 0.42 | 69 |
| Kunnya       | 25.0 | 5.30 | 1.0 | 574 | 107.3 | 41.7 | 0.1 | 642 | 0.31 | 11 |
| SP1212R      | 25.0 | 5.03 | 1.0 | 631 | 1.0 | 10.2 | 1.0 | 722 | 0.13 | 28 |
| Kibumbiro    | 24.0 | 5.14 | 2.0 | 586 | 68.4 | 40.1 | 0.1 | 650 | 0.96 | 185 |
| Kabaale      | 25.0 | 5.32 | 1.0 | 607 | 70.2 | 28.4 | 0.2 | 600 | 0.90 | 45 |
| Nababiryne   | 25.0 | 5.68 | 1.0 | 272 | 42.5 | 18.3 | 0.1 | 472 | 0.35 | 31 |
| Nsekeko      | 26.0 | 4.89 | 1.0 | 786 | 24.7 | 8.8 | 0.1 | 786 | 24.7 | 8.8 |
| Lugala       | 25.0 | 5.18 | 1.0 | 272 | 57.9 | 21.6 | 0.1 | 1090 | 0.30 | 30.8 |
| SP1010R      | 25.0 | 5.18 | 1.0 | 916 | 64.5 | 28.4 | 0.1 | 1200 | 0.03 | 78 |
| Makindye division |     |      |          |            |            |          |        |      |      |      |
| Nsambaia     | 25.0 | 5.37 | 1.0 | 1098 | 101.2 | 42.1 | 0.2 | 1250 | 0.68 | 140 |
| Kapeke       | 25.0 | 5.18 | 1.0 | 1472 | 102.5 | 64.4 | 0.2 | 1670 | 0.29 | 106 |
| Yusuf        | 25.0 | 5.45 | 1.0 | 648 | 101.4 | 42.7 | 0.2 | 1210 | 0.43 | 215 |
| Kasanvu      | 25.0 | 5.68 | 1.0 | 764 | 38.7 | 11.8 | 0.5 | 825 | 0.18 | 36 |
| Kibuuka      | 25.0 | 5.89 | 1.0 | 873 | 45.6 | 18.6 | 0.2 | 972 | 1.20 | 201.4 |
| Kisugu       | 25.0 | 5.68 | 1.0 | 764 | 125.3 | 58.5 | 0.2 | 1250 | 0.68 | 140.0 |
| SP7009M      | 26.0 | 5.24 | 2.0 | 607 | 45.6 | 18.6 | 0.2 | 648 | 0.82 | 141.0 |
| Central division |     |      |          |            |            |          |        |      |      |      |
| Nabagereka   | 25.0 | 5.54 | 2.0 | 1208 | 58.3 | 35.6 | 0.3 | 779 | 0.03 | 34 |
| Barracks     | 25.0 | 5.36 | 1.0 | 779 | 74.7 | 23.2 | 0.1 | 864 | 0.22 | 121 |
| SP5003C      | 24.0 | 5.55 | 2.0 | 1051 | 53.7 | 35.5 | 0.3 | 1251 | 0.29 | 57 |
| Kisekka      | 26.0 | 4.97 | 2.0 | 772 | 5.1 | 49.6 | 5.0 | 820 | 18.3 | 15.4 |
| Kinyoro      | 24.0 | 5.20 | 1.0 | 421 | 18.0 | 5.9 | 0.1 | 774 | 1.05 | 294.9 |
| Bativa       | 26.0 | 4.95 | 1.0 | 832 | 38.8 | 14.8 | 0.1 | 870 | 0.68 | 55.7 |
| SP5508C      | 25.0 | 5.24 | 1.0 | 680 | 44.4 | 29.4 | 0.2 | 680 | 44.4 | 29.4 |
| SP5303C      | 26.0 | 5.25 | 2.0 | 648 | 53.7 | 36.5 | 0.3 | 648 | 53.7 | 36.5 |
| SP4902C      | 26.0 | 4.92 | 1.0 | 786 | 60.5 | 23.2 | 0.1 | 1670 | 0.29 | 105.8 |

Table 7: A summary of the percentage of samples of shallow groundwater and associated surface runoff from periurban Kampala above and below the Guidelines for Canadian Drinking Water Quality and Ugandan Standards.

| Sample site Parameter | Protected spring water | Surface runoff |
|------------------------|------------------------|----------------|
|                        | EC (µS/cm) | NO₃⁻ (mg/L) | Cl⁻ (mg/L) | EC (µS/cm) | Cd²⁺ (µg/L) | Pb²⁺ (µg/L) |
| Springs above Ugandan guidelines | 13.5 | 94.6 | — | 21.6 | 2.7 | 81.1 |
| Springs below Ugandan guidelines | 86.5 | 5.4 | — | 78.4 | 97.3 | 18.9 |
| Springs above Canadian guidelines | — | 73 | 0 | — | 5.4 | 97.3 |
| Springs below Canadian guidelines | — | 27 | 100 | — | 94.6 | 2.7 |
groundwater. One of the most serious inorganic contaminants reported was fluoride with concentrations above the guideline value, 1.5 mg/l for samples of groundwater in interaction with crater lakes in Uganda [8, 36], although the fluoride levels in shallow groundwater in Kampala were lower than the guideline values, which indicated a difference in sources of fluoride which are of geochemical origin. All the surface runoff associated with the protected springs had high electrical conductivity with 21.6% of them above the guideline value and 27% with elevated levels but below the guideline value of 1000 µS/cm. Weathering, wearing, and corrosion of metals dissolve metals in the wash down and increase the electrical conductivity of surface runoff. About 2.7% of the surface runoff samples were above the Ugandan guideline value of 10 µg/l for cadmium, while 5.4% of the samples were above the Canadian guideline value of 5 µg/l. All fluoride levels were below the Ugandan guideline values and Canadian standards. When the levels of metals in surface runoff were compared to the effluent discharge standards [37], 81.1% of them were above the guideline value of 50 µg/l for lead. As per the Canadian standards [38], 97.3% of the samples had lead levels above the guideline value of 10 µg/l. The suspected source of lead contamination is mainly anthropogenic activities since there are a lot of scrap yards, motor service centres, and metal workshops in addition to wearing of parts of vehicles that may contribute to the elevated levels. Otherwise continued discharge of untreated surface runoff, wastewater, and leachate will negatively impact the shallow groundwater when the soil water is laden during the rainy season; the surface water interacts with the groundwater in shallow aquifers without reacting with the soil chemicals and thence groundwater contamination.

Table 8 shows the levels of major elements and other parameters in surface water, wastewater, and landfill leachate from selected sources in the Lake Victoria basin. Table 9 shows a summary of the levels above and below the guideline values, respectively. The pH for all the sampled sources was within the limits of the WHO guideline values (6.5–8.5). The electrical conductivity values for 53.3% of the surface water, surface runoff, and landfill leachate samples were higher than the guideline value of 1000 µS/cm, whereas samples from the hot springs and municipal landfill leachate were 3–6 times higher than the WHO guideline value. These values could be due to mobilisation of conducting ions during the decay processes of landfills and thermal mobilisation of ions as hot water rises up through mineralised soils in hot springs; moreover, the salt lake has a rich matrix of conducting ions. The mine tailings from an old copper mine had higher EC values that were attributed to copper contamination of water. The temperatures of surface water sources were within the guideline values. The exceedance above the WHO guideline values for major elements in surface water was 33.3% for sodium, 13.3% for magnesium, 33.3% for aluminium, 53.3% for potassium, 80% for manganese, and 93.5% for iron. For Ugandan standards, the samples exceeding the guideline values were 6.7% for magnesium, 13.3% for calcium, 13.3% for manganese, and 6.7% for iron. Therefore, the surface water from different sources is contaminated with major elements. The levels of metals in the surface water samples were higher than those in a study by Walakira and Okot-Okumu [39] which were reported as 17–39 mg/l for calcium, 0.6–53 mg/l for sodium, 0.05–0.26 mg/l for lead, 0.02–0.56 mg/l for copper, and below the detection level for cadmium. The main source of these elements could be weathering of mineralised soils and rocks as well as mobilisation during sorption-desorption processes for trace elements onto organic matter and soil particles.

Figures 4 and 5 give a synopsis of the levels of cadmium and lead in the shallow groundwater in comparison to the levels in surface runoff associated with the protected spring catchment areas.

The levels of Cd²⁺ ions in shallow groundwater samples were below allowable limits for groundwater, whereas the Cd²⁺ ions levels in surface runoff were 12% elevated and 12% above the limit of 3 µg/l. For Pb²⁺ ions in shallow groundwater, 24% of the levels were elevated, whereas 100% of the levels of Pb²⁺ ions in surface runoff were by 3–130 times higher than the allowable limit of 10 µg/L. The results in this study were higher than those for Lake Victoria water reported by Tole and Shitsama [40] which were 0.12–0.45 µg/l for Pb and 0.01 µg/l for Cd. Although the vertical mobility of the trace metals is controlled by the soil pH and organic matter content, the flood zones of the periurban areas where the shallow groundwater samples were picked tend to have mixing of surface water and shallow groundwater during the rainy seasons which may cause detrimental effects to the water quality of the shallow aquifers.

Tables 10 and 11 show the levels of trace elements in the surface water from various sample sites and the percentage of those samples above the guideline values, respectively. The trace elements levels exceeding the WHO guideline values in surface water were 33.3% for nickel, 25% for antimony, 31% for nickel, 6% for copper, 13% for zinc, 25% for arsenic, 6.7% for selenium, 13.4% for barium, and 40% for lead, whereas those exceeding the Ugandan guideline values were only 6.7% for copper although Taylor and Howard [32] reported minor exceedance above the WHO guideline values for barium, nickel, lead, uranium, and cadmium in their study of groundwater in Uganda. The urban streams and landfill leachate have elevated levels of trace metals: boron, antimony, arsenic, nickel, selenium, barium, and lead. The mine tailings are contaminated with copper and nickel. However, the pollution trends depict anthropogenic contamination although natural mobilisation of metal ions from the parent rock is possible. Nickel contamination results from the usage of electric cells and industrial wastewater, whereas copper was high in the copper mine tailings. Arsenic levels were evidently high in landfill leachates and Lubigi Channel which implied that anthropogenic pollution of the environment occurred since the levels in the shallow groundwater were all below the WHO guideline values.

Table 12 shows results of metal speciation studies for selected streams, waterways, and landfill leachates done by modelling the levels of elements using Visual MINTEQ. The results indicated that, in the landfill leachates, 74% of the metal ions are bound to dissolved organic matter (DOM) except for aluminium; 70% exists as inorganic aluminium,
Table 8: Mean levels of major elements (mg/L) and other parameters of surface water from selected streams and waterways in Lake Victoria basin, Uganda, compared to the WHO guidelines and Ugandan standards (maximum concentrations).

| Sampling site            | pH  | EC (µS/cm) | T (°C) | Na  | Mg  | Al  | K   | Ca  | Mn  | Fe  |
|--------------------------|-----|------------|--------|-----|-----|-----|-----|-----|-----|-----|
|                          | 6.5–8.5 | 1000 | 25 | 200 | 50 | 0.1 | 10  | 200 | 0.1 | 0.3 |
| WHO water guidelines     |      |          |       |     |     |     |     |     |     |     |
| Lubigi Channel           | 7.49 | 1530      | 29    | 51.5| 5.1 | 0.066| 25.03| 26.3| 0.80| 2.61|
| Mulago Channel           | 7.02 | 1420      | 25    | 50.7| 4.6 | 0.062| 22.60| 25.5| 0.83| 2.63|
| Nakivubo Channel         | 7.20 | 1723      | 28    | 56.4| 5.4 | 0.154| 28.62| 24.3| 0.53| 2.84|
| Lugogo stream            | 7.16 | 930       | 26    | 31.8| 5.7 | 0.001| 17.32| 26.3| 0.83| 3.49|
| Bugoloobi stream         | 7.09 | 700       | 25    | 19.9| 5.1 | 0.002| 6.28 | 18.0| 0.13| 0.33|
| Kiteezi Landfill         | 8.44 | 5100      | 30    | 52.45| 82.8| 0.140| 26.2 | 26.2| 0.29| 5.35|
| Lugazi Steel Mills       | 7.68 | 133       | 25    | 40.7| 4.6 | 0.739| 27.06| 27.5| 0.62| 14.98|
| Jinja Landfill           | 7.88 | 3120      | 27    | 400 | 184.8| 0.002| 0.07 | 135.4| 2.87| 6.49|
| Jinja Steel Mills        | 7.46 | 1772      | 27    | 36.1| 22.5| 0.001| 4.66 | 62.6| 0.68| 1.14|
| Jinja Wallukuba          | 7.90 | 300       | 26    | 11.9| 1.7 | 0.001| 3.49 | 5.8  | 0.01| 0.20|
| River Mpanga             | 6.80 | 768       | 25    | 27.8| 15.2| 0.001| 6.84 | 82.7| 1.57| 1.27|
| Kibenge Hot Springs      | 7.60 | 924       | 46    | 600.2| 4.4 | 0.040| 19.99| 199 | 0.03| 0.97|
| River Nyamwamba          | 7.03 | 127       | 22    | 6.4 | 3.8 | 0.002| 3.62 | 10.0| 0.13| 1.21|
| Kilemba Mines            | 7.45 | 1569      | 26    | 509.8| 25.1| 0.924| 578.10| 78.6| 0.45| 0.93|
| Kitagata Hot Springs     | 7.80 | 1182      | 59    | 205.6| 0.2 | 0.001| 10.50| 30.5| 0.02| 0.33|

Table 9: A summary of the percentage of samples of surface water from selected streams and waterways in Lake Victoria basin, Uganda, with mean levels of major elements and other parameters of surface water from selected streams and waterways in Lake Victoria basin, Uganda, above and below the WHO guidelines and Ugandan standards.

| Element                        | EC     | Na     | Mg     | Al     | K     | Ca     | Mn     | Fe     |
|-------------------------------|--------|--------|--------|--------|-------|--------|--------|--------|
| Springs above Ugandan guidelines | 53.5   | 6.7    | 26.7   | —      | 13.3  | 13.3   | 6.7    |        |
| Springs below Ugandan guidelines | 46.7   | 93.3   | 73.3   | —      | 86.7  | 86.7   | 93.3   |        |
| Springs above WHO guidelines  | 53.5   | 33.3   | 13.3   | 33.3   | 53.5  | 0      | 80     | 93.3   |
| Springs below WHO guidelines  | 46.7   | 66.7   | 86.7   | 66.7   | 46.7  | 100    | 20     | 6.7    |

Figure 4: Continued.
Figure 4: Outline of Cd(II) levels in the shallow groundwater and associated surface runoff from Kampala city (where the red line indicates the guideline value for levels of cadmium in surface water).

Figure 5: Outline of Pb(II) levels in the shallow groundwater and associated surface runoff from Kampala city (where the red bars indicate that the levels of lead in surface runoff were all the above guideline value).
Table 10: Trace metal elements (µg/L) in surface water from selected streams and waterways in Lake Victoria basin, Uganda, compared with WHO guidelines [30] and Ugandan standards [28, 37].

| Sampling site          | B  | Ni  | Cu   | Zn | As  | Se  | Cd  | Ba  | Pb  |
|------------------------|----|-----|------|----|-----|-----|-----|-----|-----|
| WHO water guidelines   | 2400 | 70  | 2000 | 4000 | 10 | 40  | 3   | 700 | 10  |
| Ugandan standards      | 5000 | 1000 | 1000 | 5000 | 200 | 1000 | 100 | 10000 | 100 |
| Lubigi stream          | 485 | 178.9 | 133.2 | 584.7 | 25.15 | 27.71 | 1.110 | 6227 | 97.7 |
| Mulago stream          | 14  | 5.8  | 4.9   | 25.9  | 0.70  | 0.88  | 0.047 | 215.1 | 2.9  |
| Nakivubo stream        | 32  | 10.9 | 10.9  | 66.2  | 1.0   | 1.19  | 0.255 | 181.9 | 10.9 |
| Lugogo stream          | 18  | 6.9  | 3.3   | 15.7  | 0.88  | 1.02  | 0.024 | 218.7 | 0.9  |
| Bugoloobi stream       | 199 | 126.8 | 38.4   | 506.8 | 6.11  | 16.46 | 2.307 | 2723.7 | 27.4 |
| Kiteezi Landfill leachate | 1338 | 271.2 | 119.6  | 248.3 | 23.32 | 71.37 | 1.143 | 214.5 | 99.3 |
| Lugazi Steel Mills effluent | 126  | 19.6  | 16.4  | 210.3 | 2.08  | 0.69  | 0.193 | 73.3  | 29.0 |
| Jinja Landfill leachate | 953 | 104.7 | 74.1   | 241.1 | 11.98 | 25.62 | 0.436 | 186.3 | 29.7 |
| Jinja Steel Mills effluent | 29   | 6.2   | 1.0   | 4.9   | 0.46  | 2.55  | 0.030 | 104.8 | 0.3  |
| Jinja Walukuba effluent | 10  | 0.9   | 0.5   | 6.1   | 0.21  | 0.21  | 0.004 | 30.2  | 1.0  |
| River Mpenga           | 11  | 5.5   | 1.8   | 15.2  | 0.38  | 0.47  | 0.477 | 341.7 | 5.1  |
| Kibenge Hot Springs    | 296 | 9.1   | 7.6   | 12.8  | 2.96  | 23.18 | 0.136 | 25.8  | 2.0  |
| River Nyamwamba        | 7.5  | 18.0  | 172.7  | 24.2  | 0.27  | 0.29  | 0.188 | 28.6  | 2.3  |
| Kilembe Mines effluent | 6.8  | 90.0  | 1604   | 53.4  | 2.03  | 0.60  | 0.445 | 31.0  | 2.6  |
| Kitagata Hot Springs   | 375  | 2.4   | 3.6   | 21.5  | 0.82  | 2.60  | 0.471 | 36.8  | 4.9  |

Table 11: A summary of the percentage of samples of surface water from selected streams and waterways in Lake Victoria basin, Uganda, with mean levels of trace elements above and below the WHO guidelines and Ugandan standards.

| Element | B  | Ni  | Cu   | Zn | As  | Se  | Cd  | Ba  | Pb  |
|---------|----|-----|------|----|-----|-----|-----|-----|-----|
| Springs above Ugandan guidelines | 0  | 0   | 6.7  | 0  | 0   | 0   | 0   | 0   |
| Springs below Ugandan guidelines | 100 | 100 | 93.3  | 100 | 100 | 100 | 100 | 100 |
| Springs above WHO guidelines | 0  | 33.3 | 0   | 0  | 0   | 0   | 13.4 | 40  |
| Springs below WHO guidelines | 100 | 66.7 | 100  | 100 | 100 | 100 | 86.6 | 60  |

Table 12: Percentage composition of metal ions in aqueous media as determined by speciation studies of selected surface water samples from streams in Lake Victoria basin, Uganda.

| Sampling site          | Ni²⁺ | Cu²⁺ | Zn²⁺ | Cd²⁺ | Pb²⁺ | Al³⁺ | Mn²⁺ | Fe²⁺ |
|------------------------|------|------|------|------|------|------|------|------|
| Jinja Landfill leachate |      |      |      |      |      |      |      |      |
| Bound to DOM           | 92.5 | 100  | 96.3  | 87.7 | 99.9 | 46.9 | 24.5 | 100  |
| Free ion               | 7.0  | —    | 2.9   | 5.2  | —    | —    | —    | —    |
| Inorganic              | 0.5  |      | 0.8   | 7.1  | 0.01 | 54.1 | 10.0 |      |
| Dominant ion           | FANi⁺ | FA₂CuOH | FA₂Zn | FA₂Cd | FA₂Pb | Al(OH)₄⁻ | Mn²⁺ | FA₂FeOH |
| Kiteezi Landfill leachate |      |      |      |      |      |      |      |      |
| Bound to DOM           | 96.5 | 100  | 99.4  | 97.5 | 100  | 13.5 | 37.1 | 100  |
| Free ion               | 3.4  |      | 0.4   | 0.9  | —    | —    | 61.9 | —    |
| Inorganic              | 0.1  |      | 0.2   | 1.8  | —    | 86.5 | 1.0  | —    |
| Dominant ion           | FANi⁺ | FA₂CuOH | FA₂Zn | FA₂Cd | FA₂Pb | Al(OH)₄⁻ | Mn²⁺ | FA₂FeOH |
| Lubigi Channel         |      |      |      |      |      |      |      |      |
| Bound to DOM           | 58.5 | 98.3 | 35.1  | 31.8 | 97.7 | 4.7  | 8.2  | 97.5 |
| Free ion               | 40.0 | 0.7  | 59.8  | 58.4 | 1.6  | —    | 86.3 | —    |
| Inorganic              | 1.5  | 1.0  | 6.1   | 10.8 | 1.3  | 95.3 | 5.5  | 2.4  |
| Dominant ion           | Ni²⁺ | FA₂Cu | Zn²⁺ | Cd²⁺ | FA₂Pb | Al(OH)₄⁻ | Mn²⁺ | FA₂FeOH |
| Nakivubo Channel       |      |      |      |      |      |      |      |      |
| Bound to DOM           | 9.2  | 47.1 | 3.2   | 2.8  | 42.6 | 0.5  | 0.9  | 45.7 |
| Free ion               | 86.9 | 27.6 | 87.9  | 76.6 | 38.7 | —    | 90.3 | —    |
| Inorganic              | 3.9  | 25.3 | 8.9   | 20.6 | 18.7 | 99.5 | 8.8  | 54.3 |
| Dominant ion           | Ni²⁺ | FA₂Cu | Zn²⁺ | Cd²⁺ | FA₂Pb | Al(OH)₄⁻ | Mn²⁺ | Fe(OH)₃ |
whereas most metal contaminants show toxic effects in their inorganic forms. The dominant ionic species in the landfill leachate are fulvic acid bound metals and metal hydroxides for nickel, copper, zinc, cadmium, lead, and iron, whereas manganese is a free ion and aluminium is in form of aluminium tetrahydroxyl radical. For the urban streams, 25% of the metal ions are bound to dissolved organic matter, 38% of the metal ions are free metal ions, and 19% are in form of inorganic species.

The prominent ionic species in urban streams are manganese, nickel, zinc, and cadmium ions, iron(III) hydroxide, aluminium tetrahydroxyl radical, and fulvic acid bound copper and lead. The speciation of metal ions shows that they will be bound to DOM or fulvic acid; however, if the pH, DOC, and calcium content are lowered, the metal binding to the biotic ligand will increase causing toxicity effects to sensitive water plants and animals.

In Figure 6, a comparison of the trace metal elements in surface water with the Swedish environmental guidelines for lakes and watercourses is presented, whereas Table 13 showed the criteria used. Figure 7 presents the description of the colour codes used in the criteria. The results showed that Lubigi Channel that traverses the periurban area of Kawempe Division and Bugolobi Channel, whose catchment areas are in the industrial area of Kampala, has been shown to pose a high risk of negative effects on life support systems even for short-time exposure of exposure to Zn, Cu, Pb, and Cd metals. The leachate from Jinja and Kiteezi municipal landfills pose a high risk of exposure to Zn, Cu, Pb, and Cd metals. The effluent from Lugazi Steel Mills poses high risk of negative effects on life support systems even for short-time exposure to Pb, whereas the water from Kilembe Mine tailings and River Nyamwamba poses a greater risk of exposure to copper. The results from these case studies showed high risk of negative effects on life support systems even for short-time exposure. According to the results of this study, the water samples from Lugogo Channel in Kampala, Walukuba Channel in Jinja, River Mpanga in Kasese, and Kitagata Hot Springs presented metal concentrations in water that were suspected to have no anthropogenic contribution or trace metals contamination and no significant effects to life. Documented toxicity studies in surface water from Lake Victoria basin are scarce although in studies by Ljung [19] the trace metal levels that exceeded the lower limits for acute effects on organisms reported were 55% for cadmium, 5% for nickel, 77% for copper, 100% for zinc, and 33% for lead as compared to 46% for cadmium, 30% for nickel, 76% for copper, 46% for zinc, and 46% for lead for the current study.

The effects of selected trace metals on life support systems have been done basing on the criteria from the Swedish Environmental Protection Agency [29] and are shown in Figure 6. These results of the comparison and classification of predicted risks were more general for environmental health effects. The description of the criteria used in the classification of risks due to levels of metal ions in the aquatic environment is shown in Table 13. In the selected waterways, streams, and landfill leachate, there were suspected toxicity effects due to lead, copper, and zinc with Bugolobi and Lubigi waterways being most risky. Due to the colour codes described in Figure 7, the levels of the metals in the aquatic environment that show no effects to moderate effects were accorded colours from yellow to blue. The values in blue such as those for arsenic are suspected to cause environmental disturbance, but values close to guideline values normally show no effects in organisms; moreover, the values in yellow are concentrations to which local sources or long distance atmospheric contributions have contributed although it may represent natural deviations and no significant effects to life.

The green coloured values are concentrations in water that have no anthropogenic contribution and are below guideline values. Therefore, continued discharge of untreated contaminated wastewater and landfill leachate will continue to impact on the quality of water in urban streams. The highest risk of exposure is due copper and lead followed by zinc and cadmium, whereas the water that poses the greatest risk of exposure is that from Lubigi Channel, Kiteezi Landfill leachate, Bugolobi Channel, and Jinja Landfill leachate.

Tables 14 and 15 present results of modelling values of levels of elements in the surface water using the Bio-met software tool that is applied over a range of different organisms to calculate the 5th percentile of the species sensitivity distribution (SSD).

HC5 aims at protecting at least 95% of the species and reflects the bioavailability conditions of a specific site according to the water chemistry. In Tables 14 and 15, the local HC5 values were in the ranges of 54.56–474.12 µg/L for Cu²⁺, 29.95–151.90 µg/L for Ni²⁺, 62.55–623.74 µg/L for Zn²⁺, and 30.24–92.51 µg/L for Pb²⁺ for selected surface water samples. The bioavailable metal concentration is the concentration of a metal that is bioavailable at the site or water body and were in the ranges of 0.02–29.40 µg/L for Cu²⁺, 0.18–12.45 µg/L for Ni²⁺, 0.96–74.19 µg/L for Zn²⁺, and 0.03–1.50 µg/L for Pb²⁺. The risk characterisation ratio (RCR) values that identified potential environmental risks for the selected surface water samples were 15.4% for Cu²⁺, 30.8% for Ni²⁺, 30.8% for Zn²⁺, and 15.4% for Pb²⁺. These results require more detailed risk assessments to inform policy on appropriate action.

The water source with the highest potential risk was Lubigi Channel. Johnson et al. [41] studied twelve metals in UK surface waters and found that the relative risk to organisms was highest for copper, aluminium, and zinc, whereas in this report, the highest risk of exposure to metals in surface waters was due to zinc and nickel.

Tables 16 and 17 present results of modelling values of levels of elements in the selected shallow groundwater sources using the Bio-met software tool that is applied over a range of different organisms to calculate the 5th percentile of the species sensitivity distribution (SSD). The local HC5 values in Tables 16 and 17 were in the ranges of 4.15–8.55 µg/L for Cu²⁺, 8.20–9.67 µg/L for Ni²⁺, 10.90–14.81 µg/L for Zn²⁺, and 2.70–5.38 µg/L for Pb²⁺ for selected shallow groundwater samples. The bioavailable metal concentration values were in the ranges of 0.13–1.13 µg/L for Cu²⁺, 1.03–12.20 µg/L for Ni²⁺, 2.94–34.88 µg/L for Zn²⁺, and 0.10–1.13 µg/L for Pb²⁺. The risk characterisation ratio (RCR)
| Sampling site          | Ni  | Cu  | Zn  | Cd  | Pb  | As  |
|----------------------|-----|-----|-----|-----|-----|-----|
| Lubigi Channel       | 178.9 | 133.2 | 584.7 | 1.110 | 97.7 | 25.15 |
| Mulago Channel       | 5.8 | 4.9 | 25.9 | 0.047 | 2.9 | 0.70 |
| Nakivubo Channel     | 10.9 | 10.9 | 66.2 | 0.255 | 10.9 | 1.0 |
| Lugogo stream        | 6.9 | 3.3 | 15.7 | 0.024 | 0.9 | 0.88 |
| Bugoloobi stream     | 126.8 | 38.4 | 506.8 | 2.307 | 27.4 | 6.11 |
| Kiteezi Landfill     | 271.2 | 119.6 | 248.3 | 1.143 | 99.3 | 23.32 |
| Lugazi Steel Mills   | 19.6 | 16.4 | 210.3 | 0.193 | 27.4 | 6.11 |
| Jinja Landfill       | 104.7 | 74.1 | 241.1 | 0.436 | 29.7 | 11.98 |
| Jinja Steel Mills    | 6.2 | 1.0 | 4.9 | 0.030 | 0.3 | 0.46 |
| Jinja Walukuba       | 0.9 | 1.0 | 6.1 | 0.004 | 1.0 | 0.21 |
| River Mpanga         | 5.5 | 1.8 | 15.2 | 0.477 | 5.1 | 0.38 |
| Kibenge Hot Springs  | 9.1 | 7.6 | 12.8 | 0.136 | 2.0 | 2.96 |
| River Nyamwamba      | 18.0 | 172.7 | 24.2 | 0.188 | 2.3 | 0.27 |
| Kitagata Hot Springs | 90.0 | 1604 | 53.4 | 0.188 | 2.3 | 0.27 |

Figure 6: Comparison of concentrations of selected trace metal elements (µg/L) in surface water from particular water sources in Lake Victoria basin, Uganda, with Swedish environmental guidelines.

Table 13: The Swedish Environmental Protection Agency (Naturvårdsverket) criteria.

| Metal (µg/l) | Class 1 (very low) | Class 2 (low) | Class 3 (moderate) | Class 4 (high) | Class 5 (very high) |
|-------------|--------------------|---------------|--------------------|----------------|---------------------|
| Cd          | <0.01              | 0.01–0.1      | 0.1–0.3            | 0.3–1.5        | >1.5                |
| Cu          | <0.5               | 0.5–3         | 3–9                | 9–45           | >45                 |
| Ni          | <0.7               | 0.7–15        | 15–45              | 45–225         | >225                |
| Pb          | <0.2               | 0.2–1         | 1–3                | 3–15           | >15                 |
| Zn          | <5                 | 5–20          | 20–60              | 60–300         | >300                |

Class 1: Metal concentrations in water have no anthropogenic contribution
Class 2: Concentrations to which local sources or long distance atmospheric contributions have contributed although it may represent natural deviations and no significant effects to life
Class 3: Concentrations are suspected to cause environmental disturbance, but values close to guideline values show no effects in organisms
Class 4: Increased risk of negative effects on biological systems
Class 5: High risk of negative effects on life support systems even for short-time exposure

Figure 7: Colour codes used for the Swedish Environmental Protection Agency (Naturvårdsverket) criteria.

Table 14: Results for risk assessment with respect to zinc and lead for selected surface water samples.

| Sample name          | Local HC5 (dissolved) (µg/L) | BioF | Bioavailable zinc concentration (µg/L) | RCR | Local HC5 (dissolved) (µg/L) | BioF | Bioavailable lead concentration (µg/L) | RCR |
|---------------------|-----------------------------|------|---------------------------------------|-----|-----------------------------|------|----------------------------------------|-----|
| River Mpanga        | 75.47                        | 0.14 | 2.05                                  | 0.19 | 65.88                       | 0.02 | 0.09                                   | 0.08|
| Nakivubo Channel    | 149.16                       | 0.07 | 4.76                                  | 0.44 | 75.30                       | 0.02 | 0.17                                   | 0.14|
| Lubigi Channel      | 183.54                       | 0.06 | 34.68                                 | 3.18 | 79.08                       | 0.02 | 1.50                                   | 1.25|
| Kibenge Hot Springs | 105.39                       | 0.10 | 1.22                                  | 0.11 | 68.61                       | 0.02 | 0.03                                   | 0.03|
| River Nyamwamba     | 66.13                        | 0.16 | 3.82                                  | 0.35 | 65.57                       | 0.02 | 0.04                                   | 0.04|
| Kitagata Hot Springs| 233.22                       | 0.05 | 0.96                                  | 0.09 | 86.05                       | 0.01 | 0.07                                   | 0.06|
| Kilembe Mine tailings| 84.19                        | 0.13 | 6.73                                  | 0.62 | 30.24                       | 0.04 | 0.10                                   | 0.09|
| Mulago Channel      | 62.55                        | 0.17 | 4.34                                  | 0.40 | 40.48                       | 0.03 | 0.09                                   | 0.07|
| Bugoloobi Channel   | 74.31                        | 0.15 | 74.19                                 | 6.81 | 66.34                       | 0.02 | 0.50                                   | 0.41|
| Lugogo Channel      | 75.77                        | 0.14 | 2.11                                  | 0.19 | 40.80                       | 0.03 | 0.03                                   | 0.02|
| Lugazi Channel      | 150.28                       | 0.07 | 15.16                                 | 1.39 | 67.58                       | 0.02 | 0.51                                   | 0.43|
| Jinja Landfill leachate | 111.33                      | 0.10 | 23.50                                 | 2.16 | 77.56                       | 0.02 | 0.46                                   | 0.38|
| Kiteezi Landfill leachate | 623.74                      | 0.02 | 4.32                                  | 0.40 | 92.51                       | 0.01 | 1.29                                   | 1.07|
values that identified potential environmental risks for the selected surface water samples were 4.1% for Cu\(^{2+}\), 45.8% for Ni\(^{2+}\), 62.5% for Zn\(^{2+}\), and 8.3% for Pb\(^{2+}\). These results require more detailed risk assessments to inform policy on appropriate action since the water sources are used for domestic purposes. The shallow groundwater source with the highest potential risk was Kibumbiro in Lubaga Division, whereas those that had RCR values below 1 required no action.

4. Conclusions

The shallow groundwater from protected springs in Kampala city had elevated levels of major and traces metals although some cases were below and others above the WHO guideline values, Ugandan standards, and Canadian standards. The levels of metals in surface water, landfill leachate, and surface runoff showed anthropogenic contamination and revealed increased risks of negative biological effects on organisms as well as the general environmental health. Speciation studies for selected streams, waterways, and landfill leachates using Visual MINTEQ indicated that 74% of the metal ions in the landfill leachates and 25% of the metal ions in urban streams are bound to DOM and were not available as free metal ions. Toxicity studies using the BioMet software tool showed that selected surface water sources and shallow groundwater sources had potential environmental risks and require further detailed risk assessments to inform policy on appropriate action. However, the current

| Sample name      | Local HC5 (dissolved) (µg/L) | BioF | Bioavailable copper concentration (µg/L) | RCR | Local HC5 (dissolved) (µg/L) | BioF | Bioavailable nickel concentration (µg/L) | RCR |
|------------------|-------------------------------|------|-----------------------------------------|-----|-------------------------------|------|------------------------------------------|-----|
| River Mpanga     | 119.21                        | 0.01 | 0.02                                    | 0.02| 53.20                         | 0.08 | 0.41                                     | 0.10|
| Nakivubo Channel | 185.25                        | 0.01 | 0.06                                    | 0.06| 59.21                         | 0.07 | 0.74                                     | 0.18|
| Lubigi Channel   | 191.68                        | 0.01 | 0.69                                    | 0.69| 57.50                         | 0.07 | 12.45                                    | 3.11|
| Kibenge Hot Springs | 227.55                      | 0.00 | 0.03                                    | 0.03| 56.31                         | 0.07 | 0.65                                     | 0.16|
| River Nyamwamba  | 131.48                        | 0.01 | 1.32                                    | 1.32| 42.11                         | 0.09 | 1.71                                     | 0.43|
| Kitagata Hot Springs | 159.16                     | 0.01 | 0.02                                    | 0.02| 53.90                         | 0.07 | 0.18                                     | 0.04|
| Kilembe Mine tailings | 54.56                      | 0.02 | 29.40                                   | 29.40| 3.11                          | 0.18 | 2.77                                     | 0.69|
| Mulago Channel   | 75.42                         | 0.01 | 0.06                                    | 0.06| 30.80                         | 0.13 | 0.75                                     | 0.19|
| Bugoloobi Channel | 144.60                       | 0.01 | 0.27                                    | 0.27| 43.10                         | 0.09 | 11.79                                    | 2.95|
| Lugogo Channel   | 82.05                         | 0.01 | 0.04                                    | 0.04| 31.76                         | 0.13 | 0.87                                     | 0.22|
| Lugazi Channel   | 117.74                        | 0.01 | 0.14                                    | 0.14| 39.35                         | 0.10 | 1.99                                     | 0.50|
| Jinja Landfill leachate | 474.12                | 0.00 | 0.16                                    | 0.16| 151.90                        | 0.03 | 2.77                                     | 0.69|
| Kiteezi Landfill leachate | 173.20               | 0.01 | 0.69                                    | 0.69| 100.41                        | 0.04 | 10.80                                    | 2.70|

Table 15: Results for risk assessment with respect to copper and nickel for selected surface water samples.

Table 16: Results for risk assessment with respect to copper and nickel for selected shallow groundwater samples.
The state of the surface water quality indicates that the shallow groundwater in Kampala which is tapped from weathered regolith is acidic and vulnerable to contamination when episodes of acidic rain increase desorption of metal ions from organic matter and soil particles and thence the mobility of trace metals and contamination. The surface water, wastewater, landfill leachates, and surface runoff from several subcatchments of the Lake Victoria catchment zone are contaminated with trace and major elements most likely due to anthropogenic activities and natural mobilisation of metals through weathering of rocks. Otherwise continued discharge of untreated surface runoff, wastewater, and landfill leachate will negatively impact the shallow groundwater when the soil water is laden during the wet seasons, and the surface water interacts with the groundwater in shallow aquifers without reacting with the soil chemicals and thence groundwater contamination. There is need for intervention measures including legislation enforcement, monitoring, and alternative wastewater remediation action to curb water environment contamination.

### 5. Recommendations

To ensure guaranteed groundwater quality, the urban streams need be protected through treating the surface runoff, wastewater, and landfill leachate before discharge. The impending water disaster can be deterred with proactive measures such as building a time series data base on total water quality, regular monitoring of groundwater quality, and enforcing regulation preventive remediation. Further research will aim at modelling prediction of trace metal contaminants’ mobility and distribution in the environment to be able to contaminate the meagre resource and avert environmental trace metal toxicity effects.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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### References

[1] M. Luqman, T. M. Butt, A. Tanvir et al., "Phytoremediation of polluted water by trees: a review," International Journal of Agricultural Research and Reviews, vol. 1, no. 2, pp. 22–25, 2013.

[2] P. Gleick, "An introduction to global freshwater issues," in Water in Crisis, A Guide to the World’s Freshwater Resources, pp. 3–12, Oxford University Press, Oxford, UK, 1993.

[3] USDA Forest Service, Water and the Forest Service, USDA Forest Service, Washington, DC, USA, 2000.

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**Table 17: Results for risk assessment with respect to zinc and lead for selected shallow groundwater samples.**

| Sample name | Local HC5 (dissolved) (µg/L) | BioF | Bioavailable zinc concentration (µg/L) | RCR | Local HC5 (dissolved) (µg/L) | BioF | Bioavailable lead concentration (µg/L) | RCR |
|-------------|-----------------------------|------|--------------------------------------|-----|-----------------------------|------|-------------------------------------|-----|
| Nabuze      | 11.56                       | 0.94 | 7.93                                 | 0.73| 2.70                        | 0.44 | 0.24                                | 0.20|
| Katarina    | 10.90                       | 1.00 | 15.90                                | 1.46| 2.70                        | 0.44 | 0.42                                | 0.35|
| Buwooya     | 10.90                       | 1.00 | 15.00                                | 1.38| 2.70                        | 0.44 | 1.82                                | 1.51|
| Bukoto 1     | 10.90                       | 1.00 | 12.60                                | 1.16| 2.70                        | 0.44 | 0.44                                | 0.26|
| Bukoto 2     | 14.81                       | 0.74 | 18.70                                | 1.72| 5.38                        | 0.22 | 0.43                                | 0.36|
| Nabukalu     | 14.81                       | 0.74 | 14.65                                | 1.34| 5.38                        | 0.22 | 0.19                                | 0.16|
| Abdu         | 11.56                       | 0.94 | 20.74                                | 1.90| 2.70                        | 0.44 | 0.69                                | 0.57|
| SP3406K      | 11.56                       | 0.94 | 12.91                                | 1.18| 2.70                        | 0.44 | 0.60                                | 0.50|
| Kikoni       | 11.56                       | 0.94 | 5.56                                 | 0.51| 2.70                        | 0.44 | 0.02                                | 0.01|
| SP1414R      | 11.56                       | 0.94 | 15.18                                | 1.39| 2.70                        | 0.44 | 0.34                                | 0.28|
| Sentamu      | 11.56                       | 0.94 | 7.82                                 | 0.72| 2.70                        | 0.44 | 0.10                                | 0.08|
| Kinya        | 10.90                       | 1.00 | 23.60                                | 2.17| 2.70                        | 0.44 | 0.76                                | 0.63|
| SP1212R      | 11.56                       | 0.94 | 8.29                                 | 0.76| 2.70                        | 0.44 | 0.10                                | 0.09|
| Kibumbiro    | 14.81                       | 0.74 | 34.67                                | 3.18| 5.38                        | 0.22 | 1.13                                | 0.94|
| Kabaale      | 11.56                       | 0.94 | 14.70                                | 1.35| 2.70                        | 0.44 | 0.94                                | 0.78|
| Nababiroye   | 10.90                       | 1.00 | 6.80                                 | 0.62| 2.70                        | 0.44 | 0.19                                | 0.16|
| SP1010R      | 11.56                       | 0.94 | 10.46                                | 0.96| 2.70                        | 0.44 | 0.15                                | 0.13|
| Nsambya      | 11.56                       | 0.94 | 10.18                                | 0.93| 2.70                        | 0.44 | 0.32                                | 0.27|
| Kapeke       | 11.56                       | 0.94 | 34.88                                | 3.20| 2.70                        | 0.44 | 0.80                                | 0.67|
| Yusuf        | 11.56                       | 0.94 | 9.90                                 | 0.91| 2.70                        | 0.44 | 0.35                                | 0.29|
| Kasanvu      | 11.56                       | 0.94 | 2.94                                 | 0.27| 2.70                        | 0.44 | 0.05                                | 0.04|
| Nabagereka   | 19.34                       | 0.56 | 8.40                                 | 0.77| 5.38                        | 0.22 | 0.38                                | 0.32|
| Barracks     | 11.56                       | 0.94 | 6.23                                 | 0.57| 2.70                        | 0.44 | 0.23                                | 0.19|
| SP5003C      | 14.81                       | 0.74 | 17.74                                | 1.63| 5.38                        | 0.22 | 0.63                                | 0.52|
[4] G. Bakyayita, R. Kulabako, A. Norrström, and M. Nalubega, “Equilibrium and kinetic studies for the biosorption of aqueous Cd (II) and Pb (II) ions onto coffee husks and banana peels,” in Proceedings of the 9th Regional Collaboration Conference, pp. 404–410, Entebbe, Uganda, June 2014.

[5] S. Kayombo and S. Jorgensen, Experiences and Lessons Learned Brief for Lake Victoria, World Bank, Washington, DC, USA, 2006.

[6] E. Ali, S. Shaban-Dessouki, A. Soliman, and A. El Shanawy, “Characterisation of chemical water quality in the Nile river, Egypt,” International Journal of Pure and Applied Bioresource, vol. 2, no. 3, pp. 35–53, 2003.

[7] M. I. Mattina, W. Lannucci-Berger, C. Musante, and J. C. White, “Concurrent plant uptake of heavy metals and persistent organic pollutants from soil,” Environmental Pollution, vol. 124, no. 3, pp. 375–378, 2003.

[8] BGS, Groundwater Quality: Uganda, London, British Geological Survey, Nottingham, UK, USA, 2001.

[9] R. Taylor and K. Howard, “A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: evidence from Uganda,” Hydrogeology Journal, vol. 8, no. 3, pp. 279–294, 2000.

[10] WRAP, “The annual year book of the water resources management department,” in British Geological Survey 2001 © NERC 2001, N. G. T. Azza, Ed., Water Resources Assessment Project, Kampala, Uganda, 1999.

[11] A. Muwanga and E. Balifaijo, “Impact of industrial activities on heavy metal loading and their physio-chemical effects on wetlands of Lake Victoria basin (Uganda),” African Journal of Science and Technology, vol. 7, no. 1, pp. 51–63, 2006.

[12] N. Kulabako, M. Nalubega, and R. Thunvik, “Phosphorus transport in shallow groundwater in peri-urban Kampala: results of field and laboratory measurements,” Environmental Geology, vol. 53, no. 8, pp. 1535–1551, 2008.

[13] G. Howard, S. Pedley, M. Barrett, M. Nalubega, and K. Johal, “Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda,” Water Research, vol. 37, no. 14, pp. 3421–3429, 2003.

[14] M. Olade, “Heavy metal pollution and the need for monitoring: illustrated for developing countries in West Africa,” in Lead, Mercury, Cadmium and Arsenic in the Environment, T. Hutchinson and K. Meema, Eds., pp. 335–341, John Wiley & Sons, Hoboken, NJ, USA, 1987.

[15] A. Muwanga, Environmental Impacts of Copper Mining at Kilembe, Uganda: A Geochemical Investigation of Heavy Metal Pollution of Drainage Waters, Stream, Sediments and Soils in the Kilembe Valley in Relation to Mine Waste Disposal, Universität Braunschweig, Braunschweig, Germany, 1997.

[16] C. M. Zvínowanda, J. O. Okonkwo, P. N. Shabalala, and N. M. Agyei, “A novel adsorbent for heavy metal remediation in aqueous environments,” International Journal of Environmental Science & Technology, vol. 6, no. 3, pp. 425–434, 2009.

[17] K. Sekabira, H. O. Origa, T. A. Basamba, G. Mutumba, and E. Kakudidi, “Assessment of heavy metal pollution in the urban stream sediments and its tributaries,” International Journal of Environmental Science & Technology, vol. 7, no. 3, pp. 435–446, 2010.

[18] P. Larsson, “Lake Victoria and Kampala—history of man and water, Kampala,” Uganda: Technical Report, Ministry of Water and Environment, Kampala, Uganda, 2002.

[19] K. Ljung, Heavy Metal Discharge into Lake Victoria—A Study of the Ugandan Cities of Kampala, Jinja and Entebbe, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2001.

[20] S. Moulodi and J. Thorsell, Evaluation of the Levels of Selected Trace Metal Pollutants in Groundwater and Soil from Protected Springs in Peri-Urban Kampala, Uganda, KTH Land and Water Resources Engineering, Stockholm, Sweden, 2013.

[21] M. Kishe and J. Machiwa, “Distribution of heavy metals in sediments of Mwanza Gulf of Lake Victoria, Tanzania,” Environment International, vol. 28, no. 7, pp. 619–625, 2003.

[22] E. Leitao, P. Joao, and B. Bruce, Using Biotic Ligand Models to Help Implement Environmental Quality Standards for Metals under the Water Framework Directive, Environmental Agency, Bristol, England, 2009.

[23] Bio-met, 2013. Bio-met Bioavailability Tool. http://www.biomet.net.

[24] D. M. Di Toro, H. E. Allen, H. L. Bergman, J. S. Meyer, P. R. Paquin, and R. C. Santore, “Biotic ligand model of the acute toxicity of metals. I. Technical basis,” Environmental Toxicology and Chemistry, vol. 20, no. 10, pp. 2383–2396, 2001.

[25] E. Leitao, P. Joao, and F. Lobo, “Pollution from roads and vehicles and dispersal to the local environment,” in Geotechnical, Geological and Earthquake Engineering, Springer, Berlin, Germany, 2000.

[26] J. Gustafsson, Visual MINTEQ, Version 3.0, Department of Land and Water Resources Engineering, Royal Institute of Technology-KTH, Stockholm, Sweden, 2012.

[27] J. Gustafsson, Visual MINTEQ, Version 3.1, Department of Land and Water Resources Engineering, Royal Institute of Technology-KTH, Stockholm, Sweden, 2013.

[28] Bio-met, 2013. Bio-met Bioavailability Tool. http://www.biomet.net.

[29] M. Kishe and J. Machiwa, “Distribution of heavy metals in sediments of Mwanza Gulf of Lake Victoria, Tanzania,” Environment International, vol. 28, no. 7, pp. 619–625, 2003.

[30] WHO, Guidelines for Drinking-Water Quality, World Health Organisation WHO, Geneva, Switzerland, 4th edition, 2011.

[31] GIBB, Updated Technical Appraisal Studies of the Mid-Western Towns Water Supply Project, GIBB International, Nairobi, Kenya, 1998.

[32] R. Taylor and K. Howard, “Groundwater quality in rural Uganda: hydrochemical considerations for the development of aquifers within the basement complex of Africa,” in Groundwater Quality, H. Nash and G. McCall, Eds., pp. 31–44, Chapman & Hall, London, UK, 1994.

[33] Ministry of Water and Environment, “Framework and Guidelines for Water Source Protection,” Volume 1: Framework for Water Source Protection, MWE, Kampala, Uganda, 2013.

[34] Health Canadian, “Guidelines for Canadian Drinking Water Quality-Summary Table Water and Air Quality Bureau,” Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, ON, Canada, 2014.

[35] N. R. Kulabako, M. Nalubega, and R. Thunvik, “Study of the impact of land use and hydrogeological settings on the shallow groundwater quality in a peri-urban area of Kampala, Uganda,” Science of the Total Environment, vol. 381, no. 1–3, pp. 180–199, 2007.

[36] S. Mungoma, “The alkaline, saline lakes of Uganda: a review,” Hydrobiologia, vol. 208, no. 1–2, pp. 75–80, 1990.

[37] Uganda Government, “The national environment regulations (standards for discharge of effluent in water or on land),” Uganda Government, Kampala, Uganda, 1999.
[38] Health Canada, Guidelines for Canadian Drinking Water Quality-Summary Table, Water & Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ontario, Canada, 2014.

[39] P. Walakira and J. Okot-Okumu, “Impact of industrial effluents on water quality of streams in Nakawa-Ntinda, Uganda,” Journal of Applied Sciences and Environmental Management, vol. 15, no. 2, pp. 289–296, 2011.

[40] M. Tole and J. Shitsama, “Concentrations of heavy metals in water, fish and sediments of the Winam Gulf,” in Proceedings of the LEVMP Conference, Nairobi, Kenya, March 2001.

[41] A. C. Johnson, R. L. Donnachie, J. P. Sumpter, M. D. Jürgens, C. Moeckel, and M. G. Pereira, “An alternative approach to risk rank chemicals on the threat they pose to the aquatic environment,” Science of The Total Environment, vol. 599-600, pp. 1372–1381, 2017.