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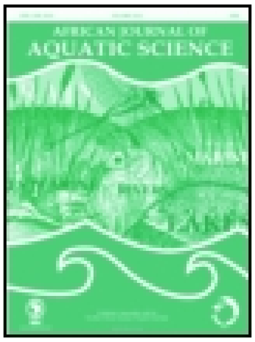

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Metal accumulation in two contiguous eutrophic peri-urban lakes, Chivero and Manyame, Zimbabwe

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Concentrations of aluminium, cadmium, chromium, cobalt, copper, iron, lead, nickel and zinc were determined in surface water, benthic sediments, and the gills, liver and stomach muscle tissues of *Oreochromis niloticus* and *Clarias gariepinus* in peri-urban lakes Chivero and Manyame, Zimbabwe. Five sites were sampled in each lake once per month in November 2015, February, May, August and November 2016. Pollution load index detected no metal contamination, whereas the geo-accumulation index reflected heavy to extreme sediment pollution, with Fe, Cd, Zn, Cr, Ni and Cu present in both lakes. Significant spatial temporal variations were detected for Al, Cr, Cu and Pb across sites within and between the two lakes. High Fe, Al and Cr concentrations in water and sediments in lakes Chivero and Manyame derive from geogenic background sources in addition to anthropogenic loads and intensity. Elevated concentrations of Al, Pb, Cu, Cd, Fe and Zn detected in gills, liver and stomach tissue of catfish corroborate concentrations in water and sediments, and pose the highest ecological and health risk for hydrobionts in lakes Chivero and Manyame. Contiguity of peri-urban lakes exposes them to similar threats, necessitating creative water management strategies, which ensure ecological continuity.

Keywords: bio-accumulation, ecological risk, hydrobionts, lentic systems, toxicodynamics

Introduction

Lakes Chivero and Manyame are two contiguous peri-urban lakes with considerable ecological and economic value for the city of Harare and surrounding dormitory towns in Zimbabwe (Marshall 2011; Nyarumbu and Magadza 2016). Both lakes sustain a substantial number of fishery-dependent livelihoods (Marshall 2011; FAO 2012; FAO 2014). However, because of their location within the catchment they receive intermittent and copious amounts of heavy-metal-laden industrial, agricultural and domestic effluent (Magadza 2003; Arizhibowa 2011; Nyarumbu and Magadza 2016). In excess amounts, metals are potentially toxic, cumulative, persistent and non-biodegradable (Zhan et al. 2010; Zheng et al. 2012; Varol and Sen 2012; Ghaleno et al. 2015). Because of their proximity to settlements, agricultural and manufacturing industries, urban and peri-urban lakes face threats of pollution from effluents laden with metals and potentially toxic organic compounds (Rzymski et al. 2014; Baldwin et al. 2016). Hence, evaluating metal concentrations and estimating potential risks to already stressed freshwater ecosystems is pertinent (Gao and Chen 2012; Mario et al. 2012; Ribeiro et al. 2014; Abalaka 2015).

Complex metal transport mechanics in water and sediments and bio-accumulation biodynamics determine their environmental availability, bioavailability and potential toxicity (Luoma and Rainbow 2005; Wepener et al. 2011; Yuan et al. 2015; Sparks et al. 2017). For polluted lentic systems, such as Chivero and Manyame, with lower flushing rates and more prolonged hydraulic residence, a combination of geogenic and anthropogenic sources, and specific reactivity determine bioavailability, bioaccessibility and toxicity of metals (Wetzel 2001; Tendaupenyu 2012; Yu et al. 2012; Hu et al. 2013; Bouwman et al. 2014; Aguilar-Hinojosa et al. 2016).

Because lakes Chivero and Manyame are located in the same catchment and contiguous, we hypothesised that they face similar anthropogenic pressures and exhibit indistinguishable metal accumulation dynamics in water, sediments and fish tissues. Conversely, we suggested that the application of creative water management strategies, such as ‘ecological continuity’ for contiguous peri-urban water bodies, must initially consider the uniqueness of each aquatic system (Mitroi et al. 2014).

The specific objectives of the current study were to determine to what extent (1) metal concentrations in water and sediment differ spatially and temporally between peri-urban lakes Chivero and Manyame, (2) metal concentrations in these lakes accumulate and pose potential ecological risks, and (3) heavy metal uptake, accumulation and sequestration occur in two common fish species, Nile

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tilapia *Oreochromis niloticus* and sharptooth catfish *Clarias gariepinus* tissues (i.e. ranking concentrations in gills, liver and stomach). The study aimed to determine concentrations of aluminium, cadmium, chromium, cobalt, copper, iron, lead, nickel and zinc in surface water, sediment and the gills, liver and stomach muscle tissues of *Oreochromis niloticus* and *Clarias gariepinus*.

Materials and methods

Study area

Lakes Chivero and Manyame (Figure 1), located in the highly urbanised and populated upper Manyame catchment, Zimbabwe, were studied from November 2015 to November 2016. The Marimba, Mukuvisi, Nyatsime and Manyame Rivers, containing large volumes of raw industrial and urban effluents that contain metals and organic compounds, discharge into Lake Chivero, whereas the effluent-laden Hunyani, Manyame, Muzururi and Gwebi Rivers discharge into Lake Manyame (Nhapi and Gijzen 2004; Nyarumbu and Magadza 2016). Lake Chivero, built in 1952, has a surface area of 2 632 ha, maximum width of 8 km and a maximum depth of 27 m and mean depth of 9.4 m with mean retention time being 1.1 years. Lake Manyame, built in 1976, occupying about three-quarters of the Darwendale Recreational Park, has a surface area of 8 100 ha at full capacity, when its maximum and mean depths are 23 m and 5.6 m, respectively, with an estimated mean retention time of 0.7 years (Marshall 2011). Though they were primarily built to provide potable water to the city of Harare, other multiple uses, such as commercial and artisanal fishing, farmland irrigation and recreational sports have evolved (Marshall 2011), putting additional pressure on water quality and quantity (Nhapi, and Gijzen 2004).

Sampling design

In Lake Chivero five sites, including inflow and outflow points, were selected for collection of water and sediment samples (Figure 1). Five sites were chosen at the broader end of Lake Manyame, because of the logistical constraints of covering this relatively bigger lake (Figure 1). Fish, sediment and water sampling was done once in November 2015 and February, May, August and November 2016. The levels of Al, Pb, Cd, Cr, Co, Cu, Fe, Ni and Zn were measured in water, sediments and two fish species, *Oreochromis niloticus* and *Clarias gariepinus*, which are commonly consumed by the surrounding community. Appropriate metal digestion protocols were used to extract the metals from the water, sediments and fish (see Nhiwatiwa et al. 2011). Metal concentrations in the digested samples were estimated using Flame Atomic Absorption Spectrophotometry (FAAS) following methods by Greenberg et al. (1980).

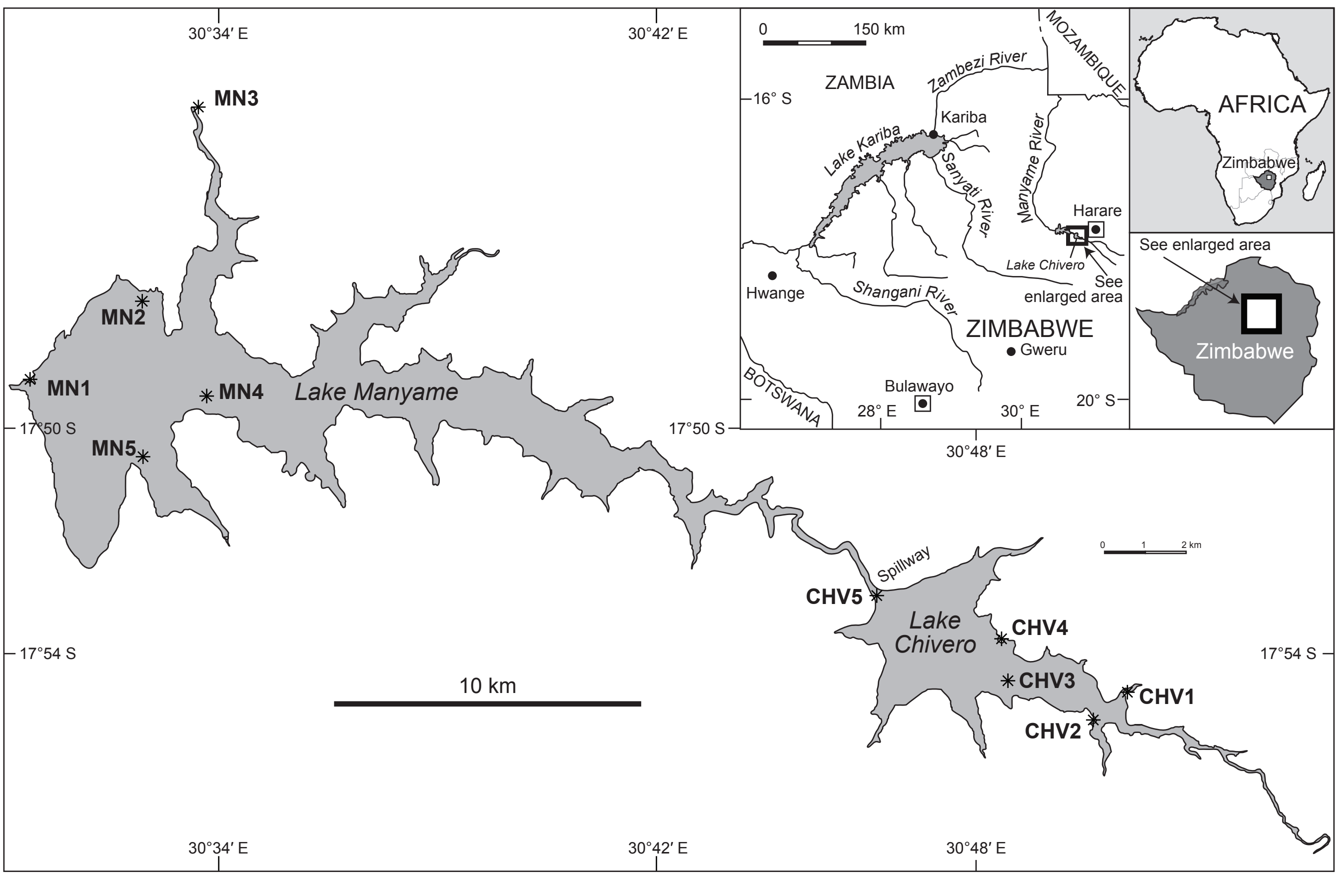

Figure 1: Locations of sampling sites in Lakes Chivero and Manyame

Water and sediment collection

Surface water was collected from three replicate points at five sampling sites in the two lakes using sterilised 250 ml polyethylene bottles. Sediment samples were also collected at the same points as water samples using a polypropylene coring device 1 m long and with 10 cm internal diameter. Typically, cores comprised a 10 cm sediment surface layer for each sample, and two subsamples were taken at chosen locations within an area of about 10 m^2 surrounding each site. These samples were thoroughly mixed so as to create composite samples for each site and were stored in polythene bags. The samples were stored at a temperature of 4 °C in a refrigerator in the laboratory in preparation for heavy metal analysis.

Fish sampling

Two commonly captured fish species, *Oreochromis niloticus* and *Clarias gariepinus* were used for this study. Fish samples were obtained from the sites that were used for water and sediment sample collection. Most of these sites are normally utilised by the local fisheries. On each sampling visit ten specimens of various sizes per species were collected, the aim being to obtain a grab sample representing what the fisheries really obtain and sell to consumers.

Extraction and analysis of metals in water, sediments and fish tissues

Water samples were filtered through 0.45 µm pore sized Whatman G/F filters into sterilised 100 ml flasks and acidified with nitric acid to a pH less than 2. Estimation of the heavy metals was conducted using air/acetylene flame Atomic Absorption Spectrophotometry (AAS). An acid digestion method adopted from Greenberg et al. (1980) was used to extract heavy metals from sediments. An acid-based digestion procedure, used for both water and sediment samples (Greenberg et al. 1980) consisted of two parts. (1) Digestion: the sediments were oven-dried at 180 °C in a muffle furnace and large aggregates were broken up. Then 20 ml nitric acid and 5 ml perchloric acid were added to 5 g of the oven-dried sample. The mixture was heated on a hot plate until fumes were produced and allowed to cool to room temperature. (2) Acidification: 20 ml of 50% hydrochloric acid was added to the mixture from the first digestion. The acidified mixture was heated until boiling and then was cooled to room temperature. The acidified mixture was filtered and distilled water was added to the filtrate in a flask up to the 100 ml mark. Digested sediments were analysed for metals in the atomic absorption spectrophotometer (Greenberg et al. 1980).

One gram wet weight of gill, liver, and stomach tissue of each fish, weighed with an electronic balance, were placed into crucibles to dry at 120°C until they reached a constant weight. Dry gill, liver and stomach tissue were then placed in digestion flasks, to which 5 ml perchloric acid and 10 ml nitric acid were added. Digestion flasks were then placed in an oven at 130 °C until all materials dissolved. Metals in the prepared water, sediments and fish tissue samples were analysed using flame atomic absorption spectrophotometer (FAAS).

The fast sequential atomic absorption spectrometer Spectra-AA 220 FS (Varian, Australia) was used for metal analysis in water, sediments and fish. The FAAS Spectra-AA 220 has different Hollow Cathode Lamps (HCL) with a sampling system based on the electronic control module SIPS-20. The calibration was performed using the standard analytical solutions. The standard analytical solutions were prepared by serial dilutions of 1 000 mg l^{-1} PerkinElmer Pure single-element standards in 2% HNO_3 (v/v). Prior to the analysis, the detection method was validated with reference materials: Merck 100473 for water, LKSD-1 for sediments and ERM-CE278K for fish. The recovery rate exceeded 90% for all determined elements, at low RSD values (below 5%). The detection limits of the FAAS for the analysed metals were 0.05 mg l^{-1} for Ni and Co, 0.2 mg l^{-1} for Al, 0.04 mg l^{-1} for Cr and Pb, 0.03 mg l^{-1} for Fe, 0.01 mg l^{-1} for Cd and 0.005 mg l^{-1} for Cu and Zn.

Quality control and assurance

Procedural blanks and standards were used to ensure quality control of heavy metal analysis readings. In all cases, for every 10 samples of sediments or water, a preparation/reagent blank with concentrations below detectable limits was prepared. For repeatability purposes each sample was analysed in triplicate with a relative standard deviation of <5% for all metals analysed. Standard analytical grade acids were used for the digestion process.

A two-part acid digestion process used for both sediments and water is a highly effective technique, and was preferred so that total metal (element) concentration could be estimated, which would enable quantification of the bioavailability of metals to fish and other aquatic organisms. This was done so as to enhance knowledge of metal concentrations in water, sediment and fish tissues of concern for public health. Moreover, the limitations of the FAAS technique, such as low precision, wavelength interference, sample matrix and inadequate atomisation when there is no good and functional monochromator, necessitates the use of the two part acid digestion method. The detection limits and the working range of the FAAS are low and depend on the sample matrix, such that there is a need to extract a sizeable amount of the metal analyte for effective atomisation, absorption and detection at the specific wavelength.

Statistical analysis

Metal concentrations in water and sediments

Metal pollution loading, geo-accumulation and potential ecological risk indices were calculated.

The pollution load index (PLI) is defined as the nth root of the multiplications of specific metal concentrations (CF_{metals}):

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots\ldots\ldots CF_n)^{1/n}$$

Values of PLI >1 imply that heavy metal pollution exists. Otherwise, if PLI <1, there is no heavy metal pollution (Tomlinson et al. 1980).

The geo-accumulation index (Igeo) is defined by the following equation:

$$Igeo = \log_2 (C_n/1.5 \times Bn)$$

Here, C_n is concentration of metal n and Bn is background concentration of the metal (n) usually adopted from sediment quality guidelines (SDQ). Constant factor K is a background matrix correction factor, because of lithospheric effects, which is usually defined as 1.5 (Müller 1969, 1981). The Müller classification for the geo-accumulation index is presented in Appendix 1.

In the Potential Ecological Risk Index (PERI) method (Hakanson 1980) potential ecological risk coefficient E^i_r of a single element, and potential ecological risk index RI of the multi-element are computed using the equations:

$$Ci_{f=} C_{is}/C_{in}$$
$$Ei_{r=} Ti_r \times Ci_f$$
$$RI = \sum i = 1nEi_r$$

Here, C^i_f is the pollution coefficient of a single element of "i" or the monomial contamination factor; C^i_s is the measured level of sedimentary heavy metal; C^i_n is the background level of sedimentary heavy metal; T^i_r is the toxic response factor for the given element of "i", which accounts for the toxic requirement and the sensitivity requirement;

RI is the sum of all risk factors for heavy metals in sediments.

The average shale background concentration of global sediments is selected as the reference baselines in this study. We adopted the Hakanson (1980) PERI classification criteria shown in Appendix 2.

In order to obtain the bioconcentration factor (BCF), that is the ratio of metal concentrations in the sediment phase to that in the water phase, the following formula used was:

Bioconcentration factor = concentration of metal in sediments/concentration of metal in water.

BCF values greater than 1 000 are considered high and those less than 250 low. Those between these extremes are classified as moderate (Wepener et al. 2001; Nhiwatiwa et al. 2011).

Metal concentrations in fish tissues
Bio-accumulation factor (BAF), and biota sediment accumulation factor (BSAF) for each metal in different fish species are defined as the ratio of the concentration of a metal in any tissue of an aquatic organism to its concentration in water and sediments, respectively. The BAF/BSAF is calculated as: BAF = C_T/C_W, OR BSAF = C_T/C_S, where, C_T = concentration of chemical in any tissue, Cw = concentration of chemical in water and C_S = concentration of chemical in sediment.

Spatio-temporal metal concentrations in water, sediments and fish tissue
Metal concentrations in water, sediment and fish tissue samples from all five sampling occasions in each lake were recorded and their mean values obtained were used for additional statistical analysis. Spatial and temporal differences in metal concentrations in water, sediments and fish tissues were analysed using non-parametric tests, Kruskal–Wallis ANOVA and Mann–Whitney U-test at 5% level of significance in SPSS version 21.

Results

Metals in water
Iron concentrations were high (above the FAAS detection limit), >300 mg l^{-1} in November 2015 and 2016 in surface water samples in Lake Chivero (Table 1). High Al, Zn, Co and Pb levels in water were observed across all sites in November 2015 and November 2016 in Lake Chivero (Table 1). High Fe concentrations were also observed in November 2015 and November 2016 in Lake Manyame (Table 1). High Al concentrations were observed across all sites in Lake Manyame. High Cr and Zn concentrations were observed across all sites in May, August and November 2016 in Lake Manyame (Table 1). Concentrations of Zn, Cd, Pb, Co, Cu and Ni were high at the tributary inflow sites, CHV1 and CHV2, in Lake Chivero. Aluminium concentrations were high in Lake Manyame, particularly at MN4 and MN5. The compositional patterns for metals in water differed slightly between the two lakes, with Lake Chivero's metal concentration patterns comprising Fe > Zn > Co > Al > Cr > Cu > Ni > Cd > Pb, and that of Lake Manyame consisting of Fe > Zn > Co > Al > Cr > Ni > Cu > Cd > Pb. Overall, there was significant spatial concentration (ANOVA; $p < 0.05$) and temporal distribution (Mann–Whitney U-test; $p < 0.05$) of Al, Cr, Cu and Pb across sites, within and between the two lakes.

Metals in sediments
Iron concentrations were significantly high in the sediments of both lakes, with high values of 600–880 mg l^{-1} from February to November 2016 recorded in Lake Manyame (Table 2). Considerably higher Al concentrations, ranging from 2.3 to 5.5 mg l^{-1}, were recorded at sites MN1, MN4 and MN5 in Lake Manyame. Relatively high Cr concentrations, ranging from 3.00 to 3.20 mg l^{-1}, were recorded in Lake Chivero at CHV1 and CHV2, the Marimba entrance and Marimba-Mukuvisi confluence points, particularly in the drier months of May and August 2016. High Cr values, with a maximum value of 12.2 mg l^{-1}, were recorded in Lake Manyame at MN2, Chrome Bay, which is located close to the mineral-rich Great Dyke. Descending compositional pattern for metals in sediments for Lake Chivero was Fe > Cr > Ni > Zn > Cu > Al > Co > Pb > Cd, whereas that for Lake Manyame was Fe > Cr > Al > Ni > Zn > Cu > Co > Pb > Cd. Only Al, Co and Cr concentrations had significantly different spatial (Kruskal–Wallis ANOVA; $p < 0.05$) and temporal distribution (Mann–Whitney U-test; $p < 0.05$) across all sites, within and between the two lakes.

Bioconcentration of metals
Nickel, Zn, Cu, Cr, Pb, Fe and Cd had notably high bioconcentration factors, with their concentrations in the solid phase (sediments) being higher relative to the liquid phase (Table 3). Using the standard defined criteria, all sites in the lakes had low BCFs of <250 (Table 3). The

Table 1: Mean ± SD (n = 5) heavy metal concentrations (mg l^{-1} dry weight) in water from Lakes Chivero and Manyame in November 2015–November 2016

Lake	Month	Ni	Cu	Fe	Pb	Cr	Zn	Co	Cd	Al
Chivero	Nov 2015	0.20 ± 0.18	0.30 ± 0.16	647.7 ± 333.56	0.90 ± 0.82	0.40 ± 0.57	0.30 ± 0.32	0.10 ± 0.19	0.10 ± 0.04	1.20 ± 1.01
	Feb 2016	0.004 ± 0.005	0.10 ± 1.09	59.9 ± 56.80	0.02 ± 0.03	0.10 ± 0.15	0.10 ± 0.06	0.70 ± 0.97	0.04 ± 0.07	0.40 ± 0.60
	May 2016	0.10 ± 0.09	0.10 ± 0.08	119.1 ± 107.76	0.10 ± 0.04	0.20 ± 0.18	1.10 ± 1.44	0.80 ± 0.86	0.12 ± 0.09	0.60 ± 0.71
	Aug 2016	0.20 ± 0.12	0.30 ± 0.23	174.6 ± 170.97	0.10 ± 0.08	0.20 ± 0.21	1.13 ± 1.28	0.90 ± 0.82	0.40 ± 0.37	0.60 ± 0.59
	Nov 2016	0.20 ± 0.12	0.30 ± 0.27	177.7 ± 222.88	0.20 ± 0.14	0.30 ± 0.29	1.60 ± 1.83	0.60 ± 0.44	0.70 ± 0.93	0.60 ± 0.73
Manyame	Nov 2015	0.10 ± 0.07	0.10 ± 0.08	383.4 ± 217.99	0.10 ± 0.12	0.20 ± 0.13	0.30 ± 0.23	0.10 ± 0.12	0.03 ± 0.04	3.70 ± 1.12
	Feb 2016	0.10 ± 0.08	0.10 ± 0.14	9.1 ± 2.80	0.10 ± 0.08	0.20 ± 0.18	0.10 ± 0.08	0.04 ± 0.05	0.004 ± 0.005	3.20 ± 0.67
	May 2016	0.11 ± 0.12	0.30 ± 0.26	43.3 ± 23.26	0.10 ± 0.09	0.40 ± 0.37	0.20 ± 0.12	0.20 ± 0.11	0.10 ± 0.09	0.90 ± 0.73
	Aug 2016	0.20 ± 0.17	0.70 ± 0.62	114.6 ± 75.37	0.20 ± 0.15	1.10 ± 0.14	0.50 ± 0.24	0.70 ± 0.36	0.20 ± 0.06	0.90 ± 0.27
	Nov 2016	0.30 ± 0.19	0.60 ± 0.50	410.9 ± 129.66	0.10 ± 0.09	1.40 ± 0.60	0.60 ± 0.49	0.90 ± 0.35	0.20 ± 0.16	1.60 ± 0.56

Table 2: Mean ± SD (n = 5) metal concentrations (mg kg^{-1} dry weight) in surface sediment from Lakes Manyame and Chivero in November 2015–November 2016

Lake	Month	Ni	Cu	Fe	Pb	Cr	Zn	Co	Cd	Al
Chivero	Nov 2015	2.60 ± 1.53	2.30 ± 3.02	793.40 ± 447.53	1.40 ± 0.93	4.60 ± 1.84	2.90 ± 3.91	0.50 ± 0.19	0.10 ± 0.04	1.70 ± 1.66
	Feb 2016	2.10 ± 1.07	1.20 ± 1.13	714.50 ± 448.07	1.60 ± 0.99	3.50 ± 0.91	1.90 ± 1.33	0.80 ± 0.22	0.10 ± 0.06	1.10 ± 1.39
	May 2016	2.80 ± 2.53	1.80 ± 1.48	529.00 ± 212.41	1.60 ± 1.07	1.90 ± 1.10	1.50 ± 0.72	0.90 ± 0.29	0.40 ± 0.36	2.20 ± 1.88
	Aug 2016	3.10 ± 2.98	1.20 ± 0.87	661.50 ± 223.95	1.50 ± 1.13	1.60 ± 1.04	1.40 ± 0.73	1.50 ± 1.08	0.50 ± 0.45	1.20 ± 1.29
	Nov 2016	2.20 ± 2.38	1.40 ± 1.64	584.80 ± 297.98	2.10 ± 2.33	1.50 ± 1.70	1.50 ± 1.83	1.20 ± 1.22	0.60 ± 0.69	0.70 ± 0.36
Manyame	Nov 2015	2.00 ± 0.89	1.30 ± 0.83	479.14 ± 231.89	0.60 ± 0.36	3.50 ± 1.55	0.70 ± 0.64	0.60 ± 0.42	0.10 ± 0.01	4.30 ± 1.73
	Feb 2016	2.40 ± 1.27	1.80 ± 1.26	694.90 ± 221.72	0.70 ± 0.38	3.60 ± 2.01	0.90 ± 0.80	0.80 ± 0.36	0.20 ± 0.10	3.60 ± 1.19
	May 2016	3.10 ± 0.96	1.60 ± 0.81	760.30 ± 218.66	0.70 ± 0.44	4.40 ± 2.59	1.40 ± 1.14	1.40 ± 0.34	0.20 ± 0.18	3.10 ± 1.01
	Aug 2016	2.40 ± 1.02	1.50 ± 0.65	818.10 ± 198.88	0.70 ± 0.43	6.32 ± 3.83	1.30 ± 0.61	1.70 ± 0.39	0.36 ± 0.31	2.30 ± 0.77
	Nov 2016	2.20 ± 1.63	1.60 ± 0.67	815.90 ± 356.80	0.50 ± 0.45	4.70 ± 2.00	1.50 ± 0.58	1.95 ± 0.12	0.32 ± 0.50	2.10 ± 0.26

Table 3: Mean ± SD sediment/water ratios for metals in Lakes Chivero and Manyame in November 2015–November 2016

Lake	Month	Ni	Cu	Fe	Pb	Cr	Zn	Co	Cd	Al
Chivero	Nov 2015	38.1 ± 59.44	7.0 ± 9.49	1.7 ± 1.22	21.4 ± 42.89	11.2 ± 18.92	15.9 ± 17.54	2.25 ± 4.49	2.4 ± 2.87	1.9 ± 0.58
	Feb 2016	85.2 ± 138.67	65.8 ± 143.24	39.1 ± 48.86	109.5 ± 132.12	63.8 ± 87.62	19.7 ± 15.81	20.9 ± 27.54	6.3 ± 8.26	1.1 ± 1.51
	May 2016	63.7 ± 61.31	17.8 ± 12.28	8.2 ± 8.18	31.7 ± 33.33	34.2 ± 49.83	9.7 ± 13.70	3.3 ± 3.23	2.6 ± 1.67	8.5 ± 8.82
	Aug 2016	17.8 ± 8.60	5.6 ± 5.12	9.7 ± 11.40	13.7 ± 4.46	16.6 ± 20.48	3.7 ± 4.26	2.2 ± 0.72	1.6 ± 0.64	4.9 ± 7.31
	Nov 2016	8.4 ± 6.66	3.8 ± 4.23	12.6 ± 13.57	12.9 ± 17.17	1.5 ± 1.70	0.9 ± 0.26	1.7 ± 1.48	6.9 ± 10.58	18.1 ± 28.24
Manyame	Nov 2015	70.01 ± 85.15	30.4 ± 56.75	1.9 ± 1.78	1.4 ± 1.25	7.1 ± 9.04	3.5 ± 1.43	4.1 ± 2.86	3.5 ± 1.82	1.2 ± 0.39
	Feb 2016	106.5 ± 177.9	33.8 ± 35.66	88.2 ± 54.07	10.4 ± 8.68	122.2 ± 139.91	36.0 ± 44.17	3.2 ± 4.61	10.8 ± 15.39	1.1 ± 0.43
	May 2016	83.7 ± 110.43	21.0 ± 25.68	27.9 ± 25.44	16.5 ± 17.29	25.6 ± 28.59	7.9 ± 5.57	8.8 ± 3.78	6.6 ± 7.77	5.8 ± 4.30
	Aug 2016	16.7 ± 13.78	4.5 ± 4.11	9.5 ± 5.28	3.7 ± 0.65	5.8 ± 3.56	3.8 ± 3.50	3.1 ± 2.32	2.60 ± 2.06	2.6 ± 0.82
	Nov 2016	12.9 ± 15.33	18.0 ± 33.58	1.9 ± 0.73	4.6 ± 5.07	3.7 ± 1.99	4.8 ± 5.40	2.4 ± 1.06	3.4 ± 4.41	1.4 ± 0.52

bioconcentration hierarchical order was Ni > Pb > Cu > Cr > Zn > Fe > Co > Cd > Al for both lakes, which differs significantly from the hierarchical order of absolute metal concentrations in both surface water and sediments in both lakes.

Geo-accumulation of metals and their potential ecological risk

The PLI across all sites in Lakes Chivero and Manyame was less than 1, showing no heavy metal pollution. High PLI values of 0.24 at CHV1, 0.21 at CHV4 suggest considerable contamination for some metals, especially in early phases of the high water flow period in November 2015, 2016 in Lake Chivero (Table 4). The geo-accumulation index shows that surface sediments in both lakes were either heavily or extremely contaminated with Fe, Cd, Zn, Cr, Ni and Cu (Appendix 1 and Table 5). Surface sediments in lakes Chivero and Manyame were moderately polluted, (I_{GEO} = 1–2), by Pb and Al, and were moderately uncontaminated with Co (Table 5 and Appendix 2). PERI scores were high for Fe, Cd, Co and Al in surface sediments of the two lakes for all sampling periods (Table 6). Iron concentrations in surface sediments posed a serious ecological risk in both lakes, with Cd posing moderate ecological risk (Appendix 2 and Table 6). The concentrations of all the metal species in surface sediments recorded posed low ecological risk (Appendix 2 and Table 6). The hierarchical potential ecological risk order of metals in surface sediments of both lakes was Er (Fe) > Er (Cd) > Er (Co) > Er (Zn) > Er (Al) > Er (Cu) > Er (Cr) > Er (Pb) > Er (Ni).

Metal concentration and bio-accumulation in fish tissues

There were high concentrations of Fe, Al, Cu, Pb and Cd particularly in the gills of catfish in Lake Chivero (Appendix 3). High concentrations of Fe (4.0–7.0 mg kg^{-1}) were recorded in gills and livers of catfish in Lakes Chivero and Manyame. The Fe, Al and Zn concentrations were high in liver and stomach tissues of catfish in both lakes, especially during low-water flow periods, May–August 2016 (Appendix 3). Consistently high Ni and Pb concentrations, ranging from 0.5 to 1.5 mg kg^{-1} were recorded in stomach tissues of catfish in Lake Chivero. High Pb concentrations ranging from 0.5 to 1.3 mg kg^{-1} were recorded in stomach tissues of catfish in Lake Manyame. The overall compositional pattern for metal concentrations in all organs was Fe > Al > Pb > Ni > Zn > Cu > Cd > Cr > Co. Metal concentration hierarchy in organs was gills > liver > stomach, though elevated concentrations of Al and Pb in stomach tissues of tilapia and catfish in low-flow periods can indicate serious contamination (Appendix 3).

The BAF for *Oreochromis niloticus* gills indicates significant metal accumulation (with BAF >5 in some cases) into gills from water for Ni, Pb, Al, Cr, Cd, and Zn, particularly in Lake Chivero during low-flow or dry months May and August 2016 (Appendix 4). The BAF for *Clarias gariepinus* gills was high for Cr, Ni, Zn, Pb, Cd, Cu and Al in Lake Chivero in the immediate post-rain period of February 2016 and the early dry season, May 2016 (Appendix 4). High BAF in gills of catfish and tilapia in Lake Manyame for Ni, Cu, Pb, Cr, Zn, Cd and Al was

Table 4: Pollution Load Index (PLI) for metals in surface sediment from Lakes Chivero (Chv) and Manyame (Mn) in November 2015–November 2016

Lake	Nov 2015	Feb 2016	May 2016	Aug 2016	Nov 2016
	PLI				
Chv 1	0.24	0.01	0.02	0.05	0.06
Chv 2	0.001	0.001	0.009	0.01	0.08
Chv 3	0.04	0.04	0.005	0.15	0.145
Chv 4	0.002	0.015	0.019	0.02	0.208
Chv 5	0.016	0.001	0.002	0.0024	0.0031
Mn 1	0.004	0.012	0.02	0.007	0.012
Mn 2	0.005	0.008	0.0004	0.0005	0.007
Mn 3	0.0002	0.001	0.001	0.001	0.001
Mn 4	0.004	0.006	0.003	0.0001	0.006
Mn 5	0.073	0.038	0.047	0.007	0.008

Table 5: Geo-accumulation Index (I_{GEO}) for metals in surface sediment from Lakes Chivero (Chv) and Manyame (Mn) in November 2015–November 2016

Lake	Month	Ni	Cu	Fe	Pb	Cr	Zn	Co	Cd	Al
	Nov 2015	4.50	5.28	11.09	1.01	1.43	1.28	1.59	6.28	1.69
	Feb 2016	2.06	4.85	10.98	4.38	5.82	6.25	0.92	5.22	1.29
Chv	May 2016	4.44	5.40	10.25	4.46	4.79	5.94	0.89	4.92	2.09
	Aug 2016	4.53	4.75	11.05	4.12	4.52	5.77	0.23	3.77	0.96
	Nov 2016	3.38	4.22	10.63	2.99	3.43	3.98	1.15	4.61	0.88
	Nov 2015	4.22	4.68	10.47	0.72	1.33	1.03	1.65	6.39	4.26
	Feb 2016	2.42	5.21	11.12	3.30	5.75	4.85	0.93	5.04	3.51
Mn	May 2016	4.88	5.39	11.26	3.33	6.01	5.53	0.15	6.34	3.32
	Aug 2016	4.45	5.35	11.38	3.27	6.52	5.85	0.13	4.22	2.87
	Nov 2016	4.18	5.50	11.19	1.80	6.16	5.98	0.38	5.47	2.76

Table 6: Potential Ecological Risk Index (PERI) for metals in surface sediments from Lakes Chivero (Chv) and Manyame (Mn) in November 2015–November 2016

Lake	Month	Ni	Cu	Fe	Pb	Cr	Zn	Co	Cd	Al
	Nov 2015	0.876	2.932	793.360	1.428	1.858	14.360	13.150	35.000	1.686
	Feb 2016	0.685	0.686	714.530	1.562	1.404	9.810	20.300	72.000	1.118
Chv	May 2016	0.930	1.012	529.044	1.618	0.763	7.360	21.250	179.000	2.198
	Aug 2016	1.047	0.136	661.478	1.506	0.642	7.000	38.500	261.000	1.190
	Nov 2016	0.749	0.796	584.846	2.058	0.594	7.340	31.150	304.000	0.654
	Nov 2015	0.671	2.598	479.140	0.594	1.394	3.320	14.600	30.000	4.260
	Feb 2016	0.806	0.986	694.878	0.688	1.454	4.550	21.200	87.000	3.590
Mn	May 2016	1.020	0.868	760.314	0.716	1.763	6.920	34.650	76.000	3.126
	Aug 2016	0.783	0.165	818.130	0.688	2.530	6.740	42.000	180.000	2.302
	Nov 2016	0.742	0.911	815.962	0.476	1.878	7.250	48.750	159.000	2.050

detected throughout the sampling period (Appendix 4), reflecting the non-seasonal nature of pollution in this reservoir. The BAF in livers of both fish species shows high accumulation values for Ni, Cu, Pb, Cr, Cd, Al, and Zn, excluding Fe and Co in Lakes Chivero and Manyame (Appendix 6). Nickel, Pb, Cr, Cd and Al had high BAF values in stomach tissues of the two fish species in both lakes (Appendix 6). Biota sediment accumulation factor (BSAF), a reflection of the ratio of metals in selected tissues to that in sediments, indicates high BSAF values for Pb, Cd, Al in gills of fish sampled in the two lakes (Appendix 4). High BSAF values in livers of the two fish species were calculated for Zn, Al, Pb and Cd across all sampling months in Lakes Chivero and Manyame (Appendix 5). Stomach tissues of tilapia and catfish had relatively higher BSAF values for Cd, Zn and Pb during low flow periods of May and August 2016 in Lake Manyame (Appendix 6).

Discussion

Metals induce detrimental and lethal effects in freshwater hydrobionts, especially at excessive concentrations (Sparks et al. 2017), destabilising ecosystem function and are even toxic to humans and apex predators (Iqbal and Shah 2014; du Preez et al. 2016). Evaluation and knowledge of metal contamination and an understanding of its potential ecological risks can influence water resources and habitat management strategies (Nhiwatiwa et al. 2011). Our results showed dominance by iron in water and sediment phases in both peri-urban lakes for the duration of sampling. Excessive iron concentrations in water and sediments were found at inlet points (site CHV1; Marimba River inflow, site CHV2; Mukuvisi and Marimba confluence, in Lake Chivero), as well as in the mid-lake sites MN3, MN2, and MN5 (Gwebi River inflow, Chrome Bay and Bird control sites in Lake Manyame). In Lake Chivero, Sites CHV1 and CHV2 mark the entry points for polluted rivers that discharge metal-laden effluent from Harare and Chitungwiza (Arizhibowa 2011; Nyarumbu and Magadza 2016).

Metal pollution at some sites in Lake Manyame is attributable to metal-laden effluent discharged by mines at Chrome Bay, MN2, and sewage and agricultural effluent inflows at MN5 and MN3. Additionally, high concentrations of Fe and Cr at some polluted sites in Lake Manyame indicate localised Fe pollution attributable to geogenic sources (Thornton and Nduku 1982; Alloway 1990; Giarratano et al. 2010). Tendaupenyu (2012) indicate that most reservoirs in the highly urbanised Manyame catchment have interchangeably high amounts of phosphates, nitrates and sulphates. These are efficient Fe-carriers, whose reactivity depends on pH and dissolved oxygen amounts in the water (Wetzel 2001). Thus, they regulate Fe concentrations in aquatic systems, because of their tendency to co-precipitate with iron, either in the ferrous or ferric state into sediments by adsorption (Balintova et al. 2009).

Zinc, cobalt and copper concentrations were high in water and sediments in both lakes (Balintova et al. 2009; Balintova and Petrilakova 2011). This finding is attributable to elevated concentrations arising from domestic, industrial, agricultural effluent input from the highly urbanised Manyame catchment (Magadza 2003; Nhapi et al. 2004). For Zn, Co and Cu, which are essential elements, the concern in the present study relates to their essentiality and possible toxicity when present at high levels (Teo and Chen 2001). Copper, Zn and Co form the essential group of metals required for metabolic activities in organisms. However, high concentrations surpassing the standard CMC and CCC levels and prolonged consumption of Zn is associated with fatigue, loss of appetite, muscle stiffness, dizziness, and neutropenia in fish and humans (Hess and Schmid 2002). Toxicological effects of elevated Co and Cu concentrations include vasodilation, flushing and cardiomyopathy in freshwater hydrobionts and humans (Teo and Chen 2001). Nickel, a naturally abundant element and a co-factor in the enzyme urease (Teo and Chen 2001), was abundant in sediments of both lakes. Widespread use of Ni in industries in the Manyame catchment derives from its superior properties such as high malleability, good thermal and electric conductivity, as well its being as an effective industrial catalyst (Mabika et al. 2014). At elevated concentrations studies report Ni-induced renal, cardiovascular, reproductive and immunological effects on fish such as rainbow trout (Pane et al. 2003).

There were high concentrations of toxic heavy metals, Al, Pb, Cr and Cd, in both water and sediments sampled in Lakes Chivero and Manyame. Chromium is an essential trace element, though toxic at elevated concentrations, whereas Al, Pb and Cd have no known functions as nutrients, and are toxic to plants and microorganisms even in minute quantities (Alloway 1990; Nies 1999). High concentrations of Al in Lake Manyame can be related to the use of aluminium sulphate as a cleaning agent at the Morton Jaffray Waterworks at Lake Chivero. The aluminium sulphate effluent is discharged into the Manyame River which flows into Lake Manyame. The Pb and Cd concentrations are enhanced by catchment activities such as automobile repairs, lead acid battery manufacturing and intensive use of cadmium-based phosphate fertilizers for agricultural purposes (Zhang and Shan 2008; Xia et al. 2011; Sayadi et al. 2015). High Cr concentrations at sites in Lake Manyame derive from chrome mining and smelting industries in the Norton and Great Dyke areas. Thornton and Nduku (1982) attributed elevated levels of Fe, Cr and Zn to the natural igneous ferric calcite geological deposits in Lake Manyame. It appears that complexation, redox and pH-mediated active transitional displacement of less reactive metals by more reactive metals determines their concentrations and mobility into different phases in Lakes Manyame and Chivero.

Significant spatial and temporal heterogeneity in individual metal element concentrations and bioconcentration factors (BCFs) within and between the two lakes indicate stochastic variable influence of exogenous anthropogenic pollution sources, in addition to geogenic sources (Alloway 1990; Wepener et al. 2001; Sparks et al. 2017). Alternatively, it shows dissimilar self-purification capacity and incremental metal absorption into sediments for the two lakes (Zhan et al. 2010). However, similarity in metal compositional patterns in water and sediments for the both lakes, regardless of some subtle spatiotemporal variations, is attributable to almost similar pollution sources within their catchments (Alloway 1990; Wepener et al. 2001). There is a mismatch in the descending hierarchy for bioconcentration factors and absolute metal concentrations in water and sediments in the two lakes studied. Metals have specific reactivities which influences their adsorption, complexation, coagulation, incorporation flocculation, desorption and co-precipitation, resuspension and sedimentation into either water or sediment phase (Campana et al. 2013; Lin et al. 2013).

The pollution load index (PLI) reflected no heavy metal pollution in water and sediments using the defined criteria (PLI <1) by Tomlinson et al. (1980). Nevertheless, the constant presence of toxic metals such as Cd, Pb and Al at most sites indicates contamination which requires the formulation of effective metal-specific creative water resources and habitat management strategies (Nhiwatiwa et al. 2011; Nyarumbu and Magadza 2016). The relatively more informative and comprehensive geo-accumulation index (Müller 1969) shows that surface sediments in the two lakes were either heavily or extremely contaminated with Fe, Cd, Zn, Cr, Ni and Cu. Potential ecological risk order index (PERI) of metals in surface sediments of both lakes tends to relate positively to the hierarchical descending order of metal concentrations in both water and sediments (Hakanson 1980). This is true for the present study, as high PERI scores for Fe, Cd, Co and Zn in high concentrations in water and sediments pose the highest ecological and health risk for hydrobionts.

The environmental availability of a metal determines its bioavailability under specific immediate environmental conditions. Hence the subsequent risk posed by any element is also specific and unique to the episodic and long-term environmental conditions at a particular site (Hakanson 1980; Qui 2010; Sorsa et al. 2016).

Heavy metals in unpolluted sediments present in the crystal lattice of minerals and other inorganic residual fractions which constitute detritus or bottom mud (Lin et al. 2013). However, when polluted, the form of heavy metals is altered, with most elements existing in the form of non–soluble ion exchangeable Fe oxides, sulphates, silicates and carbonates (Hu et al. 2013). Metals tend to present as different species, with the parent element associating with different ligands, but never being irreversibly transformed or metabolised (Yu et al. 2012; Hu et al. 2013). Thus, for future studies of metal contamination in freshwater lakes such as Chivero and Manyame, it would be better to understand and characterise the risk presented to human and ecological receptors by metals in the environment. There is a need to investigate processes that affect metal speciation and a quantification of consequent effects of speciation on metal bioavailability within peri-urban freshwater lakes (Bouwman et al. 2014).

The high concentrations of Fe, Al, Cu, Pb and Cd, particularly in the gills, liver and stomach of catfish and tilapia, reflect the concentrations of such metals in water and sediments in both lakes. Metals in higher concentrations in water and sediments are more likely to accumulate to toxic levels in fish tissues and potentially pose an ecological risk. Significant differences in BAFs and BSAFs for *O. niloticus* and *C. gariepinus* relates to the significant differences in their feeding and habitat ecology. Catfish are predominantly benthivorous and tilapia are mostly pelagic (Marshall 2011). Despite uniformity in the descending order of metal accumulation for all organs, it appears that the absorption, distribution, transformation and excretion of a metal relates to an organism's ability to regulate and/or store the metal (Luoma and Rainbow 2005). Metal bio-accumulation in fish tissues is complex, as it is influenced by multiple sources of exposure, such as diet, solution and the geochemical effects of bio-availability (Luoma and Rainbow 2005). Metal bio-accumulation in fish varies significantly from species to species, because of their inherent potential to tolerate, and even co-evolve efficient depuration mechanisms (Tsai and Liao 2006; Kousar and Javed 2014).

Overall, there is considerable metal contamination in the water, sediments and fish tissues in Lakes Chivero and Manyame. Subtle spatiotemporal variations in individual metal concentrations within and between the two lakes implies a need to consider the effects of unique and site-specific localised hydrodynamics on the environmental availability of each metal in these lakes. However, the similarity in descending order of the metal concentration and bioconcentration factors for the two lakes suggests the presence of similar anthropogenic pressures and intensity, because of their being contiguous. Therefore, the application of creative water quality and quantity management strategies based on the need for ecological continuity might reduce pollution and enhance habitat conservation in both lakes. Although quantification of bio-accumulation of metals is of significant value as an exposure indicator, metals are not metabolised. Therefore, future studies on metal accumulation in the tissues of hydrobionts in peri-urban lakes require more robust multivariate biodynamic models.

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Appendix 1: Müller (1969) classification for Geo-accumulation Index (Igeo), reference monomial metal contamination factor C_n^i and toxic response factor for each metal (toxic coefficient T_r^i) of various heavy metals

I_{GEO}	Class	Pollution status						
0	0	Practically uncontaminated						
1	0–1	Uncontaminated to moderately contaminated						
1–2	2	Moderately contaminated						
2–3	3	Moderately to heavily contaminated						
3–4	4	Heavily contaminated						
4–5	5	Heavy to extremely contaminated						
>5	6	Extremely contaminated						
metal	Al	Cr	Ni	Co	Cu	Zn	Fe	Cd	Pb
C_n^i/ (ppm)/	5	25	15	1	45	70	5	0.3	25
T_r^i	1	2	1	5	5	1	1	30	5

Appendix 2: Hakanson (1980) ecological risk classification criteria.

Risk range (E_r and RI)	Classification
E_r < 40; RI < 150	Low ecological risk
40 < E_r ≤ 80; 150 < RI < 300	Moderate ecological risk
80 < E_r ≤ 160; 150 < RI < 300	Appreciable ecological risk
160 < E_r ≤ 320; 300 < RI < 600	High ecological risk
E_r > 320; 300 < RI < 600	Serious ecological risk
E_r > 320; RI ≥ 600	Significantly high serious ecological risk

E_r = ecological risk, RI = multi-element ecological risk

Appendix 3a: Mean concentrations (mg kg^{-1}) of Ni, Cu, Fe and Pb in gills, liver and stomach tissue of catfish (CG) and tilapia (ON) in Lakes Chivero (CHV) and Manyame (MN) in November 2015–November 2016

Metal		Ni	Ni	Cu	Cu	Fe	Fe	Pb	Pb
Fish species		ON	CG	ON	CG	ON	CG	ON	CG
Gill									
CHV	Nov 2015	0.55	0.20	0.05	0.07	5.48	5.46	0.35	1.28
	Feb 2016	0.30	0.64	0.99	0.31	2.29	4.89	0.99	0.83
	May 2016	0.37	0.97	0.36	1.19	2.30	4.89	1.16	0.94
	Aug 2016	0.25	0.99	0.51	1.66	2.63	4.84	1.25	1.08
	Nov 2016	0.27	0.19	0.08	0.23	5.30	6.01	0.17	1.17
MN	Nov 2015	0.02	0.04	0.04	0.03	2.23	6.47	0.34	0.34
	Feb 2016	1.10	0.09	0.15	0.31	2.54	7.00	0.03	0.03
	May 2016	0.99	1.15	0.38	0.78	2.54	7.00	0.24	0.70
	Aug 2016	1.42	1.36	0.34	1.14	2.50	3.25	0.43	0.79
	Nov 2016	0.08	0.03	0.05	0.12	3.27	6.80	0.16	0.59
Liver									
CHV	Nov 2015	0.05	0.37	0.31	0.65	4.10	1.50	0.38	0.29
	Feb 2016	0.20	0.17	0.44	1.32	4.02	1.32	0.25	0.64
	May 2016	0.27	0.69	0.63	1.63	4.02	1.32	0.39	0.66
	Aug 2016	0.59	0.77	0.84	1.64	5.46	1.87	0.44	0.69
	Nov 2016	0.14	0.38	0.30	0.59	7.82	3.61	0.32	0.35
MN	Nov 2015	0.07	0.02	0.08	0.05	3.02	6.76	0.26	0.25
	Feb 2016	0.07	0.46	0.45	0.59	4.25	7.75	0.04	0.66
	May 2016	0.17	0.89	0.59	1.06	4.25	7.75	0.06	0.78
	Aug 2016	0.40	1.17	1.08	1.42	5.01	5.50	0.16	0.57
	Nov 2016	0.20	0.09	0.23	0.11	4.15	11.62	0.30	0.37
Stomach									
CHV	Nov 2015	0.08	1.12	0.01	0.31	1.46	2.35	0.40	0.69
	Feb 2016	0.25	1.16	0.05	0.70	1.33	3.02	0.42	0.57
	May 2016	0.15	1.48	0.08	0.96	1.33	3.02	0.04	0.41
	Aug 2016	0.22	1.70	0.20	1.07	1.45	3.28	0.04	0.48
	Nov 2016	0.13	0.53	0.01	0.39	1.24	2.05	0.41	0.72
MN	Nov 2015	0.12	0.09	0.02	0.04	2.16	1.40	0.31	0.55
	Feb 2016	0.08	0.01	0.29	0.71	2.67	5.21	0.21	0.64
	May 2016	0.09	0.67	1.04	0.91	2.67	5.21	0.63	1.22
	Aug 2016	0.36	0.89	1.16	1.01	2.49	6.20	0.64	1.27
	Nov 2016	0.27	0.11	0.12	0.05	2.54	2.10	0.46	0.87

Appendix 3b: Mean concentrations (mg kg^{-1}) of Cr, Zn, Co, Cd and Al in gills, liver and stomach tissue of catfish (CG) and tilapia (ON) in Lakes Chivero (CHV) and Manyame (MN) in November 2015–November 2016

	Metal	Cr	Cr	Zn	Zn	Co	Co	Cd	Cd	Al	Al
	Month	ON	CG	ON	CG	ON	CG	ON	CG	ON	CG
Gill											
CHV	Nov 2015	0.61	1.12	0.19	0.56	0.09	0.21	0.05	0.16	1.31	0.55
	Feb 2016	0.68	1.33	0.52	0.98	0.01	0.17	0.32	0.39	2.88	0.80
	May 2016	1.04	1.39	1.28	2.22	0.31	0.30	0.43	1.11	4.81	0.88
	Aug 2016	1.12	1.63	1.40	1.86	0.42	0.48	0.42	1.15	7.73	1.23
	Nov 2016	0.41	0.91	0.23	0.76	0.18	0.42	0.09	0.17	1.91	0.66
MN	Nov 2015	0.06	0.08	0.18	0.29	0.07	0.08	0.04	0.05	1.74	1.79
	Feb 2016	0.96	1.48	0.61	0.53	0.08	0.18	0.21	0.80	2.70	3.40
	May 2016	1.39	2.03	2.05	2.47	0.02	0.23	1.40	1.46	4.20	4.14
	Aug 2016	1.45	2.03	1.60	2.61	0.17	0.36	1.62	1.46	7.28	4.87
	Nov 2016	0.13	0.20	0.27	0.42	0.39	0.29	0.16	0.09	2.33	2.08
Liver											
CHV	Nov 2015	0.09	0.12	0.17	0.20	0.08	0.43	0.05	0.12	0.56	0.48
	Feb 2016	0.44	0.38	0.72	0.56	0.05	0.28	0.11	0.30	0.50	0.39
	May 2016	0.53	0.66	0.74	0.99	0.04	0.35	0.32	0.73	0.83	1.04
	Aug 2016	1.07	1.24	0.96	1.21	0.26	0.79	0.23	1.31	0.91	1.19
	Nov 2016	0.16	0.17	0.27	0.26	0.88	0.44	0.08	0.08	1.15	0.82
MN	Nov 2015	0.13	0.03	0.13	0.23	0.06	0.06	0.03	0.03	1.82	2.59
	Feb 2016	0.29	0.23	0.37	0.15	0.04	0.11	0.34	0.11	2.47	3.42
	May 2016	0.54	0.66	0.42	0.58	0.10	0.13	0.60	0.60	3.12	5.30
	Aug 2016	0.62	0.73	0.67	1.09	0.34	0.33	1.14	0.94	4.43	6.17
	Nov 2016	0.18	0.22	0.24	0.29	0.05	0.15	0.06	0.06	1.59	1.60
Stomach											
CHV	Nov 2015	0.12	0.46	0.11	0.19	0.08	0.19	0.05	0.03	0.45	1.15
	Feb 2016	0.36	0.54	0.01	0.47	0.02	0.17	0.36	0.46	0.25	0.52
	May 2016	0.92	0.74	0.15	0.89	0.10	0.21	1.32	1.20	0.75	0.46
	Aug 2016	1.34	0.84	0.19	0.89	0.16	0.28	1.67	1.52	0.74	0.59
	Nov 2016	0.30	0.59	0.05	0.35	0.09	0.14	0.09	0.08	0.54	0.86
	Nov 2015	0.15	0.06	0.12	0.30	0.07	0.12	0.04	0.07	1.66	1.23
	Feb 2016	0.35	0.01	0.04	1.23	0.02	0.01	0.02	0.10	1.57	2.24
MN	May 2016	0.51	0.56	0.13	0.57	0.07	0.08	0.44	0.56	2.01	2.21
	Aug 2016	0.89	1.38	0.83	1.28	0.27	0.29	0.56	1.21	1.65	1.01
	Nov 2016	0.34	0.10	0.16	0.32	0.25	0.16	0.11	0.10	1.79	0.76

Appendix 4a: Bio-accumulation Factor (BAF) and Biota Sediment Accumulation Factor (BSAF) of Ni, Cu, Fe, Pb and Cr in the gills of *Oreochromis niloticus* (ON) and *Clarias gariepinus* (CG) from Lakes Chivero and Manyame in November 2015–November 2016

Lake	Metal	Ni		Cu		Fe		Pb		Cr	
	Month	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF
Chivero	ON										
	Nov 2015	1.46	0.10	0.02	0.04	0.01	0.01	0.32	6.92	1.00	0.11
	Feb 2016	1.60	0.17	5.18	0.30	0.15	0.00	65.46	0.99	28.26	0.22
	May 2016	31.81	0.25	8.40	0.34	0.08	0.01	38.38	1.09	47.00	0.93
	Aug 2016	2.30	0.16	5.40	0.92	0.04	0.00	21.01	1.96	26.95	1.20
	Nov 2016	2.16	1.70	0.34	0.34	0.26	0.03	0.61	5.92	27.10	1.43
	CG										
	Nov 2015	4.09	0.08	0.04	0.07	0.01	0.01	1.11	47.00	1.65	0.28
	Feb 2016	35.40	0.52	20.94	1.19	0.23	0.01	38.54	0.72	37.78	0.42
	May 2016	25.01	0.40	15.68	1.06	0.12	0.02	26.33	0.72	30.64	0.85
	Aug 2016	6.34	0.44	8.28	2.43	0.11	0.01	14.71	1.26	20.33	1.26
	Nov 2016	0.52	0.16	1.00	0.60	0.14	0.01	3.50	29.30	40.39	3.49
Manyame	ON										
	Nov 2015	0.26	0.00	0.04	0.04	0.01	0.01	0.91	0.91	0.10	0.02
	Feb 2016	64.82	0.75	4.69	0.08	0.32	0.00	0.51	0.00	52.62	0.27
	May 2016	38.51	0.36	12.09	0.32	0.10	0.00	5.97	0.40	11.82	0.34
	Aug 2016	14.01	0.69	0.86	0.26	0.04	0.00	3.49	0.90	1.39	0.25
	Nov 2016	0.24	0.01	4.84	0.10	0.02	0.03	22.33	30.41	0.19	0.07
	CG										
	Nov 2015	0.00	0.00	0.03	0.03	0.02	0.01	0.89	0.89	0.22	0.02
	Feb 2016	0.00	0.03	3.76	0.11	1.43	0.01	0.86	0.06	76.50	0.41
	May 2016	50.86	0.43	19.38	0.52	0.67	0.01	37.60	1.94	23.62	0.55
	Aug 2016	15.15	0.71	4.88	0.76	0.05	0.00	8.04	2.14	2.00	0.40
	Nov 2016	0.52	0.05	2.79	0.05	0.01	0.01	2.89	8.57	0.11	0.04

Appendix 4b: Bio-accumulation Factor (BAF) and Biota Sediment Accumulation Factor (BSAF) of Zn, Co, Cd and Al in the gills of *Oreochromis niloticus* (ON) and *Clarias gariepinus* (CG) in Lakes Chivero and Manyame in November 2015–November 2016

Lake	Metal	Zn		Co		Cd		Al	
	Month	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF
Chivero	ON								
	Nov 2015	2.32	0.39	0.27	0.19	1.31	0.40	0.81	0.49
	Feb 2016	3.95	0.41	0.22	0.01	19.49	2.89	2.11	1.49
	May 2016	5.95	1.11	2.02	0.46	20.13	17.60	48.19	4.36
	Aug 2016	4.18	1.47	1.19	0.46	3.04	2.33	52.29	11.76
	Nov 2016	7.27	7.32	0.42	0.58	2.41	5.10	6.87	2.28
	CG								
	Nov 2015	9.26	1.32	0.05	0.50	5.50	1.03	1.08	0.52
	Feb 2016	9.43	0.64	3.88	0.19	11.15	2.62	0.26	0.65
	May 2016	11.94	1.89	1.33	0.35	29.29	24.11	16.65	1.30
	Aug 2016	6.57	2.14	1.02	0.42	6.90	5.31	22.72	0.60
	Nov 2016	10.67	10.89	0.81	0.67	5.96	3.67	17.92	1.09
Manyame	ON								
	Nov 2015	2.16	0.52	0.53	0.53	2.34	0.36	0.52	0.52
	Feb 2016	11.24	1.75	0.60	0.13	2.75	1.91	0.92	0.88
	May 2016	16.16	4.53	0.20	0.02	78.86	69.73	8.65	1.49
	Aug 2016	4.80	1.72	0.39	0.11	12.33	10.70	9.22	3.82
	Nov 2016	2.19	0.35	0.39	0.14	6.58	3.22	1.27	1.09
	CG								
	Nov 2015	3.72	0.91	0.49	0.49	0.31	0.49	0.61	0.49
	Feb 2016	7.08	14.58	0.34	0.00	7.56	0.00	1.05	0.99
	May 2016	17.12	6.51	1.84	0.17	77.89	76.13	14.19	1.66
	Aug 2016	10.40	3.11	0.80	0.23	13.06	8.18	6.65	2.70
	Nov 2016	1.55	0.23	0.49	0.19	10.86	4.84	1.65	1.21

Appendix 5: Bio-accumulation Factor (BAF) and Biota Sediment Accumulation Factor (BSAF) of metals in the liver of *Oreochromis niloticus* (ON) and *Clarias gariepinus* (CG) from Lakes Chivero and Manyame in Nov 2015–Nov 2016

Location	Metal	Ni		Cu		Fe		Pb		Cr		Zn		Co		Cd		Al	
	Month	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF
Chivero	ON																		
	Nov 2015	1.25	0.03	0.48	0.48	0.01	0.01	8.56	0.34	0.31	0.08	3.18	0.39	0.30	0.17	1.14	0.38	2.43	1.45
	Feb 2016	4.00	0.14	9.48	0.55	0.12	0.01	20.11	0.54	1.62	0.11	8.53	0.39	3.32	0.07	2.13	0.21	0.22	0.29
	May 2016	20.75	0.19	8.41	0.51	0.05	0.02	7.81	0.56	21.84	0.31	3.82	0.58	0.22	0.06	9.25	8.05	26.26	1.69
	Aug 2016	5.46	0.44	4.01	1.30	0.06	0.01	14.19	1.44	15.74	0.75	3.30	1.02	0.61	0.25	1.00	0.85	28.02	2.99
	Nov 2016	1.10	0.69	1.51	1.07	0.18	0.02	1.11	9.22	9.71	0.72	5.84	5.92	2.36	2.34	4.22	0.66	21.59	2.24
	CG																		
	Nov 2015	26.99	0.25	0.76	0.76	0.00	0.00	11.56	0.30	0.36	0.02	1.57	0.47	2.69	0.78	2.82	0.67	2.08	1.24
	Feb 2016	12.40	0.09	26.16	1.68	0.08	0.00	32.46	0.64	16.30	0.12	2.78	0.37	10.97	0.38	8.96	2.20	0.25	0.23
	May 2016	35.88	0.41	19.07	1.69	0.05	0.01	12.20	0.45	7.83	0.43	5.36	0.87	2.39	0.42	20.05	16.60	23.86	1.69
	Aug 2016	6.61	0.43	8.29	3.41	0.04	0.00	7.86	0.62	18.43	1.04	4.53	1.28	2.13	0.83	8.85	6.42	21.31	3.47
	Nov 2016	1.93	0.73	2.53	2.75	0.08	0.01	1.41	13.70	7.09	0.56	3.32	3.44	2.12	2.01	5.41	0.59	50.20	2.15
Manyame	ON																		
	Nov 2015	1.09	0.05	0.08	0.12	0.02	0.01	1.00	0.65	0.29	0.06	0.84	0.27	0.53	0.15	1.89	0.26	0.52	0.48
	Feb 2016	2.21	0.05	12.75	0.35	0.51	0.01	1.62	0.11	11.20	0.07	12.50	1.54	0.24	0.07	17.79	2.43	0.80	0.76
	May 2016	3.34	0.06	22.47	0.55	0.16	0.01	3.49	0.16	5.17	0.17	3.23	1.13	0.74	0.08	26.23	33.04	4.60	1.04
	Aug 2016	2.46	0.19	4.94	0.89	0.06	0.01	1.42	0.38	0.60	0.08	2.04	0.68	0.71	0.21	8.56	5.53	4.93	2.09
	Nov 2016	0.99	0.12	11.43	0.21	0.01	0.00	6.98	7.42	0.12	0.05	0.68	0.16	0.06	0.03	2.55	2.06	1.04	0.79
	CG																		
	Nov 2015	0.44	0.01	0.60	0.09	0.04	0.02	0.94	0.59	0.05	0.01	2.31	0.68	0.40	0.15	1.95	0.24	0.77	0.65
	Feb 2016	6.86	0.24	38.58	1.18	0.78	0.01	25.30	1.66	17.83	0.08	3.02	0.36	0.00	0.04	5.73	0.75	1.11	1.00
	May 2016	24.68	0.31	19.99	0.81	0.20	0.01	50.69	1.99	4.89	0.19	4.13	1.09	0.84	0.09	26.61	32.56	11.52	1.81
	Aug 2016	8.32	0.55	7.13	1.17	0.06	0.01	5.94	1.56	0.64	0.14	3.09	0.98	0.62	0.20	7.00	5.22	7.31	3.00
	Nov 2016	0.27	0.06	0.96	0.08	0.03	0.02	7.38	9.25	0.18	0.05	1.32	0.23	0.17	0.08	2.42	1.19	1.02	0.78

Appendix 6a: Bio-accumulation Factor (BAF) and Biota Sediment Accumulation Factor (BSAF) of metals in the stomach tissue of *Oreochromis niloticus* (ON) and *Clarias gariepinus* (CG) from Lakes Chivero and Manyame in Nov 2015–Nov 2016

Location	Metal	Ni		Cu		Fe		Pb		Cr	
	Month	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF
Chivero	ON										
	Nov 2015	2.43	0.04	0.02	0.02	0.00	0.00	8.75	0.37	0.25	0.03
	Feb 2016	3.80	0.13	0.11	0.03	0.11	0.00	30.83	0.65	3.38	0.10
	May 2016	7.88	0.09	1.11	0.07	0.06	0.01	0.13	0.00	17.82	0.59
	Aug 2016	1.81	0.00	1.18	0.31	0.05	0.00	0.39	0.03	17.21	1.05
	Nov 2016	0.76	0.25	0.02	0.01	0.04	0.00	1.85	5.45	13.12	1.20
	CG										
	Nov 2015	26.67	0.44	0.87	0.46	0.01	0.00	6.98	0.63	0.53	0.09
	Feb 2016	40.40	0.75	24.90	0.64	0.13	0.01	36.23	0.61	25.41	0.19
	May 2016	59.96	0.84	14.03	0.94	0.06	0.01	16.75	0.50	25.75	0.52
	Aug 2016	11.43	0.00	7.51	2.14	0.05	0.01	13.69	1.39	11.09	0.69
	Nov 2016	4.39	2.14	1.43	1.26	0.07	0.01	3.78	7.01	27.58	2.16
Manyame	ON										
	Nov 2015	1.15	0.08	0.46	0.03	0.01	0.01	1.22	0.75	0.38	0.08
	Feb 2016	1.60	0.01	13.26	0.22	0.25	0.00	2.89	0.33	17.11	0.08
	May 2016	5.34	0.03	24.22	0.83	0.05	0.00	18.54	1.17	3.32	0.15
	Aug 2016	3.17	0.00	5.17	0.96	0.03	0.38	5.03	1.33	0.89	0.19
	Nov 2016	0.69	0.15	3.58	0.09	0.01	0.00	9.03	7.30	0.24	0.10
	CG										
	Nov 2015	0.00	0.06	4.00	0.03	0.00	0.00	5.00	2.50	0.00	0.02
	Feb 2016	0.00	0.00	0.00	0.24	1.18	0.01	2.78	1.45	1.00	0.00
	May 2016	67.00	0.24	91.00	1.38	0.58	0.01	61.00	5.30	5.09	0.26
	Aug 2016	17.80	0.00	14.43	1.36	0.16	0.01	15.88	4.70	1.55	0.43
	Nov 2016	1.10	0.09	5.00	0.06	0.01	0.01	0.00	87.00	0.08	0.05

Appendix 6b: Bio-accumulation Factor (BAF) and Biota Sediment Accumulation Factor (BSAF) of Zn, Co, Cd and Al in the stomach tissue of *Oreochromis niloticus* (ON) and *Clarias gariepinus* (CG) from Lakes Chivero and Manyame in Nov 2015–Nov 2016

Location	Metal	Zn		Co		Cd		Al	
	Month	BAF	BSAF	BAF	BSAF	BAF	BSAF	BAF	BSAF
Chivero	ON								
	Nov 2015	1.55	0.24	0.19	0.17	2.79	0.36	0.56	0.31
	Feb 2016	0.02	0.00	0.33	0.02	6.93	3.29	0.19	0.11
	May 2016	0.53	0.19	0.46	0.13	33.21	26.58	15.78	1.23
	Aug 2016	0.56	0.25	0.33	0.14	11.38	8.67	17.31	2.87
	Nov 2016	1.65	1.65	0.25	0.26	2.83	0.21	12.69	0.79
	CG								
	Nov 2015	2.91	0.45	0.42	0.41	0.64	0.13	3.75	15.35
	Feb 2016	5.98	0.36	5.55	0.16	24.92	3.38	0.01	0.50
	May 2016	5.59	0.85	1.48	0.32	34.40	28.41	10.94	0.90
	Aug 2016	3.13	1.05	0.75	0.30	7.23	5.40	16.91	2.47
	Nov 2016	13.82	13.87	0.80	0.40	2.42	0.20	58.74	2.70
Manyame	ON								
	Nov 2015	1.16	0.33	0.53	0.18	2.17	0.28	0.48	0.50
	Feb 2016	0.75	0.12	0.05	0.02	0.60	0.11	0.54	0.44
	May 2016	0.83	0.16	0.41	0.05	14.00	9.73	4.15	0.65
	Aug 2016	1.61	0.56	0.47	0.16	4.09	2.00	2.03	0.82
	Nov 2016	0.74	0.12	0.29	0.13	4.26	1.90	1.18	0.92
	CG								
	Nov 2015	2.14	0.47	1.71	0.30	0.64	0.64	0.41	0.22
	Feb 2016	8.79	1.68	0.00	0.02	0.00	0.91	0.74	0.70
	May 2016	8.14	0.52	0.73	0.08	2.43	56.00	9.61	1.05
	Aug 2016	11.64	1.19	1.07	0.15	7.56	15.13	1.80	0.47
	Nov 2016	3.56	0.25	0.21	0.08	10.00	10.00	0.32	0.36