Article

Are catfish from metal-polluted impoundments in the Olifants River, South Africa, safe for human consumption?

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Abstract

Many impoverished rural communities rely on fish from inland waters for dietary protein; however, inland waters are becoming increasingly contaminated due to anthropogenic activities. The Olifants River is one of the most polluted river in South Africa. The upper catchment is characterized by acid mine drainage and elevated levels of contaminants from domestic, agricultural, industrial, and mining effluents. A human health risk assessment was conducted to determine whether 2 catfish species from 2 impoundments in the Olifants River were safe for human consumption. The concentrations of metal in the fish muscle were in most cases higher at Lake Flag Boshielo than at the downstream Phalaborwa Barrage. Consumption of catfish from Lake Flag Boshielo on a weekly basis could result in adverse health impacts from antimony, chromium, cobalt, and lead. For the Phalaborwa Barrage, only lead would be likely to pose a health risk for consumption of catfish at weekly frequency.

Key words: antimony, chromium, *Clarias gariepinus*, human health, lead, risk assessment, *Schilbe intermedius*

Introduction

Globally, inland waters have been adversely impacted by increases in water abstraction and discharge of effluents containing toxic contaminants (Vörösmarty et al. 2010). Freshwater organisms take up contaminants from the environment (sediment and water) and their diet (Chen et al. 2000, Warren and Haack 2001) and incorporate them into aquatic food webs, concentrating them up the food chain and posing a toxicity risk to predatory fish, fish-eating birds, and mammals, including humans (Adams et al. 2000). Fish are a vital food source for many communities, especially low income groups (Sayer and Cassman 2013), because they are a rich source of protein, micronutrients, and essential fatty acids (Beveridge et al. 2013) and are cheap and available from inland waters. Communities that regularly consume contaminated fish are at risk of genotoxic, carcinogenic, and noncarcinogenic health impairment due to long-term exposure to toxic contaminants (du Preez et al. 2003). Many rural communities in South Africa are impoverished, and their economic outlook is dire due to high population growth rates and global economic trends. Fish from local impoundments are becoming an important component of rural communities' diets (Ellender et al. 2009, McCafferty et al. 2012); however, South African inland waters have become contaminated due to unsustainable water abstraction and increased release of mining, agricultural, industrial, and domestic effluents (Ashton and Dabrowski 2011).

The Olifants River, a tributary of the Limpopo River in eastern southern Africa, has been systematically impaired by acid mine drainage; mining, industrial and agricultural chemicals; organic pollutants; and domestic waste and is now one of the most polluted river systems in South Africa (Ashton and Dabrowski 2011). Acid mine drainage from mines in the upper catchment acidifies streams and mobilises metals (McCarthy 2011). Four major impoundments and a water abstraction barrage have been constructed on the main-stem of the Olifants River: Lakes Witbank, Loskop, and Flag Boshielo in South Africa; Lake Massingir in Mozambique; and the Phalaborwa Barrage near the border of the Kruger National Park (Fig. 1). The water quality of the impoundments in the Olifants River is deteriorating, especially in lakes Witbank, Loskop, and Flag Boshielo (de Villiers

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and Mkwelo 2009, Ashton and Dabrowski 2011). Water quality of the Olifants River improves substantially upstream of the Phalaborwa Barrage due to dilution by the relatively unpolluted Blyde River (Ashton and Dabrowski 2011).

Because the Olifants River has become increasingly polluted, it has become necessary to assess whether fish from its impoundments are suitable for human consumption (Heath et al. 2004), especially for proposed new fisheries in these impoundments. The aim of this study was to compare the concentration of metals in the muscle tissue of 2 catfish species from 2 impoundments on the Olifants River, Lake Flag Boshielo (24°46′51.46″S; 29°25′32.57″E) and the Phalaborwa Barrage (24°4′12″S; 31°8′43″E; Fig. 1), to evaluate the potential risk to human health posed by weekly consumption of the catfish. Suitability of food for human consumption is generally evaluated in one of two ways: by comparison against acceptable concentrations (e.g., Ikem et al. 2003) or by desktop risk assessment (e.g., Addo-Bediako et al. 2014a), both of which require analysis of the contaminants of interest in the food. To compare the concentration of the food contaminant to a limit set by a legislative authority requires that acceptable contaminant levels are available. Acceptable contaminant levels for metals have been established by a number of regions (Nauen 1983), including Australia and New Zealand (FSANZ 2012), the European Union (Commission of the European Communities 2006), and South Africa (Department of Health 2004), but these are available for only a few metals (e.g., 5 for South Africa; Department of Health 2004, and 7 for Australia; Nauen 1983, FSANZ 2012). Rapid human health risk assessments of fish products are usually conducted using the methodology developed by the US Environmental Protection Agency (US-EPA 2000). This method calculates an average daily intake of the contaminant assuming the portion size, average body mass, and consumption frequency, all of which could be verified through surveys. The average daily intake is then compared to a reference dose, a threshold intake level above which adverse health impacts could be expected, and expressed as a hazard quotient (HQ). For a particular contaminant, HQ < 1 suggests that adverse health effects are unlikely, and HQ > 1 suggests a high probability of long-term health impacts from that contaminant. Reference doses for more than 20 metals are available from the US-EPA Integrated Risk Information System (IRIS) database (US-EPA 2013). A risk assessment methodology based on the US-EPA methodology was therefore chosen for this study.

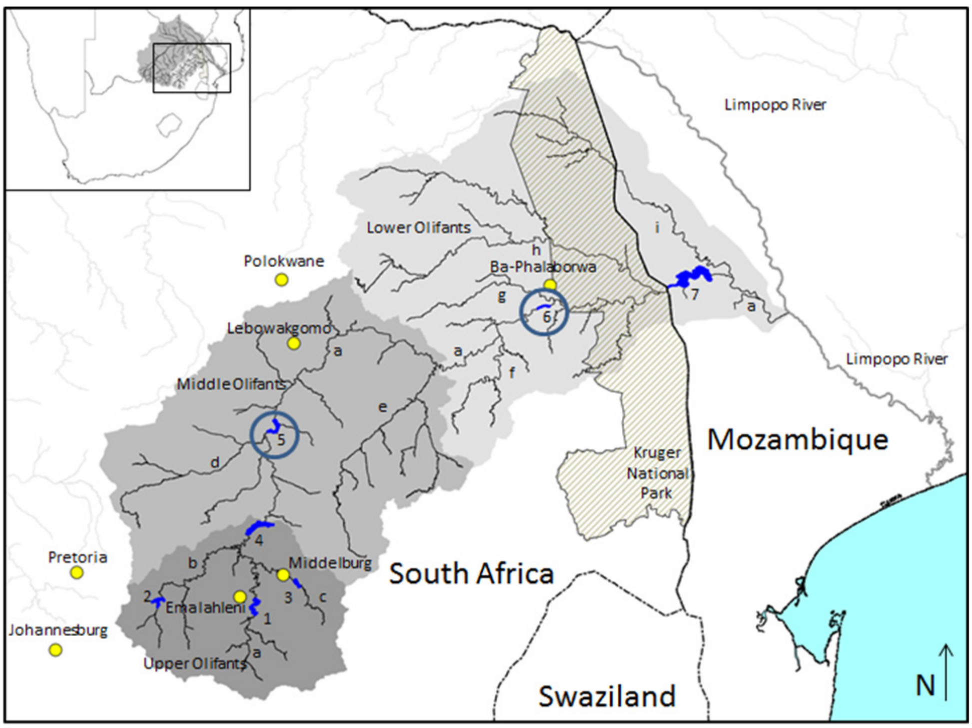

Fig. 1. Olifants River system showing the location of major towns, impoundments, and tributaries. Major impoundments are depicted by numbers: (1) Lake Witbank, (2) Lake Bronkhorstspruit, (3) Lake Middelburg, (4) Lake Loskop, (5) Lake Flag Boshielo, (6) Phalaborwa Barrage, and (7) Lake Massingir. The Olifants River and its tributaries are depicted by letters: (a) Olifants main-stem, (b) Wilge, (c) Klein Olifants, (d) Elands, (e) Steelpoort, (f) Blyde, (g) Ga-Selati, (h) Lethaba, and (i) Shingwedzi. The study sites, Lake Flag Boshielo and the Phalaborwa Barrage, are circled.

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Two catfish species were selected for this study. Sharptooth catfish (*Clarias gariepinus* [Burchell, 1822]), a large opportunistic demersal scavenger, is one of the most widely distributed native fish species in Africa and the most important freshwater fish for consumption by rural communities throughout Africa. Silver catfish (*Schilbe intermedius* [Rüppell, 1832]) is a smaller, schooling pelagic predator widely distributed throughout tropical Africa (Skelton 2001).

Methods

Water collection and analysis

Water samples were collected at a depth of 50 cm at Lake Flag Boshielo and the Phalaborwa Barrage from March to May 2010 and stored frozen prior to analyses. *In situ* pH, water temperature, dissolved oxygen, and electrical conductivity were recorded at this depth (YSI Model 554 Datalogger). The water samples were thawed then analysed in batches with blanks using inductively coupled plasma–optical emission spectrophotometry (ICP-OES; Perkin Elmer, Optima 2100 DV) at WATERLAB, an accredited laboratory (ISO/IEC 17025:2005) in Pretoria. Analytical accuracy was determined using certified standards (De Bruyn Spectroscopic Solutions 500MUL20-50 STD2), and recoveries were within 10% of certified values. The mean and standard deviation were calculated for each impoundment. A one-way ANOVA was used to evaluate whether the water chemistry parameters varied between impoundments using R 3.1.0 statistical software (R Development Core Team 2014).

Fish collection and analysis

Fish were collected using gill nets set overnight from March to May 2010. Live *C. gariepinus* and *S. intermedius* were kept in aerated holding tanks until processing for a parasitological study; fish were sacrificed by severing the spinal cord. Skinless samples of muscle tissue (±15 g) were collected from selected fish, frozen on site, and stored at −80 °C prior to analysis. The samples were freeze-dried and analysed for metals in batches with blanks following Bervoets and Blust (2003) at ICP-OES at WATERLAB in Pretoria. Analytical accuracy was determined using certified standards (De Bruyn Spectroscopic Solutions 500MUL20-50 STD2), and recoveries were within 10% of certified values. The mean concentration and standard deviation were calculated for each metal species at each impoundment. A two-way ANOVA was used to evaluate whether the metal content in muscle tissue varied between catfish species, the impoundments, or the interaction between impoundment and species using R 3.1.0 statistical software. For significant results ($p < 0.05$) for the interaction between impoundment and species, independent one-way ANOVAs were performed for both impoundment and species.

Human health risk assessment

A human health risk assessment was conducted using the methodology of the US-EPA (US-EPA 2000) as revised for South Africa by Heath et al. (2004). The risk of chronic noncarcinogenic health effects from oral exposure was calculated using the average daily dose (ADD; mg/kg body mass per day):

$$\text{ADD} = \frac{(\text{average metal oncentration in fish muscle (fw)}) \times (\text{mass of portion})}{(\text{adult body mass}) \times (\text{no. of days between fish meals})}, \quad (1)$$

where the average metal concentration is in mg/kg, mass of portion in kg, adult body mass in kg, and no. of days between fish meals in days. Reference doses (RfD) are thresholds above which adverse health impacts could be expected. HQ was calculated to estimate the long-term risk to human health (US-EPA 2000):

$$\text{HQ} = \frac{\text{ADD}}{\text{RfD}}. \quad (2)$$

To calculate ADD, we assumed that a 70 kg adult consumed a 150 g fresh fish portion once a week (Heath et al. 2004) and used RfD levels published in the IRIS database (US-EPA 2013). In addition, because rural communities consume both catfish species, the average metal concentration for a catfish diet was calculated based on the relative catch biomass for the respective species.

Results

Water analysis

Concentrations of many metals in the water column were below the detection levels of the chemical analysis at both impoundments. The one-way ANOVA of water parameters between impoundments returned significant results ($p < 0.05$) for temperature, turbidity, sulphate, chloride, fluoride, silicon, and barium (Table 1). Of these, turbidity, fluoride, and barium concentrations were higher at the Phalaborwa Barrage. The arithmetic mean and standard deviation for the water parameters for each impoundment were calculated for the period March to May 2010 (Table 1).

Bioaccumulation of metals

Of the 52 metals and metalloids (hereafter metals) analysed for by ICP-OES, 20 were consistently above the lower detection limits: aluminium (Al), antimony (Sb), arsenic (As), barium (Ba), boron (B,) cadmium (Cd),

Table 1. Autumn mean and standard deviation of water chemistry parameters at Lake Flag Boshielo Dam and the Phalaborwa Barrage.

Water Quality Parameters	Lake Flag Boshielo		Phalaborwa Barrage		ANOVA Result
	Mean	±SD	Mean	±SD	
Water temperature °C	25.5	0.9	21.5	0.4	$p < 0.01$
Dissolved oxygen (%)	94.3	11.4	96.3	1.0	
pH	7.09–7.44	7.33–7.46			
Conductivity (EC) mS/m	38.3	2.9	37.1	0.1	
TDS (mg/L)	248.9	18.6	240.9	0.4	
Salinity (‰)	0.18	0.01	0.18	0.0	
Alkalinity (as mg/L $CaCO_3$)	64	2	64	4	
Turbidity (NTU)	2.1	0.7	8.5	4.8	$p < 0.1$
Total nitrogen (mg/L)	0.27	0.12	0.2	0.0	
Sulphate (mg/L)	112	2	58	16.5	$p < 0.01$
Chloride (mg/L)	25	1	20.3	0.6	$p < 0.01$
Fluoride (mg/L)	0.4	0	0.7	0.00	$p < 0.001$
Calcium (mg/L)	22.7	2.01	23	3	
Magnesium (mg/L)	14.5	3.0	16.3	0.1	
Potassium (mg/L)	4.9	0.8	3.9	0.1	
Sodium (mg/L)	20.5	0.8	21	0	
Silicon (mg/L)	1.68	0.24	5.6	0.17	$p < 0.001$
Barium (mg/L)	0.05	0.01	0.03	0.00	$p < 0.005$
Iron (mg/L)	0.14	0.15	0.10	0.03	
Manganese (mg/L)	0.02	0.01	0.03	0.01	

chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), selenium (Se), silver (Ag), strontium (Sr), tin (Sn), titanium (Ti), vanadium (V), and zinc (Zn). The average metal concentrations in the fish muscle samples from Lake Flag Boshielo were in most cases higher than those from the Phalaborwa Barrage for both *C. gariepinus* and *S. intermedius* (Table 2) with the exception of Ba, B, and Zn. The two-way ANOVA between impoundments and species returned significant results ($p < 0.05$) in the interaction between impoundment and species for Sb, Cd, Cr, Co, Cu, Pb, Mn, Ni, Sr, and Zn. Of these, Sb, Mn, Sr, and Zn returned significant results for one-way ANOVAs for both the impoundment and the species; Cr, Co, Cu, Pb, and Ni returned significant one-way ANOVA results for impoundments only; and only Cd returned a significant one-way ANOVA result for species. The two-way ANOVA returned a significant result for impoundment and species but not interaction for Al and B, and for impoundments only for Ba, Fe, Ag, and Sn. The two-way ANOVA returned a non-significant result for impoundment, species, and interaction for As, Se, and Ti.

Human health risk assessment

The estimated catfish catch biomass for Lake Flag Boshielo was 57% for *C. gariepinus* and 43% for *S. intermedius*, whereas that for the Phalaborwa Barrage was 43% for *C. gariepinus* and 57% for *S. intermedius*. The HQ values for each species at each impoundment were summarised as box plots (Fig. 2). For Lake Flag Boshielo, all *C. gariepinus* exceeded the recommended HQ of 1 for Pb, >75% exceeded the recommended HQ for Sb, and ~50% exceeded the recommended HQ value for Co and Cr. For *S. intermedius*, all exceeded the recommended HQ of 1 for Pb and Cr, and ~50% exceeded the recommended HQ value for Sb. For the Phalaborwa Barrage, >75% of the *C. gariepinus* exceeded the recommended HQ for Pb, whereas almost all *S. intermedius* exceeded the recommended HQ (= 1) for Pb, and >50% exceeded the recommended HQ value for As. The weekly consumption of a combined diet of both species exceeded the recommended HQ of 1 for Sb, Cr, Co, and Pb for Lake Flag Boshielo and for Pb at the Phalaborwa Barrage (Table 3).

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Table 2. Mean and standard deviation calculated for metals found in the muscle tissue of 2 catfish species from Lake Flag Boshielo Dam and the Phalaborwa Barrage.

Lake Flag Boshielo

***Clarias gariepinus* (*n* = 10)**	Al	Sb	As	Ba	B	Cd	Cr	Co	Cu	Fe	Pb	Mn	Ni	Se	Ag	Sr	Sn	V	Zn
Mean metal concentration (mg/kg wet wt)	14.2	17.9	0.3	6.3	23.2	0.0	9.6	2.6	1.4	237	1.7	1.5	0.6	0.6	0.1	0.4	0.9	7.0	6.6
Standard Deviation (mg/kg wet wt)	1.1	19.7	0.1	0.4	5.3	0.0	1.8	3.1	0.9	337	0.5	1.9	0.4	0.5	0.2	0.2	1.0	1.0	4.0

***Schilbe intermedius* (*n* = 8)**	Al	Sb	As	Ba	B	Cd	Cr	Co	Cu	Fe	Pb	Mn	Ni	Se	Ag	Sr	Sn	V	Zn
Mean metal concentration (mg/kg wet wt)	23.2	2.9	0.2	8.2	30.3	0.0	12.0	0.4	2.4	386	0.8	9.0	0.8	0.5	0.0	22.1	1.3	7.3	41.0
Standard Deviation (mg/kg wet wt)	11.0	3.4	0.2	1.2	4.7	0.0	1.0	0.5	0.9	138	0.3	6.8	0.3	0.2	0.1	19.1	0.6	0.7	24.5

Phalaborwa Barrage

***Clarias gariepinus* (*n* = 13)**	Al	Sb	As	Ba	B	Cd	Cr	Co	Cu	Fe	Pb	Mn	Ni	Se	Ag	Sr	Sn	V	Zn
Mean metal concentration (mg/kg wet wt)	10.6	0.4	0.2	75.1	59.0	0.0	3.4	0.1	1.0	22.5	0.4	0.8	0.3	0.9	0.4	0.7	0.3	0.0	49.8
Standard Deviation (mg/kg wet wt)	3.4	0.4	0.5	12.5	9.7	0.0	0.4	0.0	0.2	13.1	0 .2	0.4	0.2	0.7	0.1	0.3	0.3	0.0	12.0

***Schilbe intermedius* (*n* = 15)**	Al	Sb	As	Ba	B	Cd	Cr	Co	Cu	Fe	Pb	Mn	Ni	Se	Ag	Sr	Sn	V	Zn
Mean metal concentration (mg/kg wet wt)	13.8	0.1	0.9	81.1	65.0	0.0	3.8	0.1	1.1	28.4	0.8	1.1	0.2	0.6	0.4	1.9	0.4	0.1	52.8
Standard Deviation (mg/kg wet wt)	4.3	0.2	1.1	18.4	12.5	0.0	0.3	0.1	0.4	11.1	1.4	1.1	0.1	0.7	0.1	4.5	0.6	0.2	10.1

Table 3. The Hazard quotients, based on one fish meal (150 g) eaten on a weekly basis, calculated for metals found in the muscle tissue of 2 catfish species from Lake Flag Boshielo Dam and the Phalaborwa Barrage. The shaded cells indicate where the recommended hazard quotient (HQ) value of 1 has been exceeded.

Lake Flag Boshielo	Al	Sb	As	Ba	B	Cd	Cr	Co	Cu	Fe	Pb	Mn	Ni	Se	Ag	Sr	Sn	V	Zn
Metal concentration (mg/kg wet wt)	18.1	11.5	0.3	26.3	7.1	0.0	10.6	1.6	1.9	301.2	1.3	4.8	0.7	0.6	0.1	9.7	1.1	7.1	21.4
Average daily dose (µg/kg)	5.54	3.52	0.08	8.04	2.17	0.00	3.26	0.50	0.57	92.20	0.41	1.46	0.20	0.17	0.02	2.98	0.33	2.18	6.56
Reference dose (µg/kg)	1000	0.4	0.3	200	200	0.5	3	0.4	40	700	0.057	140	20	5	5	600	600	5	300
Hazard quotient	0.01	8.79	0.27	0.04	0.01	0.00	1.09	1.25	0.01	0.13	7.15	0.01	0.01	0.03	0.00	0.00	0.00	0.44	0.02

Phalaborwa Barrage lake	Al	Sb	As	Ba	B	Cd	Cr	Co	Cu	Fe	Pb	Mn	Ni	Se	Ag	Sr	Sn	V	Zn
Metal concentration (mg/kg wet wt)	12.4	0.3	0.6	78.5	62.4	0.0	3.6	0.1	1.0	25.9	0.6	1.0	0.2	0.7	0.4	1.4	0.3	0.0	51.5
Average daily dose (µg/kg)	3.81	0.08	0.19	24.02	19.10	0.00	1.11	0.02	0.32	7.92	0.19	0.30	0.08	0.23	0.13	0.42	0.11	0.01	15.77
Reference dose (µg/kg)	1000	0.4	0.3	200	200	0.5	3	0.4	40	700	0.057	140	20	5	5	600	600	5	300
Hazard quotient	0.00	0.21	0.64	0.12	0.10	0.00	0.37	0.06	0.01	0.01	3.32	0.00	0.00	0.05	0.03	0.00	0.00	0.00	0.05

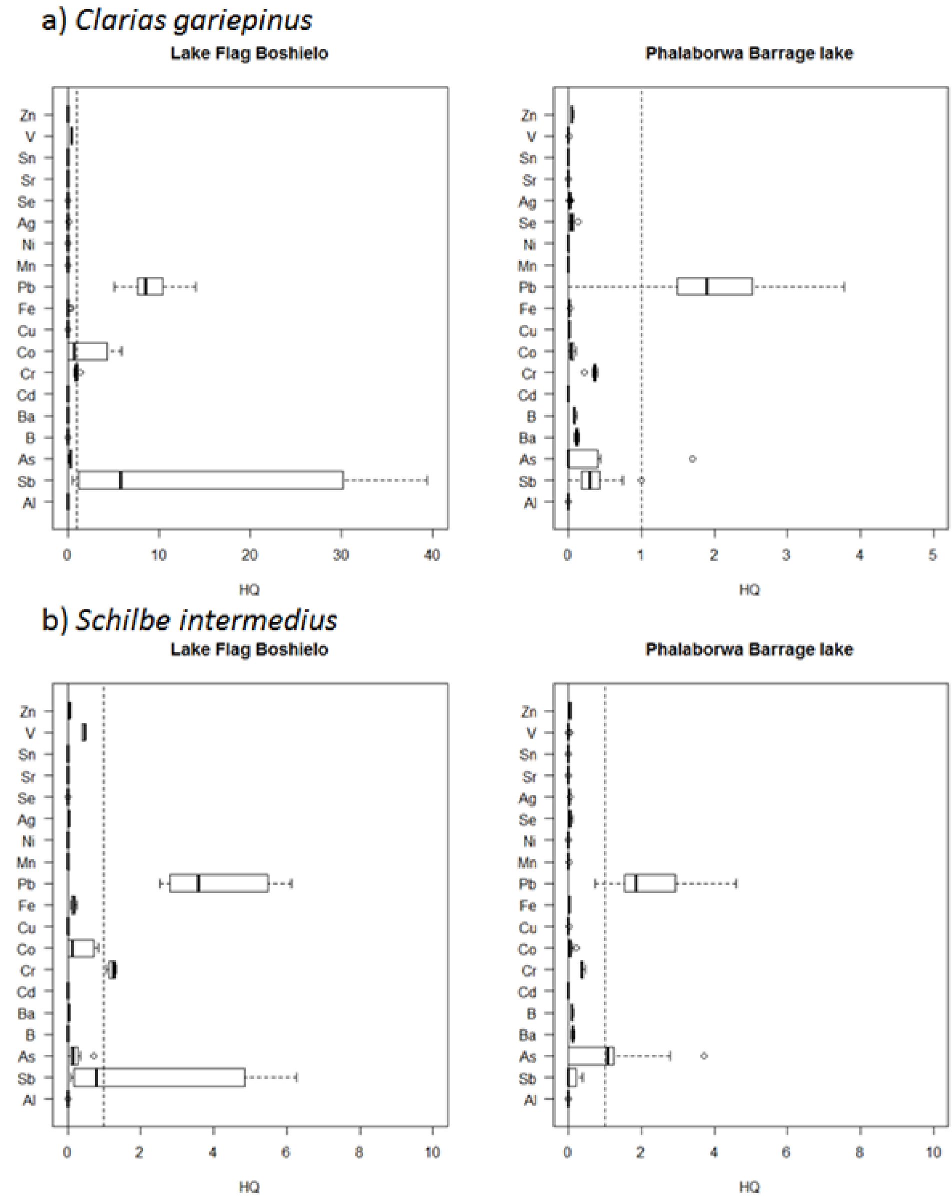

Fig. 2. Box plot of the hazard quotient (HQ) of the respective metals for *Clarias gariepinus* and *Schilbe intermedius* from Lake Flag Boshielo and the Phalaborwa Barrage. The dotted line (HQ = 1) indicates the maximum acceptable level for long-term exposure.

Discussion

Metal mobilization from river sediments in the Olifants River by acid mine drainage (Netshitungulwana and Yibas 2012) seems to be the source of the uptake of metals into the food chain and into fish tissue. The concentration of most metals in the water column was below our ICP-OES detection limits, whereas the sediment contained higher levels (Jooste et al. 2015a). Jooste et al. (2015a) found that the metals in tissues of the 2 species followed similar patterns within impoundments but differed between impoundments, possibly due to differences in water and sediment quality between the impoundments and the diets, foraging styles, and habitat preferences of the 2 catfish. Further studies are required to identify the pathways for metal uptake by the respective species and the relative importance of food, sediment, and water as sources of metals; however, the condition of the catfish at both impoundments seems to be unaffected by the elevated metal concentrations in the muscle tissue (Addo-Bediako et al. 2014b, Jooste et al. 2015b).

Metal bioaccumulation in *C. gariepinus* has previously been studied in South Africa (du Preez et al. 1997, Avenant-Oldewage and Marx 2000a, 2000b, Crafford and Av-

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enant-Oldewage 2010, 2011) and internationally (Al-Kahtani 2009, Osman and Kloas 2010), whereas *S. intermedius* has largely been ignored, even though the need for chemical contaminant studies for this species has been highlighted (du Preez et al. 2003). The metal concentrations in *C. gariepinus* muscle tissue seem to have increased over the last 20 years at both impoundments, in particular the concentrations of Al, Cr, Cu, Mn, and Zn (Jooste et al. 2015b). Lead concentrations in *C. gariepinus* muscle tissue were comparable to previous studies in the Olifants River and elsewhere in Africa (Obasohan et al. 2008, Crafford and Avenant-Oldewage 2010). Chromium concentrations for *C. gariepinus* were similar to those found for the Nile River (Osman and Kloas 2010), and Sb concentrations were comparable to those found in an Sb mining area of China (Fu et al. 2010). Cobalt levels in *C. gariepinus* muscle from the Phalaborwa Barrage were similar to other fish studies in the US and Turkey (Ikem et al. 2003, Kandemir et al. 2010), but those for Lake Flag Boshielo were 10 times higher than in these studies. The Pb, Sb, As and Cr concentrations in the muscle tissue were comparable to results from studies of metal accumulation in *Oreochromis* species (Al-Kahtani 2009, Yilmaz 2009, Jabeen and Chaudhry 2010, Addo-Bediako et al. 2014a).

Human health risk assessment

The results show that an adult consuming a 150 g fish portion weekly may have health risks from exposure to metals (e.g., Pb, Sb, Cr, and Co). Considering that rural populations are likely to continue to grow with concomitant increases in poverty, supplementation of diet to meet daily protein requirements might be required, achieved through the consumption of fish from impoundments of the Olifants River. More frequent consumption of contaminated fish (e.g., by subsistence fishers) could lead to unacceptable exposure to As and V in addition to the metals identified above.

Many rural communities care for the offspring of siblings or children working or residing in major urban centres. Because the current risk assessment was based on a 70 kg adult, children and infants will be exposed to double and quadruple the adult HQ values because their weights in the dose guidelines are one-half and one-fourth those for adults, respectively. Lead is of particular concern due to its wide range of health impacts. The most sensitive targets for Pb toxicity are the developing nervous, haematological, renal, and cardiovascular systems. Lead can potentially affect any system or organ in the body (ATSDR 2007), and its haematological and neurological health impacts may have no lower level threshold (US-EPA 2004). Cromium is a recognised human carcinogen, and oral exposure could result in gastrointestinal cancers, and respiratory, gastrointestinal, immunological, haematological, reproductive, and developmental complications (ATSDR 2008). Sb decreases longevity, results in cardiovascular, gastrointestinal, haematological, hepatic, and other systemic impacts, including disruption of glucose and cholesterol metabolisms (ATSDR 1992).

Previous studies have shown that the water quality of the Olifants River has been severely impaired by mining, industry, and human settlements in the upper catchment and has steadily deteriorated over the last 30 years (de Villiers and Mkwelo 2009, Ashton and Dabrowski 2011). The metal concentrations in the water, sediment, and fish of the Olifants River are projected to continue increasing. To reverse the trend of increasing metal contamination, projects targeted at reducing the influx of acid mine drainage and other harmful effluents into the upper Olifants River are required. In addition, an assessment of the current metal exposure experienced by rural communities should be conducted by the national health authority to ground-truth the findings of this risk assessment. If necessary, health advisories should be issued warning rural communities to consume fish from impoundments on the Olifants River less frequently. Regular monitoring of the metal concentration in fish muscle tissue should be instituted to determine the seasonal and interannual variations relative to the river flow to predict the health risks associated with consuming fish from the Olifants River.

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