African Journal of Environmental Science and Technology Vol. 4(11), pp. 729-739, November, 2010
Available online at http://www.academicjournals.org/AJEST
ISSN 1991-637X ©2010 Academic Journals

Full Length Research Paper

Heavy metal contamination of soil and sediment in Zambia

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Accepted 4 October, 2010

Heavy metal pollution is one of the most important problems in Zambia and causes serious effects to humans and animals. The aim of the present study was to evaluate the spatial distribution of heavy metals in main areas of Zambia and understand the characteristics of the pollution in each area. River and lake sediments and soil samples were collected from a large area of Zambia and analyzed for ten heavy metals (Cr, Co, Ni, Cu, Zn, As, Cd, Pb, Sr and Hg). The results indicate that heavy metal pollution in Zambia has strong regional differences. Using cluster analysis, the patterns of heavy metal pollution were divided into three major clusters: (1) Kabwe, (2) Copperbelt and (3) Lusaka and other areas. Heavy metals in the Copperbelt area are transported to downstream areas by the Kafue River. Pollution was also detected in national parks, and Lake Itezhi-tezhi has been polluted with high concentrations of Cu, possibly from mining activities in the upper reaches of the river. However, areas geographically distant from mining beds had only moderate or low heavy metal concentrations, although the concentrations of Pb and Zn were highly correlated with the populations of each town. Our findings indicate that heavy metal pollution in Zambia is still increasing, due to human activities, especially mining.

Key words: Heavy metal, contamination, mining, soil, sediment.

INTRODUCTION

Africa is a continent located in the southern hemisphere and known for its rich diversity of wildlife including birds, amphibians, reptiles and large mammals. However, in recent years, there have been concerns about significant environmental problems caused by the mining of rare and major metals and metallurgical activities in African countries by domestic and foreign corporations (Oelofse, 2008). Environmental pollution due to the rapid progress of economic development in Africa can cause various problems and heavy metals are some of the major contaminants in these countries (Akiwumi and Butler, 2008; Norman et al., 2007; Rashad and Barsoum, 2006). Humans and wildlife can be exposed to heavy metals by drinking water and inhaling air or soil contaminated by mining activities and the metal industry (Nakayama et al., 2010).

Mining activities are considered to have the potential for causing heavy metal pollution and associated diseases (Lacatusu et al., 2009; Kodom et al., 2010). Therefore, many researchers worldwide have focused on and reported assessments of heavy metal concentrations (Zhai et al., 2008; Higueras et al., 2004; Razo et al., 2004; von Braun et al., 2002). However, currently most data on heavy metals in African countries are the result of regional investigations that have been limited to the area around the source of the heavy metals (Aguilar et al., 2002). Surveys of heavy metals across the whole country and comprehensive analyses which include economic activities, are needed to clarify the impact of these chemicals on humans and wildlife and are essential for the protection and management of the environment in

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African countries.

The Republic of Zambia is an African country that is rich in mineral resources such as copper (Cu), cobalt (Co), zinc (Zn) and lead (Pb) (Stockwell et al., 2001). Mining is the most important industry in Zambia. In 1997, 3% of the world's annual Cu production and 20% of the annual Co production were mined in Zambia and most of this ore was smelted within the country (Stockwell et al., 2001). The core mining areas in Zambia are Kabwe town and the Copperbelt. However, heavy metal pollution is one of the most important environmental issues in Zambia and causes serious effects on humans and animals (Nwanko and Elinder, 1979; Syakalima et al., 2001).

In this study, we suggested that road soils and river and lake sediments are useful to assess widespread environmental pollution. Actually, in polluted aquatic systems, sediments have been increasingly recognized as the most important sink for contaminants and as a reservoir and possible future source of pollutants (Ikenaka et al., 2005a, 2005b). These data can provide basic information on the accumulation and transportation of these pollutants into both human life and ecosystems. Thus, we collected the sediments of the three largest river basins in Zambia, the Zambezi River (including Lake Kariba), the Kafue River (including Lake Itezhi-tezhi) and the Luangwa River. The purpose of the present study was to evaluate the spatial distribution of heavy metals in the main areas of Zambia and to understand the characteristics of pollution in each area, using road soil and sediment.

MATERIALS AND METHODS

Soil sampling sites

We collected 47 soil samples from various cities and towns in Zambia including Lusaka (n = 7), Kabwe (n = 3), and the Eastern (n = 10), western (n = 5), southern (n = 12) and Northern (n = 10) areas (Figure 1 and Table 1).

Lusaka, the capital and largest city of Zambia, is located in the southern part of the central plateau of the country and is the center of economic and industrial activity in the country. We collected two soil samples from the sides of major roads (Lusaka 1, 4) and five samples from industrial areas (Lusaka 2, 3, 5, 6, and 7) (Table 1). Kabwe is located about 130 km North of Lusaka and is one of the main areas of mining activity in Zambia. We collected three samples in Kabwe (Kabwe 1, 2 and 3) (Table 1). In the Eastern area, we collected samples along the T4 road (Chongwe, Chinyunyu, Kachalola, Nyimba, Petauke, Sinda, Chipata, and Mumbwe) and in the South Luangwa National Park (Mfuwe) which is a large wildlife preserve. In the Western area, we collected samples from three towns, Namwala, Mumbwa, and Itezhi-tezhi (ITT). In the Southern area, we collected samples along the T1 road (at Kafue (n=3), Mazabuka, Monze, Muzoka, Choma, Kalomo, Zimba, Livingstone), and at Mambova and Siavonga. The northern area including the Copperbelt is one of the main areas of mining activity in Zambia. In the northern area, we collected samples along the T3 road (Kapiri Mposhi, Luanshya, Ndola, Kitwe, and Chingola (n=3)), and from rural towns along the Kafue River (Mpongwe, Shingwa, and Masaiti).

Sediment sampling sites

River sediment samples were collected from three rivers that flow through Zambia, the Zambezi (n = 8), Luangwa (n = 5), and Kafue rivers (n = 8) (Figure 1). Samples were also collected from the tributaries of the Kafue and Luangwa rivers. Of Kafue River tributaries, we collected sediments from the Mushishima (n = 3) and Kakosa streams (n = 1) and one sample was collected from a Luangwa River tributary, the Chongwe Stream.

Sampling procedure

Soil and sediment samples were collected during the dry season between May and September 2008. Approximately 500 g of soil or sediment was collected from each site at a depth of 0 - 5 cm and stored in a plastic bottle. At least three composite soil samples were collected from each sampling point. The soil samples were passed through a 2 mm sieve before extraction. The surface sediment samples were collected using an Ekman grab sampler. Each sediment sample was air-dried in the laboratory at room temperature and was passed through a 2 mm sieve before extraction. The dry weight of each sample was measured after 12 h of drying in an oven at 105°C.

Reagents

Sulfuric acid (poisonous metal analysis grade, 96%), nitric acid (atomic absorption spectrometry grade, 60%), perchloric acid (atomic absorption spectrometry grade, 60%), standard solutions of each heavy metal (Cr, Co, Ni, Cu, Zn, As, Cd, and Pb: chemical analysis grade, 100 mg/L in 0.1 M nitric acid; Sr and Hg: chemical analysis grade, 1000 mg/L in 0.1 M nitric acid) were purchased from Kanto Chemical Corp., Tokyo, Japan. Ammonium chloride, hydrochloric acid (special grade: 36%) and lanthanum chloride solution (atomic absorption spectrometry grade, 100 g La/L solution) were purchased from Wako Pure Chemical Industries Ltd., Osaka, Japan.

Extraction and analysis of heavy metals

All laboratory equipment used for the heavy metal analysis was washed in 3% HNO_3 and rinsed at least twice with distilled water. One gram of each soil or sediment sample was placed into a 200 mL flask. Then, 0.2 mL of sulfuric acid, 1 mL of nitric acid and 5 mL of perchloric acid were added. The soil and acid mixture was heated to 180°C for 3 h on a hotplate. After cooling, 1 g of ammonium chloride and 20 mL of 0.5 N HCl were added. Samples were reheated to 180°C for one hour and evaporated to approximately 10 mL. After cooling, the extracts were filtered into 100 mL plastic bottles through an ashless 5B filter paper (Advantec, Tokyo, Japan) and 1 mL of lanthanum chloride was added. A reagent blank was also prepared using same the process.

The concentrations of nine of the elements (Cr, Co, Ni, Cu, Zn, As, Sr, Cd, and Pb) were determined using an Analyst™ 800 atomic absorption spectrophotometer (AAS) (Perkin Elmer Instruments, USA) with either an acetylene flame (Cu and Zn) or an argon non-flame (Cr, Co, Ni, As, Sr, Cd and Pb) after preparation of the calibration standards. The concentration of Hg was determined using a mercury analysis system MA-2000 (Nippon Instruments Corp., Tokyo, Japan) after preparation of the calibration standards. The overall recovery rates (mean ± SD) for Cr, Co, Cu, Zn, Cd, Pb and Ni were 91 ± 3.0, 92 ± 3.4, 89 ± 5.6, 91 ± 2.3, 111 ± 8.3, 90 ± 3.5 and 92 ± 4.2%, respectively. The heavy metal concentration in soil or sediment was calculated in mg/kg dry weight (wt). Recommended values for Cr, Ni, Cu, Zn, As, Cd, Hg and Pb in soil

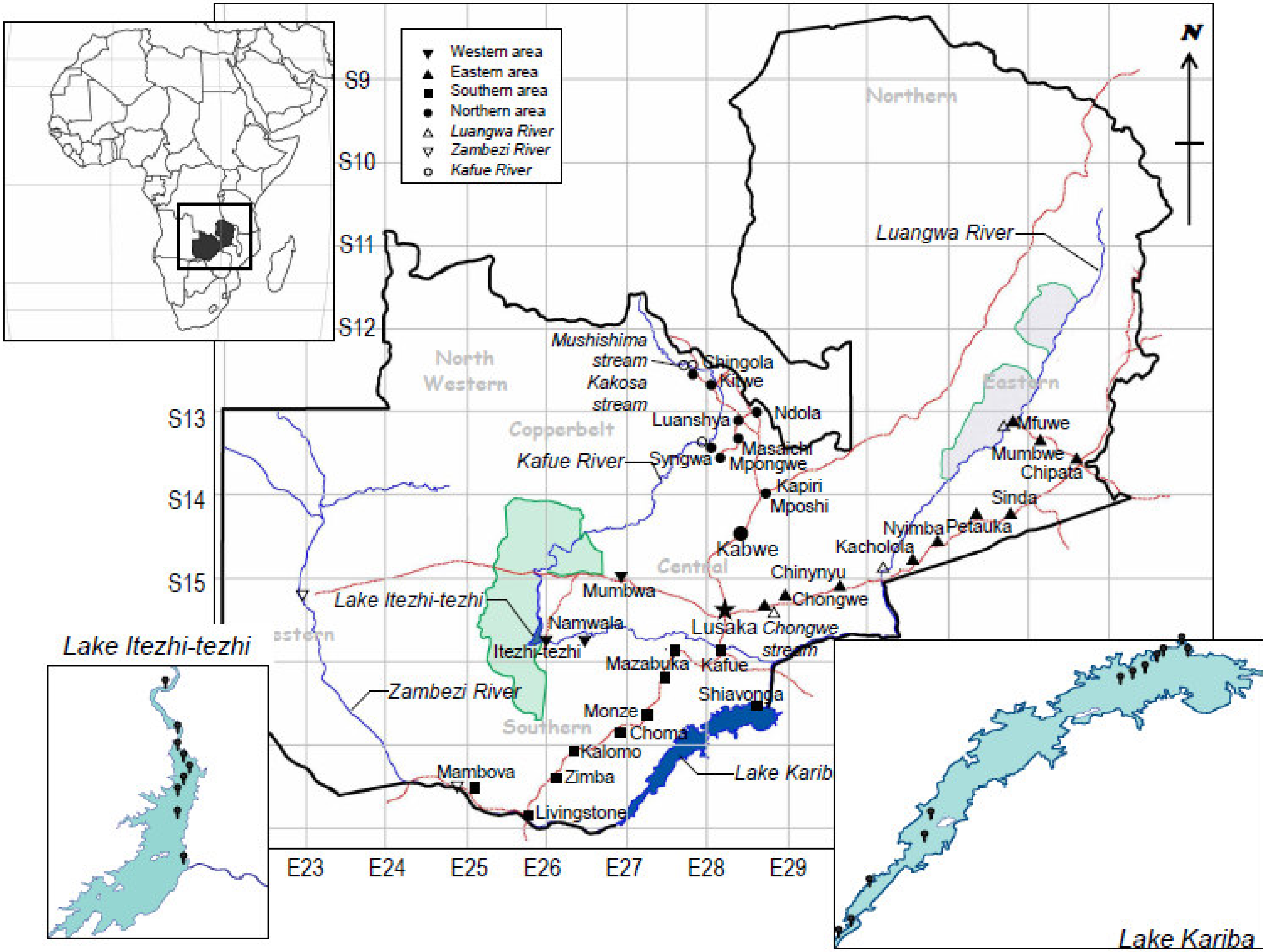

Figure 1. Sampling sites for soils and sediments in Zambia.

Table 1. Sampling locations.

Sampling points	Latitude	Longitude	Remarks
Lusaka 1	15°26'50.9"S	28°16'13.9"E	Road side
Lusaka 2	15°24'41.1"S	28°16'04.5"E	Industrial area
Lusaka 3	15°23'00.1"S	28°16'08.1"E	Industrial area
Lusaka 4	15°23'52.6"S	28°18'30.4"E	Road side
Lusaka 5	15°22'38.4"S	28°22'15.9"E	Industrial area
Lusaka 6	15°23'23.0"S	28°14'14.9"E	Industrial area
Lusaka 7	15°23'00.1"S	28°16'08.1"E	Industrial area
Kabwe 1	14°28'15.6"S	28°25'23.5"E	Mining
Kabwe 2	14°26'29.0"S	28°26'49.0"E	Mining
Kabwe 3	14°27'25.3"S	28°25'48.8"E	Mining

were referenced from ICRCL (International Committee on the Redevelopment Contaminated Land, 1987) in the UK.

Statistical analysis

Each sample was classified using a cluster analysis according to the Euclidean distance based on the composition ratio of each heavy metal. Significant differences ($p < 0.05$) for each sample group were analyzed using either the Mann-Whitney U test or Tukey's test. The significance of correlations was analyzed using the Pearson product-moment correlation coefficient ($p < 0.05$). Statistical analyses were performed using JMP 7.0.1 (SAS Institute, Cary, NC, USA).

RESULTS AND DISCUSSION

Concentration and distribution of heavy metals in Zambia

Table 2 shows the heavy metal concentrations in soil samples in each area. A cluster analysis was performed to identify the accumulation pattern in each soil sample using the relative proportions of the ten heavy metals (Figure 2). The results of the cluster analysis divided the 47 individual soil samples into three major groups. Cluster 1 mainly included Kabwe samples. Cluster 2 mainly included the Northern area samples, in particular, the Copperbelt. Cluster 3 mainly included rural towns in the Eastern, Western and Southern areas. Figure 3 shows the concentration ratios of each heavy metal in these three clusters. It shows that each cluster had a characteristic composition. High ratios of Zn (57%) and Pb (32%) were found in Cluster 1, while a high Cu ratio (63%) was observed in Cluster 2. The major components of Cluster 3 were Cr (21%) and Cu (22%), but no individual component exceeded 50%. Interestingly, in Cluster 3, positive correlations were observed between the population of each town and the Zn and Pb concentrations (Figure 4).

These results show that heavy metal pollution in Zambia includes very high Zn, Pb, and Cd concentrations compared with the values recommended by the UK ICRCL (Tables 2, 3 and 4). Furthermore, heavy metal pollution in Zambia has strong regional differences (Table 2, Figures 2 and 3).

Kabwe (Cluster 1)

In Kabwe, concentrations of Zn, As, Cd, Pb were significantly higher than in other areas (Table 2). Mining and smelting of Pb, Zn and Cd are the major industries around Kabwe. A previous study also showed that mining around Kabwe was responsible for heavy metal pollution, especially by Pb (Tembo et al., 2006). That paper indicated that the heavy metal concentrations decreased with increasing distance from the mine, confirming that mining activities are the main cause of soil contamination.

Lead (Pb) toxicity causes many diseases including hematological, gastrointestinal and neurological dysfunctions, and nephropathy (Lockitch, 1993). It is reported that children have a greater susceptibility to Pb toxicity because intestinal absorption of Pb is five times greater in children than in adults. The Blacksmith Institute (2007) reported that blood Pb concentrations of 200 μg/dL or more have been recorded in children in some neighborhoods in Kabwe. These records also showed average blood Pb levels for children in Kabwe ranging between 50 and 100 μg/dL. On average, children's blood Pb levels in Kabwe were 5 to 10 times the permissible WHO/EPA maximum of 10 μg/dL. It was observed that children who played in the soil were most susceptible to Pb pollution caused by mines and smelters.

In the present study, positive correlation coefficients were observed between Pb and Cd, Zn and Cd, As and Pb and As and Zn (Table 5). Because Cd and As are frequently found with Pb (Tembo et al., 2006; Ratnaike, 2003), the Cd and As pollution observed is also related to Pb and Zn mining. The maximum values of Cd and As in Kabwe were 18.7 and 51.5 mg/kg dry-wt, respectively. These concentrations of Cd and As could have the potential for poisoning, as the trigger values for Cd and

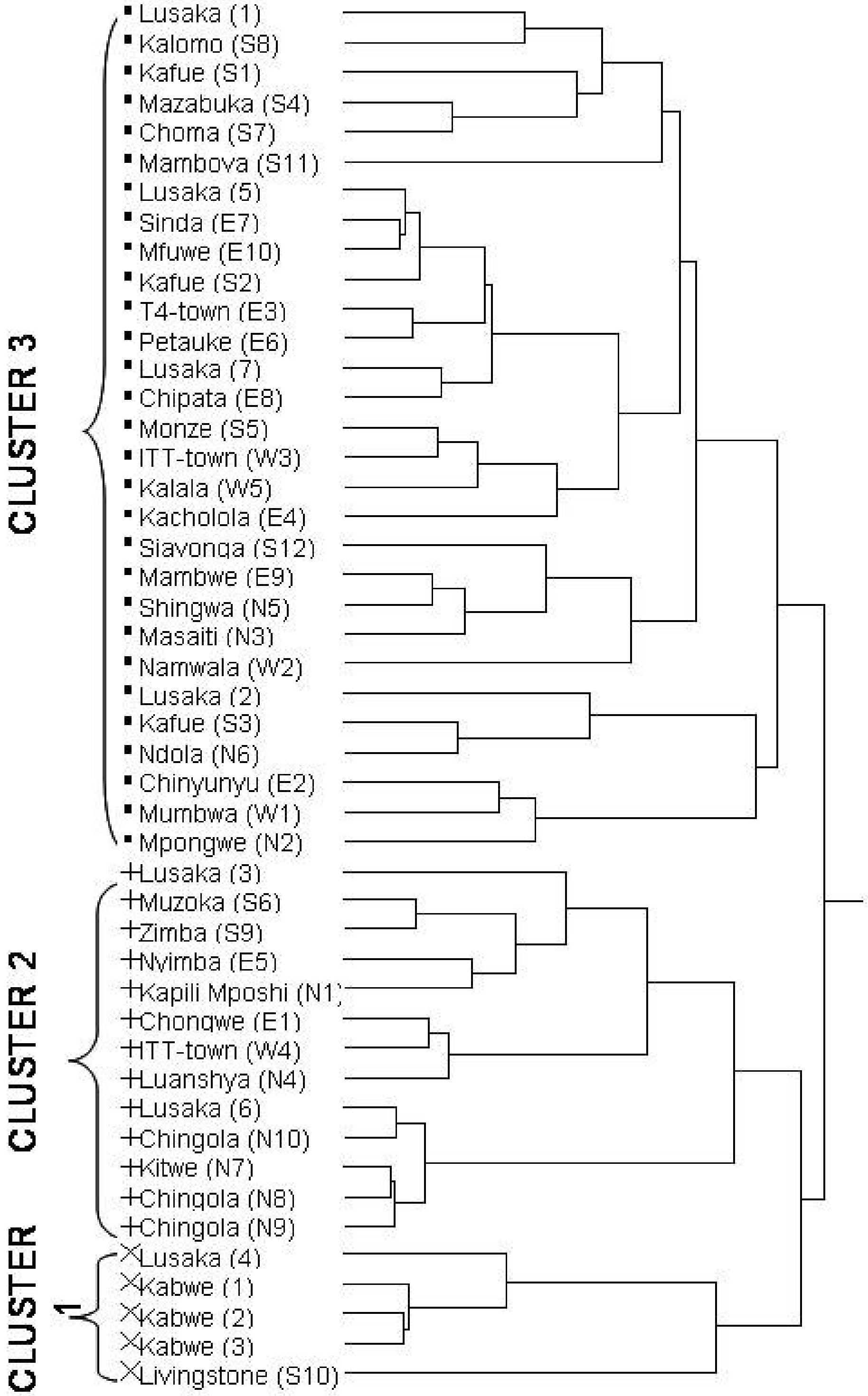

Figure 2. Cluster analysis of each soil sample based on the composition ratios of ten heavy metals.

As are reported to be 3.0 and 10.0 mg/kg (ICRCL, 1987; UK, 1987), respectively. Therefore, in Kabwe, pollution by Cd and As should not be ignored. In Chenzhou City, one of the oldest and largest mining cities in China, high concentrations of Cd were reported in paddy soil (0.35 – 48.3 mg/kg) and rice (0 – 4.4 mg/kg)

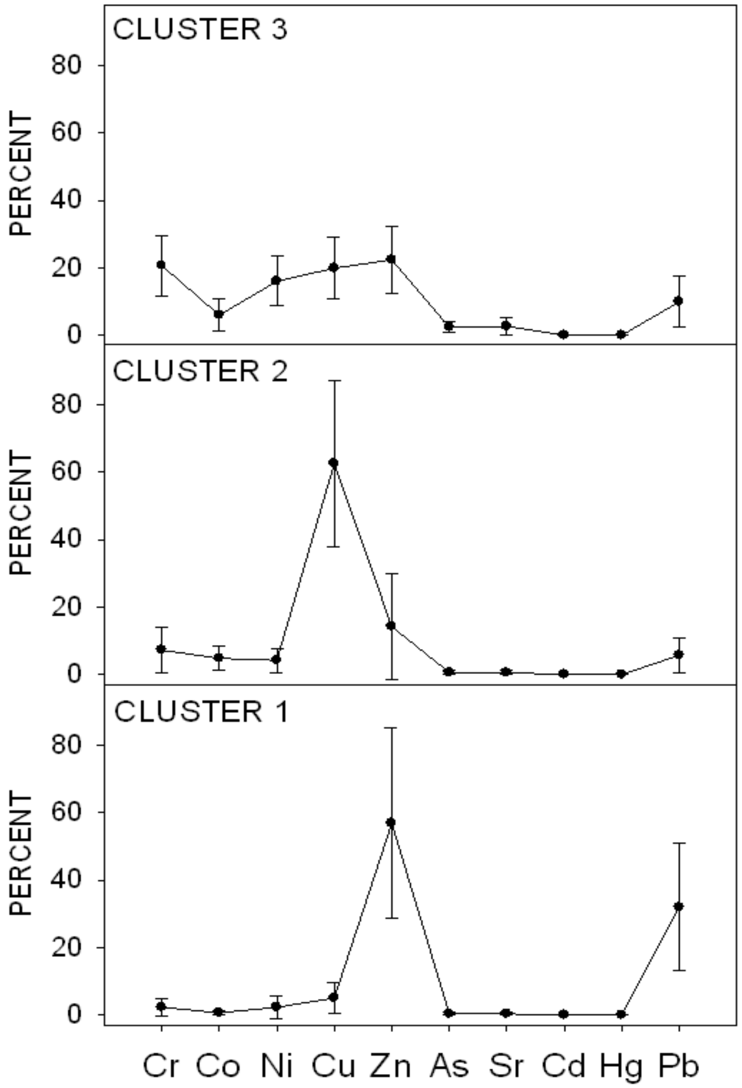

Figure 3. Concentration ratios of each heavy metal in the three clusters.

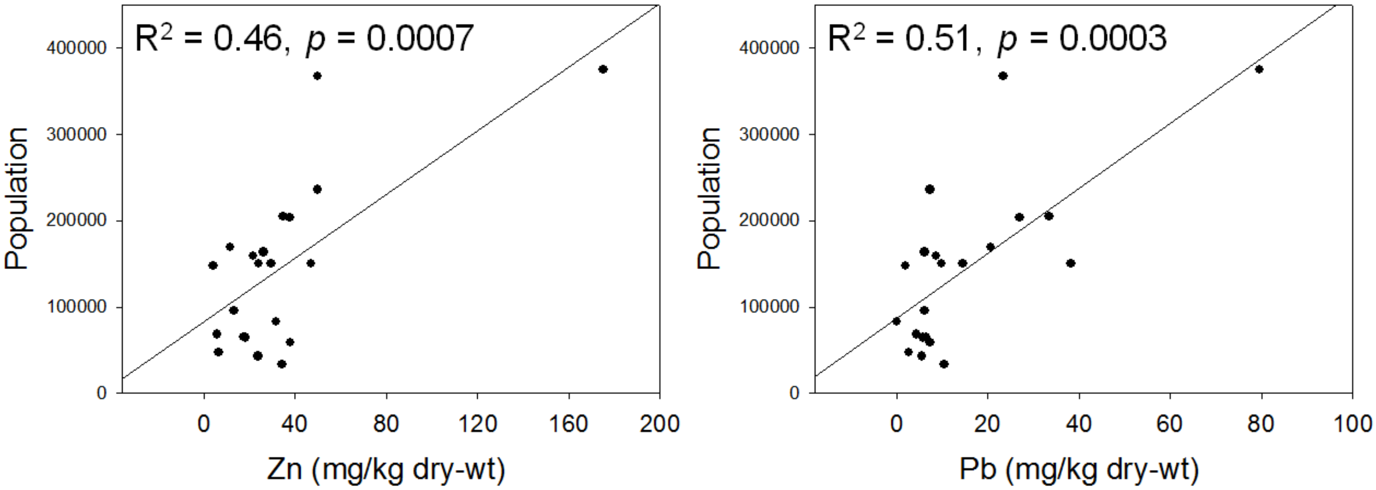

Figure 4. Correlation between the populations of each town and concentrations of Zn and Pb.

Table 2. Mean (± S.D.) and median values and concentration range (mg/kg dry-wt) of heavy metals in soils.

	Cr(mg/kg)	Co(mg/kg)	Ni(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	As(mg/kg)	Sr(mg/kg)	Cd(mg/kg)	Hg(mg/kg)	Pb(mg/kg)
Lusaka (n = 7)										
Average	39±11^{A}	11±9^{B}	20±7^{BC}	343±686^{AB}	147±278^{B}	4±1^{B}	9±10^{A}	0.11±0.10^{B}	0.02±0.01^{B}	48±49^{B}
Median	39	9	21	31	48	4	3	0.08	0.01	26
Range	27–52	3–31	7–31	19–1874	17–777	1–5	2–30	0.03–0.33	0.00–0.04	8–134
Kabwe (n = 3)										
Average	39±18^{A}	46±43^{AB}	47±9^{A}	572±597^{AB}	16991±20614^{A}	32±26^{A}	13±4^{A}	7.12±9.98^{A}	0.1±0.1^{A}	7076±8644^{A}
Median	33	35	51	330	8259	41	14	1.36	0.06	3398
Range	26–59	8–93	36–53	135–1252	2180–40534	3–52	9–16	1.36–18.65	0.03–0.22	880–16951
Eastern area (n = 10)										
Average	31±16^{A}	11±14^{B}	18±6^{BC}	37±48^{B}	32±27^{B}	2±0^{B}	3±2^{A}	0.05±0.02^{B}	0.00±0.00^{B}	13±12^{B}
Median	29	6	17	16	24	2	2	0.04	0.00	9
Range	14–61^{A}	0–41	6–29	6–164	6–95	1–3	0–8	0.02–0.07	0.00–0.01	2–42
Western area (n = 5)										
Average	32±25^{A}	13±15^{AB}	23±7^{BC}	36±44^{AB}	22±8^{B}	3±1^{B}	3±4^{A}	0.04±0.03^{B}	0.01±0.00^{B}	5±3^{B}
Median	26	4	24	16	24	2	1	0.04	0.01	5
Range	7–72	0–32	14–33	9–113	9–32	2–4	0–10	0.03–0.09	0.01–0.01	0–9
Southern area (n = 12)										
Average	17±9^{A}	7±9^{B}	15±8^{C}	39±40^{B}	42±41^{B}	3±1^{B}	3±6^{A}	0.06±0.02^{B}	0.01±0.00^{B}	27±35^{B}
Median	15	4	12	27	32	3	2	0.06	0.01	18
Range	9–39	1–33	8–33	10–137	6–161	1–4	0–21	0.03–0.1	0.00–0.01	4–132
Northern area (n = 10)										
Average	33±29^{A}	94±102^{A}	29±10^{B}	1646±2415^{A}	99±113^{B}	3±3^{B}	23±41^{A}	0.14±0.12^{B}	0.02±0.02^{B}	52±58^{B}
Median	19	67	27	495	60	2	2	0.10	0.01	36
Range	7–78	1–307	11–45	10–7057	4–372	1–9	0–113	0.03–0.34	0.00–0.06	2–184

Different letter (A,B, C) indicate significant differences (Tukey's tet, $p < 0.05$).

which exceeded the WHO guideline (Zhai et al., 2008). In that paper, the calculated total dietary Cd intake in the vicinity of the mine was similar to the intake of patients with Itai-itai disease. Kabwe soil could pose a risk to human health, particularly children playing around the mining area, not only due to the high Pb levels but also high Cd and As levels.

Copperbelt area (Cluster 2)

High Co and Cu concentrations were observed in the northern area, particularly in the Copperbelt. Furthermore, the Co and Cu concentrations were strongly positively correlated ($R^2 = 0.93$). It has been reported that the bedrock within the area contains sulfidic mineralization, rich in Co and Cu, embedded in carbonate rich shale and argillite (Mendelsohn, 1961). The high concentrations of Co and Cu observed in the northern area were considered to be the result of mining and smelting activities.

The heavy metal concentrations in river sediments are shown in Table 3. Average concentrations of Cu, Co, and Pb along the Kafue

Table 3. Mean (± S.D.) and median values and concentration range (mg/kg dry-wt) of heavy metals in river sediments.

	Cr (mg/kg)	Co (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	As (mg/kg)	Sr (mg/kg)	Cd (mg/kg)	Hg (mg/kg)	Pb (mg/kg)
Zambezi River (n = 8)										
Average	7±7^{B}	0.9±1.51^{B}	13±11^{B}	6±4^{B}	6±8^{B}	3±1^{B}	1±1^{A}	0.047±0.008^{A}	0.004±0.002^{B}	1±1^{B}
Median	5	0	11	5	4	2	0	0.05	0.00	1
Range	3–24	0-4	3-39	4-15	1-25	1–3	0–3	0.04–0.06^{A}	0.00–0.01	0–5
Luangwa River (n = 5)										
Average	21±11^{AB}	3.5±3.5^{B}	17±8^{B}	16±18^{B}	14±12^{AB}	1±1^{B}	2±3^{A}	0.039±0.011^{A}	0.003±0.003^{B}	3±2^{AB}
Median	15	2	14	7	11	1	1	0.03	0.00	2
Range	14–39	1–7	9–27	6–48	2–33	1–3	0-8	0.03–0.05	0.00–0.01	1–6
Kafue River (n = 8)										
Average	24±8^{AB}	277±256^{A}	42±21^{A}	4745±4464^{A}	49±43^{A}	7±4^{A}	13±15^{A}	0.122±0.118^{A}	0.026±0.027^{B}	22±22^{A}
Median	23	256	46	5254	35	77	10	0.09	0.02	11
Range	8–38	6.5–748	2–75	23–12906	6–134	1–12	0-42	0.041–0.406	0.003–0.087	5–63
Rivers in Lusaka (n = 3)										
Average	36±39^{A}	14±20^{AB}	14±10^{B}	19±15^{AB}	65±42^{A}	3±2^{AB}	10±13^{A}	0.11±0.00^{A}	0.1±0.08^{A}	19±16^{AB}
Median	16	3	13	12	45	4	3	0.11	0.07	13
Range	10–81	2–37	4–24	9–36	37–113	0–5	3–25	0.11–0.12	0.04–0.19	6–37

Different letters (A, B,C) indicate significant differences (Tukey's test, $p < 0.05$).

Table 4. Maximum values (mg/kg dry-wt) for each heavy metal and sampling site.

	Maximum value	Maximum place	Recommended value*
Cr	99	Lake Kariba	5-200
Co	748	Mushishima Stream	-
Ni	98	Lake Kariba	40-70
Cu	12906	Mushishima Stream	50
Zn	40534	Kabwe	300
As	52	Kabwe	10
Sr	113	Ndola	-
Cd	19	Kabwe	3
Hg	0.2	Kabwe	0.5-1
Pb	16951	Kabwe	200

* Recommended value by the ICRCL in UK (1987).

Table 5. Correlation coefficients (R^2) for each heavy metal.

	Cr	Co	Ni	Cu	Zn	As	Sr	Cd	Hg	Pb
Cr	1.00									
Co	0.01	1.00								
Ni	0.54	0.20	1.00							
Cu	0.00	**0.93**	0.13	1.00						
Zn	0.00	0.00	0.02	0.00	1.00					
As	0.05	0.05	0.15	0.04	**0.69**	1.00				
Sr	0.24	0.16	0.34	0.15	0.00	0.04	1.00			
Cd	0.00	0.00	0.02	0.00	**0.98**	0.59	0.00	1.00		
Hg	0.02	0.09	0.07	0.08	0.41	0.35	0.10	0.43	1.00	
Pb	0.00	0.00	0.02	0.00	**0.99**	**0.69**	0.00	**0.98**	0.41	1.00

Bold type indicates a significant correlation between each heavy metal determined by the Pearson product-moment correlation coefficient ($p < 0.05$).

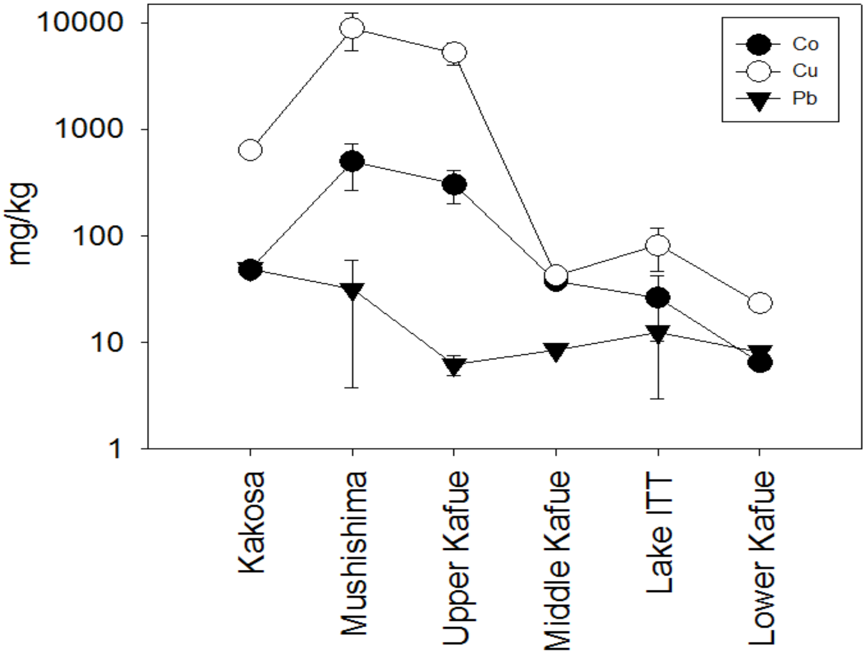

Figure 5. Average concentrations of Cu, Co, and Pb in sediment along the Kafue River.

River, including Lake ITT, are shown in Figure 5. The concentration of Pb did not change significantly along the Kafue River. However, the Co and Cu concentrations increased significantly after the confluence with the Mushishima Stream, which drains one of the key mining areas in the Copperbelt. Although, the Co and Cu concentrations decrease down the Kafue River, the Cu concentration observed in Lake ITT was still higher than the UK ICRCL guideline value (50 mg/kg dry-wt). This indicates that copper waste discharged into the upper reaches of the Kafue River was transported to and remained in such areas as Lake ITT, which is more than 450 km downstream from the major mining area. Pettersson and Ingri (2001) also found that dissolved concentrations of Cu (0.88 µmol/L) and Co (0.02 µmol/L) in water of the Kafue River about 100 km downstream from the mining areas in the Copperbelt were elevated compared to average world river concentrations (0.024 µmol/L for Cu and 0.003 µmol/L for Co). Their results support the findings of the present study with high Cu concentrations in the lower reaches of the Kafue River, including Lake ITT sediments (Figure 5).

Copper (Cu) is an essential trace element, but high concentrations of Cu may cause increased oxidative damage to lipids, proteins and DNA (Gaetke and Chow, 2003). Chronic Cu toxicity causes liver cirrhosis and tubular necrosis in the kidney (Gaetke and Chow, 2003; Barceloux, 1999). The high Cu concentrations measured in this study could affect humans, livestock and wildlife living in the area. A study by Syakalima et al. (2001) found that the Kafue Lechwe (Kobus leche kafuensis) which depends on the Kafue River in the Lochinvar and Blue Lagoon national parks had high Cu concentrations in the liver (42.8 ± 22.1 and 75.7 ± 26.4 mg/kg from the two national parks, respectively), which has potential to cause adverse effects. This report and our results suggest that the accumulation of Cu in the lower reaches of the Kafue River might even affect wildlife in National Parks.

Lusaka and other areas (Cluster 3)

Unlike Kabwe and the Copperbelt, no individual heavy metal component was dominant in Lukasa (Table 2 and Figure 3), and no particular point source was identified, but complex sources have been assumed. For example, in Lusaka, higher concentrations of Cu (357 and 1,874 mg/kg dry-wt at Lukasa 3 and 6, respectively) were observed in industrial areas, but high concentrations of Zn (777 mg/kg dry-wt) and Pb (133 mg/kg dry-wt) were found in soil beside major roads (Lusaka 4). High concentrations of Pb (1521.8 ppm) and Cu (1197.6 ppm) were reportedly found in central Transylvania, Romania, which is known as a pollution source due to chemical and metallurgical activities (Suciu et al., 2008). Fatoki (1996) showed that there was an association between the Zn concentration and the distance from road traffic. High concentrations of Pb in topsoil have been reported in the vicinity of a battery factory in Nigeria (Onianwa and Fakayode, 2000). These results indicate that human activities such as the metal industry and combustion of fossil fuels might be major sources of heavy metal contamination in Lusaka. As Lusaka is the capital city and has 10% of the country’s population, a number of people are at risk from this pollution.

In other areas, mainly the Eastern, Western and Southern areas, the levels of heavy metals were relatively low. However, we found positive correlations between the population of each town and concentrations of Zn (R^2 = 0.46) and Pb (R^2 = 0.51) (Figure 4). Previous reports indicate that these pollutants are commonly found in automobile and waste incinerator exhaust emissions (Bradl, 2005). Our findings indicated that the main sources of heavy metals in rural areas of Zambia are human activities such as combustion of fossil fuels.

Conclusion

In Zambia, the major sources of heavy metals are the mining areas, Kabwe and the Copperbelt, and heavy metals are then transported within each area by rivers. Even sediments in national park areas are polluted with high concentrations of Cu and moderate levels of Pb, indicating that mining is the source of the heavy metals. In areas geographically distant from mines, the heavy metal concentrations are moderate or low, but metals were detected in almost areas of Zambia. The findings are summarized as follows:

1. Heavy metal pollution in Zambia has strong regional differences.
2. Kabwe is highly polluted by Pb, Zn, Cu, Cd and As.
3. The Copperbelt area is highly polluted by Cu and Co.
4. Other sampling sites showed relatively low concentrations of heavy metals. However, the heavy metal pollution is currently increasing and caused by human activities. Furthermore, sources in each area were not only mining but other human activities such as metal industries and combustion of fossil fuels.
5. High concentrations of heavy metals, especially Cu, were found in the aquatic environment in the Copperbelt area. This also affected concentrations in Lake ITT, located 450 km downstream on the Kafue River, and in the Kafue National Park.

ACKNOWLEDGMENTS

This study was partly supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (M. Ishizuka, No. 19671001 and Y. Ikenaka, 21810001), by JSPS AA Science Platform Program and by The Sumitomo Foundation.

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