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Assessment of Trace Metal Contamination of Sediments in the Lubumbashi River Basin, Kafubu, Kimilolo and Kinkalabwamba Rivers in Lubumbashi City, Democratic Republic of Congo

Bamba Bukengu Muhaya[1], Matthieu Kayembe wa Kayembe[2], Clarisse Zoza Kunyonga[3], Sonia Catherine Mulongo[4] and Fidele Mushagalusa Cuma[5]

1. Department of Chemistry, Faculty of Science, Lubumbashi University, P.O. Box 1825 Lubumbashi, D.R. Congo

2. Department of Geography, Faculty of Science, Lubumbashi University, P.O. Box 1825 Lubumbashi, D.R. Congo

3. Department of Material Engineering, Higher School of Industrial Engineers, Lubumbashi University, P.O. Box 1825 Lubumbashi, D.R. Congo

4. Department of Geology, Faculty of Science, Lubumbashi University, P.O. Box 1825 Lubumbashi, D.R. Congo

5. Department of Renewable Natural Resources Management, Faculty of Agricultural Science, Lubumbashi University, P.O. Box 1825 Lubumbashi, D.R. Congo

Abstract: Arsenic (As), Barium (Ba), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Manganese (Mn), Lead (Pb) and Zinc (Zn) concentrations were investigated in sediments collected from sixteen sampling sites in the Lubumbashi river basin and five sites in Kafubu, Kimilolo and Kinkalabwamba rivers during February, March and April 2016. Analyses of the samples were carried out using a portable X-RFS (X-Ray Fluorescence Spectrometer). Water pH and OM (Organic Matter) content of the sediments were also determined. Trace metal toxicity risk to aquatic organisms was assessed using SQGs (Sediment Quality Guidelines)—TELs (Threshold Effect Levels) and PELs (Probable Effect Levels)—for freshwater sediments. Mean values of pH and OM ranged from 4.2 to 7.8 and from 1.27% to 6.22%, respectively. The highest mean levels of trace metals in sediments were 5,438 $mg \cdot kg^{-1} \cdot dw$ and 902.5 $mg \cdot kg^{-1} \cdot dw$ for Cu and Co, respectively in Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap, 1,534.5 $mg \cdot kg^{-1} \cdot dw$ and 342 $mg \cdot kg^{-1} \cdot dw$ for Zn and Pb, respectively at the confluence of Lubumbashi and Kafubu rivers, 108,900 $mg \cdot kg^{-1} \cdot dw$, 547 $mg \cdot kg^{-1} \cdot dw$ and 174.5 $mg \cdot kg^{-1} \cdot dw$ for Fe, Ba and Cr, respectively in Kinkalabwamba river, 531 $mg \cdot kg^{-1} \cdot dw$ and 22 $mg \cdot kg^{-1} \cdot dw$ for Mn and Cd, respectively in Kimilolo river, and 37 $mg \cdot kg^{-1} \cdot dw$ for As at the confluence of Tshondo and Lubumbashi rivers. The mean concentrations of As, Cd, Cr, Cu, Pb and Zn in the sediments exceeded the corresponding SQGs' PELvalues and could have adverse effects on aquatic organisms of those rivers. Trace metal contamination of the studied sediments might be partially attributed to natural processes, unplanned urbanization and poor waste management and mostly to abandoned and ongoing mining and ore processing activities in Lubumbashi city.

Key words: Trace metals, contamination, river sediments, pH, organic matter, Lubumbashi city.

1. Introduction

Sediments have a high storage capacity of chemical pollutants [1, 2] and act as a sink for trace metals [3-7]. Trace metals accumulated in sediments may persist in the environment long after their primary source has been removed [8] and create a potential for continued environmental degradation [7, 9-12] even where water column contaminant levels comply with established water quality criteria [11]. Sediment-associated trace metals represent a risk for organisms living in the

Corresponding author: Bamba Bukengu Muhaya, Ph.D., professor, research field: assessing and mapping the environmental and health impacts of abandoned mines in Sub-Saharan African countries.

sediments and in the water column, especially invertebrates and fish, but also for humans through human food chain [1, 3, 8, 13-15]. Sediments have been reported to be one of the most important tools to assess the contamination level of aquatic ecosystems [1, 3, 5, 8, 14-17].

The origin of trace metals which accumulate in sediments is partly from natural sources through the weathering of rocks and partly from a variety of human activities, including mining, smelting, electroplating and chemical manufacturing plants, as well as domestic discharges, shipping, boating activities … [11, 18]. In many developing countries such as D.R. Congo, millions of people do not have access to safe drinking water, especially those living in rural areas and most of the poor people in urban areas, and they largely depend on surface water for their domestic water needs [19]. As those people use rivers and streams as water source for their drinking, cooking, washing, irrigation and recreation needs, river sediments heavily polluted by trace metals represent a great risk for public health. Indeed, resuspension events from natural or anthropogenic origin can disturb the biogeochemistry of sediments and potentially result in the remobilization of trace metals from sediment particles to the water column [7, 20-23]. The use of metal polluted water for irrigation can also cause the death of crops or interfere with the uptake of essential nutrients [19, 24-26].

In the Upper-Katanga province, south-eastern D.R. Congo, factors which may be responsible for the pollution of water bodies are mainly industrial and artisanal mining and ore processing activities [27-30] as well as unplanned urbanization and population growth [31], and the easy accessibility of rivers for the disposal of untreated domestic and industrial wastes [27, 28, 32].

The aim of the current study was to investigate trace metal contamination of sediments in the Lubumbashi river basin water courses, as well as Kafubu, Kimilolo and Kinkalabwamba rivers in Lubumbashi city, and to compare the sediment metal levels to the sediment quality guidelines—TELs (Threshold Effect Levels) and PELs (Probable Effect Levels)—to know the possible risk of the sediment metals for aquatic organisms [33]. The Lubumbashi river basin includes Lubumbashi, Tshamalale, Kipopo, Kalubwe, Kashobwe, Kabulameshi, Munua, Tshondo, Kamalondo and Kamama rivers, as well as Tshibal channel and the adjusted Adventist spring and Tshamalale-1 quarter spring. Lubumbashi, Kimilolo and Kinkalabwamba rivers are Kafubu river tributaries. All those water courses are used without prior treatment by the people who live along them to meet their domestic, agricultural and recreational needs.

2. Material and Methods

2.1. Study Area and Sampling

The study area includes various water courses of the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers in Lubumbashi city. The Lubumbashi river basin includes Tshamalale, Kipopo, Kalubwe, Kashobwe, Lubumbashi, Kabulameshi, Munua, Tshondo, Kamalondo and Kamama rivers, as well as Tshibal channel, adjusted Adventist spring and Tshamalale-1 quarter spring. Waters from both springs flow into Tshamalale river. All those water courses flow through Lubumbashi, the capital city of the Upper-Katanga province in south-eastern D.R. Congo (Fig. 1).

Surface sediment samples of 25-centimeter depth were collected from sixteen sampling sites in the Lubumbashi river basin and from five sites in Kafubu, Kimilolo and Kinkalabwamba rivers. Of the twenty-one sampling sites, there were three in each of Kafubu and Kabulameshi rivers, two in each of the Kamalondo, Munua, Tshamalale and Tshondo rivers, one in each of the Kamama, Kashobwe, Kimilolo, Kinkalabwamba and Tshibal channel, as well as one sampling site at each of the adjusted Adventist spring and Tshamalale-1 quarter spring (Fig. 1) during February, March and April 2016 sampling campaigns.

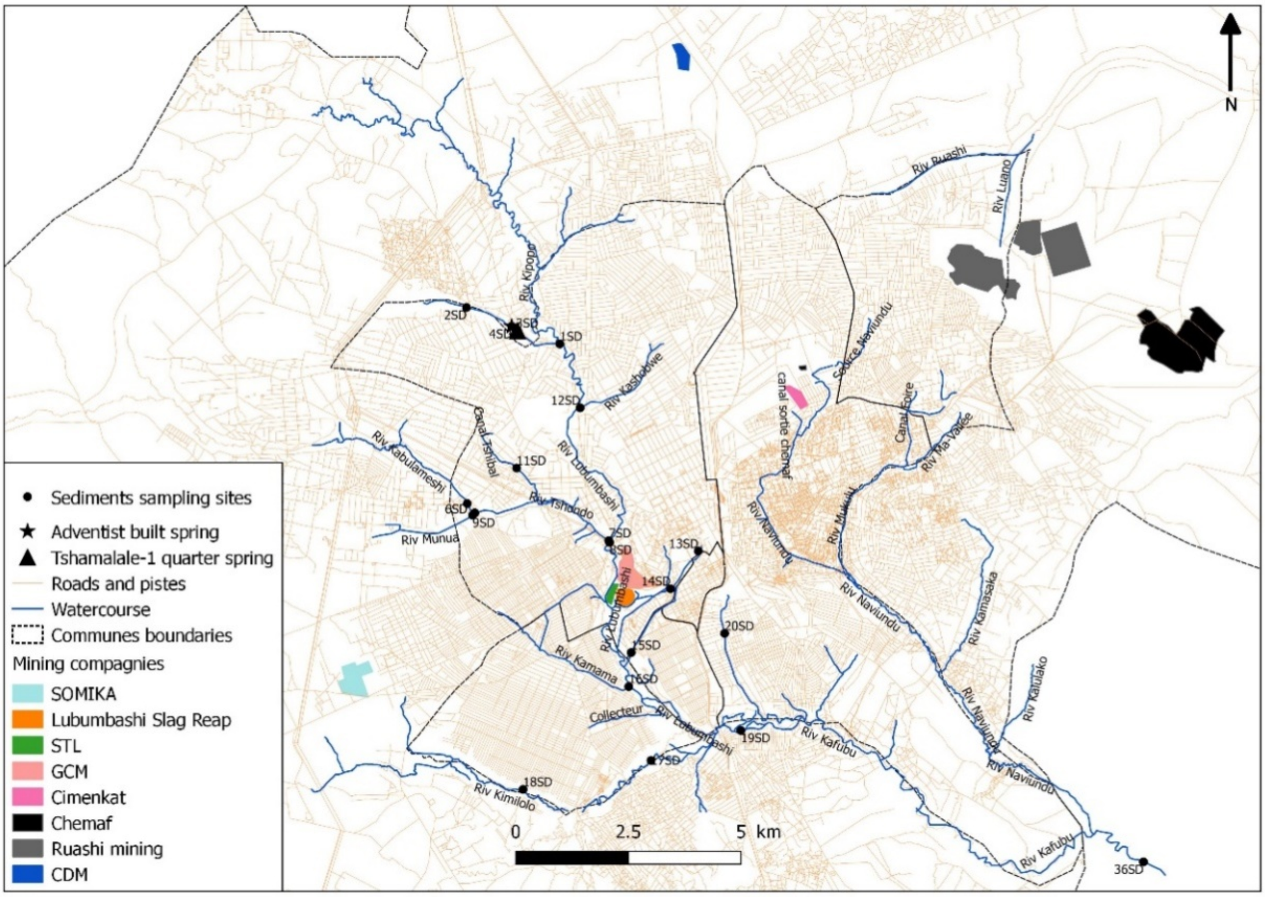

Fig. 1 Map of the river sediment sampling sites in Lubumbashi city.

A Garmin Etrex GPS was used for the determination of geographic coordinates of each sampling site. A sediment corer was used for the collection of 25-cm deep surface sediment samples. Upon collection, each sediment sample was put in a sealed plastic bag on which a sample code was written with a permanent marker. A transparent plastic sticker was sticked on the sample code to prevent it from being erased.

2.2 Sample Preservation

After collection, the samples were immediately taken to the laboratory where they were stored in a deep freezer. Later on, they were thawed and dried in an oven at 35 °C for 5 days [34]. They were then grinded in a porcelain mortar and sieved trough a 2-mm sieve to obtain fine grain size. Organic matter content of the sediments was determined using the Walkley and Black method [34]. According to that method, the quantitative analysis of OM (Organic Matter) is accomplished by analyzing one of its constituents, the OC (Organic Carbon). On average, OM contains 58% OC or % OC ∗ 1.724 = % OM. The method of measuring OC is based on the oxidation of the latter by potassium dichromate ($K_2Cr_2O_7$) in a strong acid solution (H_2SO_4). The grinded and sieved samples were then stored into 25-mm diameter sealed glass vials [X-RFS (X-Ray Fluorescence Spectrometer) sample cells] until they were analyzed for trace metals' content.

2.3 Analytical Method

The sediment samples were analyzed using an X-RFS. The accuracy and precision of the X-RFS measurements were evaluated by analyzing a standard reference material (soil). That indicated an acceptable quality of this method as a screening tool.

3. Results and Discussion

Sediment concentrations of ten trace metals including As, Ba, Cd, Co, Cr, Cu, Fe, Mn, Pb and Zn ($mg \cdot kg^{-1} \cdot dw$), pH and OM at the different sampling stations (Fig. 1), as well as the SQGs (Sediment Quality Guidelines) for freshwater sediments [33] are presented in Table 1. Water pH was very acid and ranged from 4.2 to 5.5 in Tshamalale-1 quarter spring, Tshamalale river, Kafubu river 1.36 kilometer downward its confluence with Naviundu river, Munua river, Lubumbashi river at its confluence with Tshondo river, Tshondo river at its confluence with Kabulameshi river, and Kafubu river at its confluence with Lubumbashi river (Table 1). The water pH was acid and varied from 5.8 to 6.2 in adjusted Adventist spring, Kalubwe river at its confluence with Kipopo river, Tshibal channel, and Kabulameshi river. In Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap, water pH was close to neutral with the value of 6.9. It was alkaline and varied from 7.2 to 7.8 in Kinkalabwamba river, Tshondo river, Kamalondo river near Wima Lycée, Kimilolo river, Kafubu river, Kamalondo river 60 meters from the GCM-Lubumbashi smelter (General of Quarries and Mines-Lubumbashi smelter), and Lubumbashi river at its confluence with Kamama river.

Sediment mean OM content varied from 1.27% to 6.22% (Table 1). They were very low in sediments of adjusted Adventist spring (1.27%), Tshibal channel (1.30%), Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (1.34%), Kamalondo river near Wima Lycée (1.43%), Kinkalabwamba river (1.47%), Kabulameshi and Munua rivers' confluence (1.99%), Kalubwe river at its confluence with Kipopo river (2.47%), Kafubu river 1.36 kilometer downward its confluence with Naviundu river (2.53%), Kabulameshi river (2.57%) and Tshondo river (2.70%). Sediments of Munua river, Kashobwe river, Tshamalale river, and Kamalondo river 60 meters from the GCM-Lubumbashi smelter had low OM content values of 3.0%, 3.84%, 3.97% and 4.0%, respectively. High OM content of sediments was noted in Lubumbashi river at its confluence with Tshondo river (4.13%), Kimilolo river (4.16%), Tshamalale river at its confluence with water of both springs (4.26%), Tshamalale-1 quarter spring (4.49%), Kafubu river (4.75%), Lubumbashi river at its confluence with Kamama river (5.05%) and Kafubu river at its confluence with Lubumbashi river (6.22%).

Trace metal concentrations in sediments of the different rivers are compared to the sediment quality guidelines for freshwater sediments [33]. The SQGs were used to determine the possible toxic effects of the metals on aquatic organisms (Table 1). The results indicated that trace metal concentrations in sediments from most of the sampling sites largely exceeded the recommendation limits of the SQGs for the protection of aquatic life. The highest mean trace metal concentrations were recorded in sediments of Lubumbashi river (29-45 $mg \cdot kg^{-1} \cdot dw$ for As, 2,739-6,941 $mg \cdot kg^{-1} \cdot dw$ for Cu, 127-278 $mg \cdot kg^{-1} \cdot dw$ for Pb and 755-1,520 $mg \cdot kg^{-1} \cdot dw$ for Zn), except Cr concentrations which were highest in Kinkalabwamba river sediments (165-184 $mg \cdot kg^{-1} \cdot dw$). The highest mean Cu and Co concentrations were recorded in Lubumbashi river sediments 1.45 kilometer downward the Lubumbashi Slag heap (5,438 $mg \cdot kg^{-1}$ and 902.5 $mg \cdot kg^{-1}$, respectively) but the sediment OM content (1.34%) was very low and the pH was below neutral (6.9). The very low OM content of the sediments and the pH in that river increase the metal bioavailability to organisms dwelling in those sediments. It has been reported that pH and organic matter are among the factors which favor heavy metal retention in soils [30, 35], and that organic-rich soils or sediments play, for the same reasons as those presenting alkaline pH, the role of trapping heavy metals [6, 7, 35, 36]. Those mean Cu and Co concentrations in Lubumbashi river sediments 1.45 kilometer downward the Lubumbashi Slag heap (5,438 $mg \cdot kg^{-1}$ and 902.5 $mg \cdot kg^{-1}$, respectively) and that of Pb in sediment of Kafubu river at its confluence with Lubumbashi river

Table 1 Mean trace metal concentrations in sediments (mg·kg^{-1}·dw) of the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers in Lubumbashi city during February, March and April 2016.

Sampling site	Sample code	pH water	OM (%)	As (mg·kg^{-1})	Ba (mg·kg^{-1})	Cd (mg·kg^{-1})	Co (mg·kg^{-1})	Cr (mg·kg^{-1})	Cu (mg·kg^{-1})	Mn (mg·kg^{-1})	Pb (mg·kg^{-1})	Zn (mg·kg^{-1})	Fe (mg·kg^{-1})
	SQGs												
	TELs	Na	Na	5.9	Na	0.6	Na	37.3	35.7	Na	35	123	Na
	PELs	Na	Na	17.0	Na	3.5	Na	90.0	197	Na	91.3	315	Na
Kalubwe river	1SD	6.0	2.47	ND	222	ND	ND	50	180	134	ND	102	28,900
Confluence of Tshamalale & Kipopo rivers	2SD	4.6	3.97	ND	382	ND	ND	69	503	124	56	198	24,900
Tshamalale river	3SD	4.4	4.26	ND	134	ND	ND	ND	120	182	ND	62.5	7,150
Adjusted Adventist spring	4SD	5.8	1.27	ND	170	ND	ND	25	164	144.5	ND	47	18,900
Tshamalale-1 quarter spring	5SD	4.2	4.49	ND	214.5	ND	ND	ND	347	40.5	27	64.5	34,900
Kabulameshi river	6SD	6.2	2.57	ND	466	ND	ND	ND	545	331.5	55.5	225.5	43,700
Tshondo river	7SD	7.4	2.70	23.5	468.5	ND	ND	33	3,467.5	252	240.5	895.5	38,500
Confluence of Tshondo & Lubumbashi rivers	8SD	5.1	4.13	37	397	ND	ND	26.5	3,304	433.5	255	856	34,200
Munua river	9SD	4.9	3.00	29.5	392.5	ND	ND	59.5	1,630.5	171.5	159.5	481	53,850
Confluence of Munua & Kabulameshi rivers	10SD	5.2	1.99	9	327	ND	ND	ND	178	349	ND	134	24,000
Tshibal channel	11SD	6.1	1.30	ND	291	ND	ND	ND	1321	139	79	787	45,000
Kashobwe river	12SD	5.9	3.84	ND	379	ND	ND	ND	682.5	219.5	101	402.5	33,100
Kamalondo river near Wima Lycée	13SD	7.5	1.43	ND	460	ND	ND	ND	661	354	53	313	48,400
Kamalondo river 60 m from the GCM-Lubumbashi smelter	14SD	7.8	4.0	9.5	253.5	18.5	ND	ND	946	297.5	100.5	655	25,450
Lubumbashi river 1.45 km downward the Lubumbashi Slag heap	15SD	6.9	1.34	16	348.5	ND	902.5	ND	5,438	339.5	146.5	1,342.5	98,450
Kamama river	16SD	7.8	5.05	17	375.5	ND	ND	33	1,786	274.5	209	845,5	26,000
Kafubu river	17SD	7.7	4.75	ND	250	ND	ND	20.5	272	241.5	35.5	228.5	20,450
Kimilolo river	18SD	7.6	4.16	22	420	ND	ND	ND	271	531	47	270	43,350
Confluence of Kafubu & Lubumbashi rivers	19SD	5.5	6.22	ND	472.5	56	ND	ND	3,161	184	342	1,534.5	40,300
Kinkalabwamba river	20SD	7.2	1.47	16	547	ND	ND	174.5	1,070	347.5	44.5	371	108,900
Kafubu river 1.3 km downward its confluence with Naviundu river	36SD	4.5	2.53	21.5	396.5	ND	ND	ND	185.5	152.5	14	418.5	37,350

SQGs: Sediment Quality Guidelines (Canadian Council of Ministers of the Environment, 2001); PELs: probable effect levels refer to concentration levels above which adverse effects are likely to occur; TELs: threshold effect levels represent concentrations below which a toxic effect on aquatic organisms will rarely occur; dw: dry weight; Na: no available data; ND: not detected; OM: organic matter; SD: sediment.

(342 mg·kg^{-1}) were lower than those (47,468 mg·kg^{-1}, 13,199 mg·kg^{-1} and 851.9 mg·kg^{-1}, respectively) reported for surface sediments of Luilu river [27], but they were higher than the Cu, Co and Pb levels (370.8 mg·kg^{-1}, 240.6 mg·kg^{-1} and 5.5 mg·kg^{-1}, respectively) noted in sediments of Musonoie river in the Kolwezi district (Lualaba province, D.R. Congo) [27]. Following the recommendation limits of the Canadian SQGs for the protection of aquatic life, the TELs (concentrations below which a toxic effect on aquatic organisms will rarely occur) and the PELs (concentration levels above which adverse effects are likely to occur) [33] are respectively 5.9 mg·kg^{-1} and 17.0 mg·kg^{-1} for As, 37.3 mg·kg^{-1} and 90.0 mg·kg^{-1} for Cr, 35.7 mg·kg^{-1} and 197 mg·kg^{-1} for Cu, 35 mg·kg^{-1} and 91.3 mg·kg^{-1} for Pb and 123 mg·kg^{-1} and 315 mg·kg^{-1} for Zn (Table 1).

Mean sediment trace metal levels above the SQGs' PEL values were recorded at different sampling sites. This was the case for As in sediments of Kafubu river (21.5 mg·kg^{-1}·dw), Kimilolo river (22.0 mg·kg^{-1}·dw), Tshondo river (23.5 mg·kg^{-1}·dw), Munua river (29.5 mg·kg^{-1}·dw), and at the confluence of Tshondo river with Lubumbashi river (37.0 mg·kg^{-1}·dw), for Cd in sediments of Kamalondo river near Wima Lycée (16.5 mg·kg^{-1}·dw), and at the confluence of Lubumbashi and Kafubu rivers (56 mg·kg^{-1}·dw) (Table 1, Fig. 2). That was also the case for Cr in Kinkalabwamba river sediments (174.5 mg·kg^{-1}·dw), for Cu in sediments at all the sampling sites, except in Kalubwe river, adjusted Adventist spring and Tshamalale-1 quarter spring (Table 1, Fig. 2). Mean Pb concentrations higher than the SQGs' PEL value of 91.3 mg·kg^{-1}·dw were recorded in sediment samples from Kamalondo river 60 meters from the GCM-Lubumbashi smelter (100.5 mg·kg^{-1}·dw), Kashobwe river (101 mg·kg^{-1}·dw), Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (146.5 mg·kg^{-1}·dw), Munua river (159.5 mg·kg^{-1}·dw), Kamama and Lubumbashi rivers' confluence (209 mg·kg^{-1}·dw), Tshondo river (240.5 mg·kg^{-1}·dw), Tshondo and Lubumbashi rivers' confluence (255 mg·kg^{-1}·dw), and Lubumbashi and Kafubu rivers' confluence (342 mg·kg^{-1}·dw) (Table 1, Fig. 2). The sediment mean concentrations of Cr and Fe in Kinkalabwamba river (174.5 mg·kg^{-1}·dw and 108,900 mg·kg^{-1}·dw), respectively and that of Zn in Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (1,342.5 mg·kg^{-1}·dw) were higher than the highest concentrations respectively noted in Luilu river (69.3 mg·kg^{-1}·dw and 116.4 mg·kg^{-1}·dw) and Musonoie river (24.6 mg·kg^{-1}·dw and 14.5 mg·kg^{-1}·dw) [27].

Mean concentrations of Zn in sediments of Kinkalabwamba river (371 mg·kg^{-1}·dw), Kashobwe river (402.5 mg·kg^{-1}·dw), Kafubu river 1.36 kilometer downward its confluence with Naviundu river (418.5 mg·kg^{-1}·dw), Munua river (481 mg·kg^{-1}·dw), Kamalondo river 60 meters from the GCM-Lubumbashi smelter (655 mg·kg^{-1}·dw), Tshibal channel (787 mg·kg^{-1}·dw), confluence of Kamama and Lubumbashi rivers (845.5 mg·kg^{-1}·dw), and that of Tshondo and Lubumbashi rivers (856 mg·kg^{-1}·dw), Tshondo river (895.5 mg·kg^{-1}·dw), Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (1,342.5 mg·kg^{-1}·dw), and the confluence of Lubumbashi and Kafubu rivers (1,534.5 mg·kg^{-1}·dw) were higher than the SQGs' PEL value of 315 mg·kg^{-1} (Table 1, Fig. 3). Mean Cr levels of sediments were 50 mg·kg^{-1}·dw at the confluence of Kipopo and Kalubwe rivers, 69 mg·kg^{-1}·dw in Tshamalale river, 25 mg·kg^{-1}·dw in the adjusted Adventist spring, 33 mg·kg^{-1}·dw in Tshondo river, 26.5 mg·kg^{-1}·dw at the confluence of Tshondo and Lubumbashi rivers, 59.5 mg·kg^{-1}·dw in Munua river, 33 mg·kg^{-1}·dw at the confluence of Kamama and Lubumbashi rivers, 20.5 mg·kg^{-1}·dw in Kafubu river, and 174.5 mg·kg^{-1}·dw in Kinkalabwamba river, but that metal was not detected in sediments of the other studied rivers, channel and spring. The mean Cr concentrations in sediments of Munua, Tshamalale and Kinkalabwamba rivers were higher than those reported for sediments of Mvudi river, south Africa [3]. The Cu,

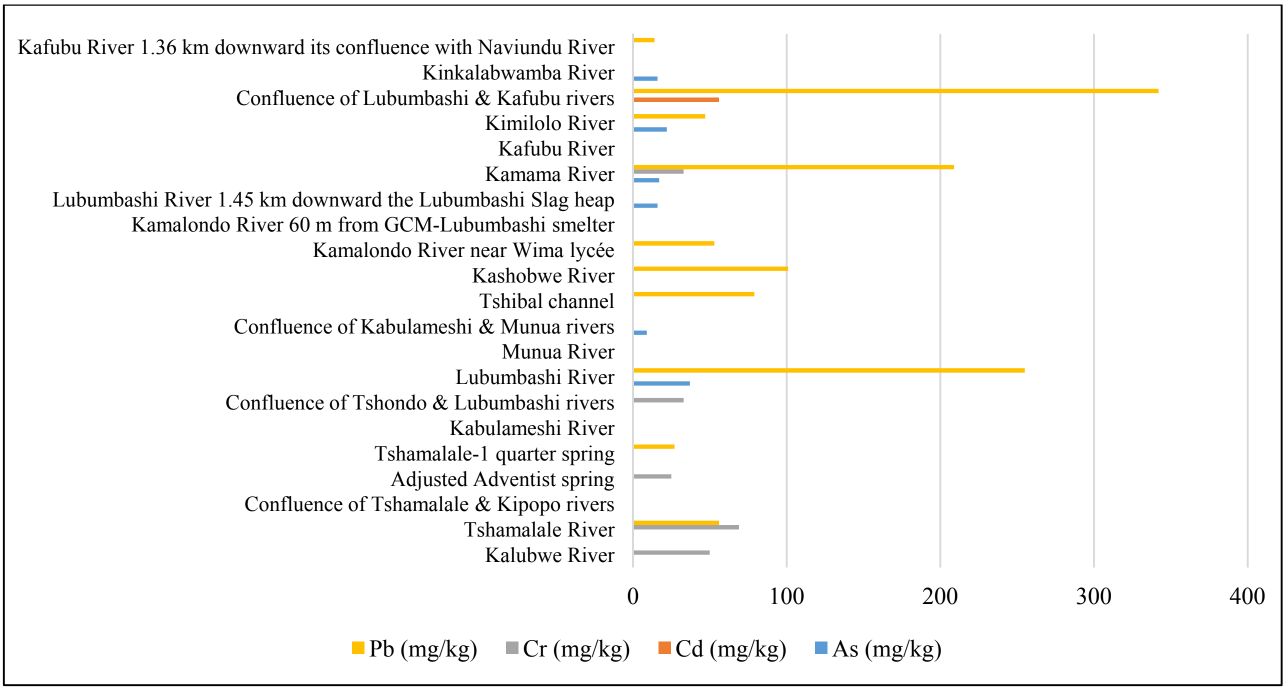

Fig. 2 Concentrations of As, Cd, Cr and Pb in sediment samples from the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers (mg·kg^{-1}·dw) in Lubumbashi city during February, March and April 2016.

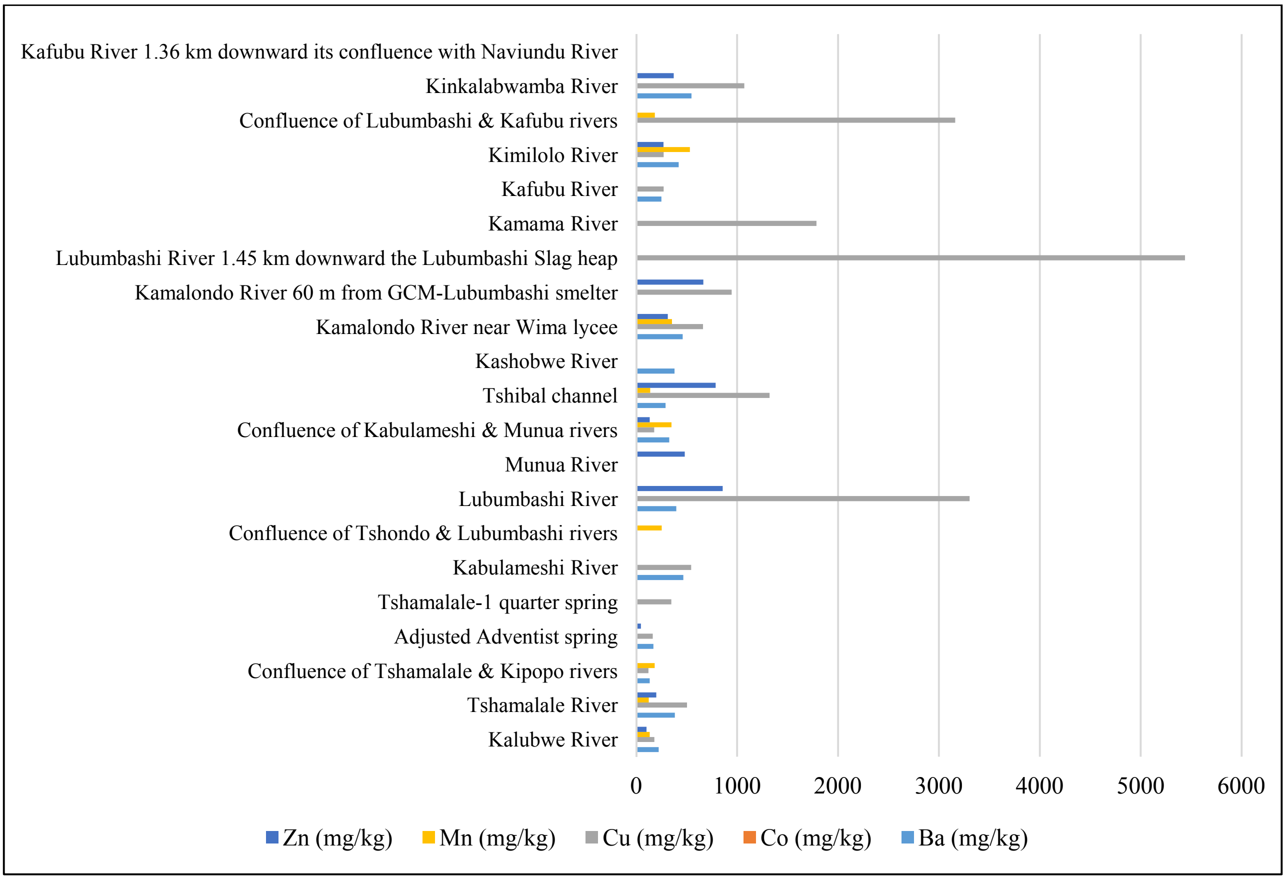

Fig. 3 Concentrations of Ba, Co, Cu, Mn and Zn in sediment samples from the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers (mg·kg^{-1}·dw) in Lubumbashi city during February, March and April 2016.

Fe, Pb and Zn concentrations noted in Mvudi river sediments [3] were much lower than those respectively found in sediments of most rivers of the Lubumbashi river basin, as well as Kafubu, Kimilolo and Kinkalabwamba rivers. Only Mn concentrations noted in sediments of Mvudi river [3] were higher than those recorded in this study, except those in sediments samples from the confluence of Tshondo and Lubumbashi rivers (433.5 mg·kg^{-1}), and from Kimilolo river (531 mg·kg^{-1}). The concentrations of Cu, Pb and Zn reported by the same authors [37] were significantly lower than those respectively recorded in sediments of most rivers of the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers in Lubumbashi city. On the other hand, the mean concentrations of Zn found in sediments of Tshibal channel (787 mg·kg^{-1}·dw), Kamama river (845.5 mg·kg^{-1}·dw), Tshondo and Lubumbashi rivers' confluence (856 mg·kg^{-1}·dw), Tshondo river (895.5 mg·kg^{-1}·dw), Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (1,342.5 mg·kg^{-1}·dw), and Kafubu river at its confluence with Lubumbashi river (1,534.5 mg·kg^{-1}·dw) were much higher than those noted in sediments of Winterbeek river (Belgium) [38]. Also, sediment mean concentrations of Cd at the confluence of Lubumbashi river with Kafubu river (56 mg·kg^{-1}·dw), Pb in Tshibal channel (79 mg·kg^{-1}·dw), Kamalondo river 60 meters from the GCM-Lubumbashi smelter (100.5 mg·kg^{-1}·dw), Kalubwe river (101 mg·kg^{-1}·dw), Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (146.5 mg·kg^{-1}·dw), at the confluence of Kamama river with Lubumbashi river (209 mg·kg^{-1}·dw), that of Tshondo river with Lubumbashi river (255 mg kg^{-1}dw), in Tshondo river (240.5 mg·kg^{-1}·dw) and at the confluence of Lubumbashi river with Kafubu river (342 mg·kg^{-1}·dw), were higher than those respectively reported for the sediments of Winterbeek river [38].

The mean Cu concentrations in sediments of all the studied rivers, channel and springs in Lubumbashi city (except at the confluence of water from both springs with Tshamalale river) were much higher than the concentrations of that metal reported for Winterbeek river sediments [38]. The sediment mean concentrations of Cr in Kinkalabwamba river (174.5 mg·kg^{-1}·dw), Co in Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (902.5 mg·kg^{-1}·dw), Cu in Kimilolo river (271 mg·kg^{-1}·dw), Kafubu river (272 mg·kg^{-1}·dw), Tshamalale-1 quarter spring (347 mg·kg^{-1}·dw), Kabulameshi river (545 mg·kg^{-1}·dw), Kamalondo river near Wima Lycée (661 mg·kg^{-1}·dw), Kashobwe river (682.5 mg·kg^{-1}·dw), Kamalondo river 60 meters from the GCM-Lubumbashi smelter (946 mg·kg^{-1}·dw), Kinkalabwamba river (1,070 mg·kg^{-1}·dw), Tshibal channel (1,321 mg·kg^{-1}·dw), Munua river (1,630.5 mg·kg^{-1}·dw), Lubumbashi river at its confluence with Kamama river (1,786 mg·kg^{-1}·dw), Kafubu river at its confluence with Lubumbashi river (3,161 mg·kg^{-1}·dw), Lubumbashi river at its confluence with Tshondo river (3,304 mg·kg^{-1}·dw), Tshondo river (3,467.5 mg·kg^{-1}·dw) and Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (5,438 mg·kg^{-1}·dw) were respectively much higher than the respective Cr, Co, Cu, Zn and Pb concentrations reported for the most polluted sediments of the Tisza river, Hungary [13].

Combined with the low (acid) pH of the water and the low OM contents of sediments in most of the studied rivers, those sediment metal levels largely exceeding the SQGs' probable effect level values increase the metal risk for aquatic organisms living in those rivers, and for the health of people who depend on those rivers to meet their water supply, irrigation and recreational needs.

The high trace metal contamination of sediments in the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers might be partially due to urban, hospital and domestic waste dumped in rivers and channel, run off from metal-rich soils and mostly to artisanal and industrial mining activities with emphasis on the GCM-Lubumbashi smelter and the Lubumbashi Slag heap. Untreated hospital effluents have been shown to contribute to the accumulation of toxic metals in sediments of receiving systems [39]. Solid waste and untreated effluents from all those activities, atmospheric deposition from the smelters and the slag heap to the rivers, channel, springs and soils, as well as rain that runs off metal-contaminated soils into various rivers and channel account for so high trace metal levels of the studied sediments. It has been reported that in various hydrometallurgical and smelter plants, copper and cobalt extraction is accompanied with discharge of by-products rich in Zn, Pb, As, Cd or sulfur compounds [40]. Atmospheric fallout from the SO_2-rich fumes discharged through the chimney of the GCM-Lubumbashi smelter contributed to metal accumulation in the soils of Penga-Penga plateau in Lubumbashi city, and the exploitation of quartz and brick-making contributed to the remobilization of trace metals through the landscape, soil, air and water [29]. Also, during the rainy season, hydromorphic soils in the Lubumbashi city bottom valleys collect waste enriched with trace metals from various plants all around the city, ore-washing carried out by artisanal mining exploiters in their residential parcels, malachite jewellery-making scattered in the city quarters and from a layer of slag spread on avenues to combat dust during dry season and mud during rainy season [41].

4. Conclusion

The results of the current study proved that sediments of the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers are heavily contaminated with trace metals, such as As, Ba, Cd, Co, Cr, Cu, Fe, Mn, Pb and Zn. The highest mean levels of Cu and Co were recorded in sediments of Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap, those of Cd, Pb and Zn were found in sediments at the confluence of Lubumbashi river with Kafubu river, and those of Ba, Cr and Fe were noted in sediments of Kinkalabwamba river, whereas those of Mn and As were respectively registered in sediments of Kimilolo river and at the confluence of Tshondo river with Lubumbashi river. Mean levels of As, Cd, Cr, Cu, Pb and Zn in most sediments of the Lubumbashi river Basin, Kafubu, Kimilolo and Kinkalabwamba rivers exceed the respective TEL values and PEL values of the Canadian SQGs. They are at risk for aquatic organisms of the concerned rivers and for human beings who live along those rivers, especially that low pH and sediment organic matter contents make the metals more available for bioaccumulation in most of the rivers. Trace metal contamination of sediments in the studied rivers, channel and springs in Lubumbashi city might be partially attributed to natural processes, unplanned urbanization and poor waste management and mostly to abandoned and ongoing mining and ore processing activities.

Authors suggest that (i) the provincial and national governments strictly implement the Congolese Mining Regulations for better protection of the environment; (ii) swimming in the rivers at heavily polluted sites be forbidden; and (iii) environmental monitoring of the rivers be regularly carried out and provincial authorities be informed of the results to let them take adequate protection measures for the population.

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