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

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Abstract: Concentrations of fifteen trace metals including Aluminum (Al), Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Strontium (Sr), Molybdenum (Mo), Silver (Ag), Cadmium (Cd), Tin (Sn), Caesium (Cs), Barium (Ba), Lead (Pb), Bismuth (Bi) and Uranium (U) were investigated in water samples collected from sixteen sampling locations in the Lubumbashi river basin and five locations in Kafubu, Kimilolo and Kinkalabwamba rivers during February, March and April 2016. Chemical analyses of the samples were carried out using ICP-MS (Inductively Coupled Plasma-Mass Spectrometer). Water pH was determined using a pH-meter and pH values ranged from 4.2 to 7.8. The highest mean trace metal levels of water were 5,515.816 $\mu g \cdot L^{-1}$, 166.925 $\mu g \cdot L^{-1}$, 3.898 $\mu g \cdot L^{-1}$ and 1.879 $\mu g \cdot L^{-1}$ for Al, Ba, Cr and U, respectively in Kashobwe river, 2,419.522 $\mu g \cdot L^{-1}$ and 17.994 $\mu g \cdot L^{-1}$ for Fe and Cd, respectively in Kafubu river at its confluence with Lubumbashi rivers, 1,408.136 $\mu g \cdot L^{-1}$ for Mn in Kafubu river 1.36 kilometer downward its confluence with Naviundu river, 222.406 $\mu g \cdot L^{-1}$ and 0.092 $\mu g \cdot L^{-1}$ for Sr and Cs, respectively in Kamalondo river 60 meters from the GCM-Lubumbashi (General of Quarries and Mines-Lubumbashi) smelter, 140.294 $\mu g \cdot L^{-1}$, 12.063 $\mu g \cdot L^{-1}$ and 0.008 $\mu g \cdot L^{-1}$ for Pb, V and Bi, respectively in Munua river, 3.544 $\mu g \cdot L^{-1}$ for Ag in Kabulameshi river, 1.49 $\mu g \cdot L^{-1}$ for Mo in Kafubu river and 0.081 $\mu g \cdot L^{-1}$ for Sn in Tshondo river. The mean concentrations of Al, Cd, Fe, Mn and Pb in water of many rivers and the channel exceeded the maximum admissible limits of the WHO (World Health Organization), USEPA (United States Environmental Protection Agency) and EU (European Union) drinking-water standards. Trace metal contamination of water of the studied rivers, channel and springs might be partially attributed to natural processes, unplanned urbanization, poor waste management and mostly to abandoned and ongoing mining and ore processing activities in Lubumbashi city.

Key words: Trace metal contamination, channel, river, spring, water, pH, Lubumbashi city.

1. Introduction

Anthropogenic activities, including industrial, agricultural and transport activities, are the main cause of environmental deterioration worldwide. In the African Copperbelt region which includes Zambia and the D.R. Congo provinces of Upper-Katanga and Lualaba, and in other parts of eastern D.R. Congo such as the Ituri, North-Kivu, South-Kivu, Maniema and Tanganyika provinces, atmosphere, soils, surface waters and groundwater are negatively impacted with

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trace metals and other contaminants as a result of abandoned and ongoing artisanal and industrial mining activities, metallurgical activities, as well as agricultural and transport activities [1-6]. In those regions, local air and soil environments, surface water and groundwater are deteriorated by factory emanations and dust from artisanal and industrial mining, tailings, discharge of untreated industrial and hospital effluents, discharge of mine water and mining wastewater into rivers, agricultural and urban runoff, and domestic wastewater [1-11].

Millions of people in many developing countries such as D.R. Congo 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 [6, 12]. Thus, the use of surface water and groundwater heavily contaminated with trace metals represent a great risk for public health in those countries.

The aim of the current study was to investigate trace metal contamination of water in the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers in Lubumbashi city, and to compare the water metal levels with the WHO (World Health Organization) guidelines for drinking-water quality [13], USEPA (United States Environmental Protection Agency) standards for water quality [14] and EU (European Union) drinking-water regulations [15]. Water of all those rivers, channel and springs is 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 Locations

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

Surface water samples were collected from sixteen sampling locations in the Lubumbashi river basin (sample codes 1ER to 3ER, 4ES and 5ES, 6ER to 16ER) and from five locations in Kafubu river (sample codes 17ER, 19ER and 36ER), Kimilolo river (sample code 18ER) and Kinkalabwamba river (sample code 20ER). Of the twenty-one sampling locations, there were three in each of Kafubu and Kabulameshi rivers, two in each of Kamalondo, Munua, Tshamalale and Tshondo rivers, one in each of Kamama, Kashobwe, Kimilolo and Kinkalabwamba rivers and Tshibal channel, as well as one sampling location at each of the adjusted Adventist spring and Tshamalale-1 quarter spring (Fig. 1) during February, March and April 2016 sampling campaigns. The samples were collected in clean 100-milliliter polyethylene bottles after rinsing the bottles three times with the water to be sampled. A sample code as well as the sampling site and the sampling date were written on each bottle and on the bottle lid. To prevent the sample code, sampling site and date from being erased, a transparent plastic sticker was stuck on the bottle and on its lid. Geographic coordinates of each sampling location were determined using a Garmin Etrex GPS and they were used later on for elaborating the sampling locations map (Fig. 1).

2.2 Sample Preservation

After collection, the samples were immediately taken to the laboratory where pH was determined using a pH-meter. After pH determination, samples

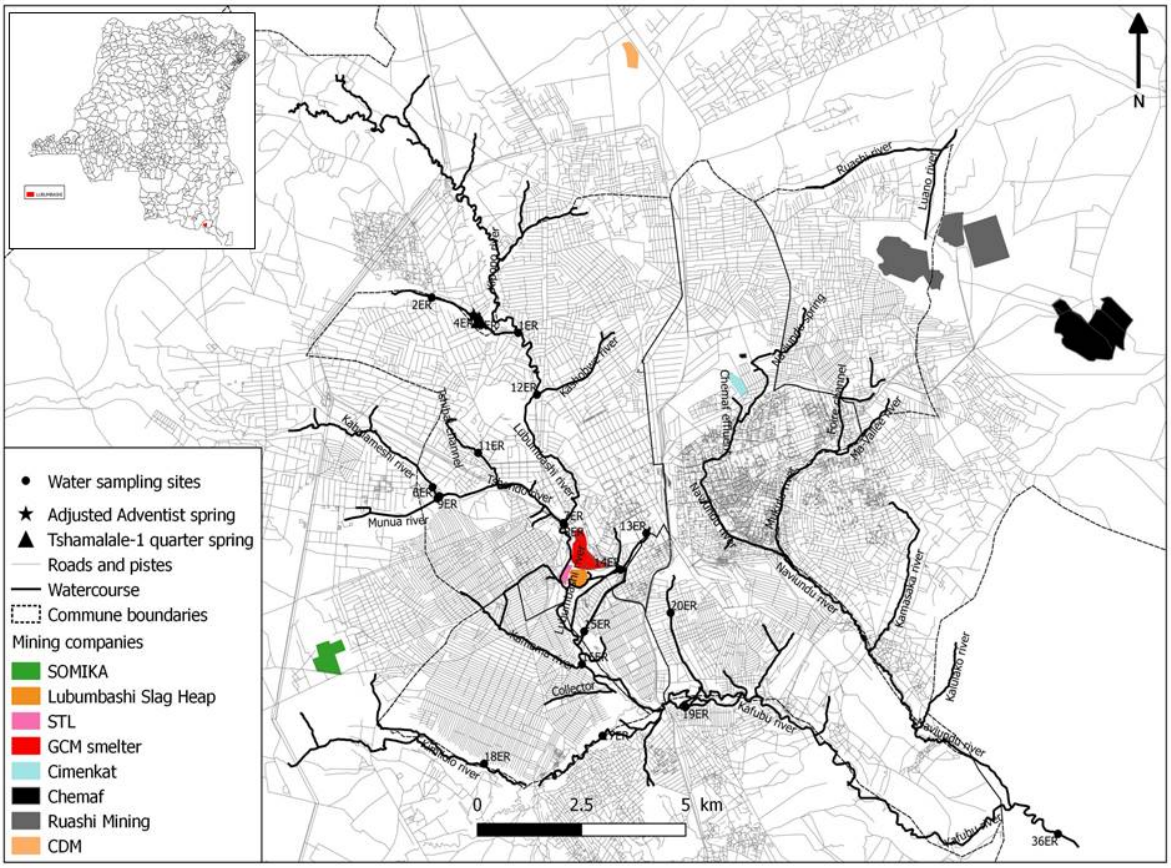

Fig. 1 Map of water sampling locations in the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers in Lubumbashi city during February, March and April 2016.

were acidified with two to three drops of concentrated ultrapure hydrochloric acid. Then they were stored in a clean place at room temperature in the laboratory until they were analyzed for trace metals' content.

2.3 Analytical Method

The samples were analyzed using ICP-MS (Inductively Coupled Plasma-Mass Spectrometry) at the AMGC (Analytical, Environmental and Geochemical) Laboratory, at VUB (Vrije Universiteit Brussel) in Belgium.

3. Results and Discussion

Water concentrations of fifteen trace metals including Ag, Al, Ba, Bi, Cd, Cr, Cs, Fe, Mn, Mo, Pb, Sr, Sn, U and V ($mg \cdot L^{-1}$) and water pH at the different sampling locations (Fig. 1), as well as the WHO guidelines for drinking-water quality [13], USEPA drinking-water standards and health advisories [14] and EU drinking-water regulations [15] 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, Fig. 2). 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, the pH was close to neutral with the value of 6.9 (Table 1, Fig. 2). It was alkaline

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

Sampling site	Sample code	pH	Sr-88 (μg·L^{-1})	Mo-98 (μg·L^{-1})	Ag-107 (μg·L^{-1})	Cd-114 (μg·L^{-1})	Sn-118 (μg·L^{-1})	Cs-133 (μg·L^{-1})	Ba-137 (μg·L^{-1})	Pb-208 (μg·L^{-1})	Bi-209 (μg·L^{-1})	U-238 (μg·L^{-1})	Al-27 (μg·L^{-1})	V-51 (μg·L^{-1})	Cr-52 (μg·L^{-1})	Mn-55 (μg·L^{-1})	Fe-56 (μg·L^{-1})
	WHO	6.5-8.5	Na	Na	Na	3	Na	Na	1,300	10	Na	30	200	Na	50	50	300
	EPA	6.5-8.5	Na	Na	100*	5	Na	Na	2,000	15	Na	30	50-200*	Na	100	50*	300*
	EU	6.5-8.5	Na	Na	Na	5	Na	Na	Na	10	Na	30	200*	Na	50	50*	200*
Kalubwe river	1ER	6.0	59.266	0.028	1.614	0.185	0.002	0.012	41.797	2.199	0.001	0.225	231.38	1.445	0.363	107.927	564.142
Confluence of Tshamalale & Kipopo rivers	2ER	4.6	14.93	0.044	1.522	0.201	0.007	0.012	13.696	1.009	0	0.035	97.749	0.69	0.331	41.472	1,091.825
Tshamalale river	3ER	4.4	17.325	0.051	1.593	0.14	0.006	0.014	19.531	0.986	0.001	0.034	120.252	0.699	0.464	55.884	1,178.548
Adjusted Adventist spring	4ES	5.8	5.2	0.008	0.912	0.059	0.003	0.005	42.408	0.651	0	0.025	39.929	0.134	0.179	12.818	24.982
Tshamalale-1 quarter spring	5ES	4.2	38.343	0.016	0.329	0.042	0.001	0.012	118.12	0.237	0	0.031	64.65	0.228	0.177	10.503	9.931
Kabulameshi river	6ER	6.2	71.394	0.093	3.544	0.544	0.001	0.019	95.224	4.9	0.003	0.227	222.364	1.384	0.549	126.055	1,146.827
Tshondo river	7ER	7.4	69.459	0.06	3.298	2.394	0.081	0.03	98.364	26.35	0.006	0.31	565.927	3.344	1.035	170.198	1,562.875
Confluence of Tshondo & Lubumbashi rivers	8ER	5.1	68.924	0.036	2.675	1.41	0.004	0.031	82.244	17.158	0.004	0.334	821.887	4.06	1.069	133.342	1,660.158
Munua river	9ER	4.9	53.05	0.034	1.935	7.286	0.033	0.046	62.845	140.294	0.008	0.82	3,546.49	12.063	3.17	232.267	2,090.783
Confluence of Munua & Kabulameshi rivers	10ER	5.2	56.517	0.04	1.708	2.411	0.03	0.028	88.333	47.378	0.003	0.311	1,073.125	3.549	1.036	110.484	1,142.357
Tshibal channel	11ER	6.1	110.476	0.154	1.521	0.878	0.017	0.038	55.848	5.752	0.003	0.38	417.087	2.585	0.843	134.052	887.919
Kashobwe river	12ER	5.9	123.501	0.024	1.252	2.454	0.054	0.029	166.925	59.735	0.001	1.879	5,515.816	9.332	3.898	391.221	1,420.026
Kamalondo river near Wima Lycée	13ER	7.5	162.156	0.348	1.102	0.185	0.014	0.017	126.953	1.858	0.003	0.434	168.372	1.499	0.468	213.169	799.971
Kamalondo river 60 m from the GCM-Lubumbashi smelter	14ER	7.8	222.406	0.65	0.5	0.462	0.042	0.092	121.986	5.038	0.002	0.558	172.694	1.612	0.557	357.894	953.364
Lubumbashi river 1.45 km downward the Lubumbashi Slag heap	15ER	6.9	87.234	0.172	1.844	10.42	0.009	0.035	80.083	32.979	0.005	0.514	815.918	3.665	1.117	192.975	1,740.296
Kamama river	16ER	7.8	157.07	0.184	2.219	0.751	0.025	0.068	87.544	17.152	0.004	0.799	614.791	3.789	0.876	252.464	1,801.356
Kafubu river	17ER	7.7	153.226	1.49	0.738	0.107	0.011	0.036	96.969	0.833	0.001	0.321	57.791	0.619	0.42	517.763	1,077.086
Kimilolo river	18ER	7.6	100.933	0.183	1.657	0.043	0.02	0.007	92.802	1.168	0.001	0.138	63.67	0.704	0.406	202.514	404.994
Confluence of Lubumbashi & Kafubu rivers	19ER	5.5	104.729	0.195	2.17	17.994	0.015	0.042	74.941	46.404	0.007	0.704	990.581	4.058	1.139	228.789	2,419.522
Kinkalabwamba river	20ER	7.2	209.718	0.712	1.708	0.736	0.059	0.079	119.745	8.823	0.003	0.896	420.362	3.769	1.163	632.024	1,312.175
Kafubu river 1.36 km downward its confluence with Naviundu river	36ER	4.5	114.875	0.371	1.281	7.337	0.007	0.027	74.782	19.674	0.004	0.803	343.053	2.435	0.604	1,408.136	1,482.27

* EPA Secondary Drinking-Water Regulations [14], EU Indicator Parameters [15]; EPA: United States Environmental Protection Agency Drinking-Water Standards and Health Advisories, 2011 [14]; EU: European Union Drinking-Water Regulations, 2014 [15]; Na: no available data; WHO: World Health Organization Guidelines for Drinking-Water Quality, 2017 [13].

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 (General of Quarries and Mines-Lubumbashi) smelter and Lubumbashi river at its confluence with Kamama river (Table 1, Fig. 2).

Trace metal concentrations in water of the studied rivers, channel and springs were compared with the WHO guidelines for drinking-water quality [13], EPA drinking-water standards and health advisories [14] and EU drinking-water regulations [15] to know the risk for the populations who use that water to meet their domestic, recreational and agricultural needs. The highest mean concentrations of Al (5,515.816 $\mu g{\cdot}L^{-1}$), Ba (166.925 $\mu g{\cdot}L^{-1}$), Cr (3.898 $\mu g{\cdot}L^{-1}$) and U (1.879 $\mu g{\cdot}L^{-1}$) were recorded in water of Kashobwe river, those of Fe (2,419.522 $\mu g{\cdot}L^{-1}$) and Cd (17.994 $\mu g{\cdot}L^{-1}$) were noted in Kafubu river at its confluence with Lubumbashi river, those of Pb (140.294 $\mu g{\cdot}L^{-1}$), V (12.063 $\mu g{\cdot}L^{-1}$) and Bi (0.008 $\mu g{\cdot}L^{-1}$) were found in Munua river, and those of Sr (222.406 $\mu g{\cdot}L^{-1}$) and Cs (0.092 $\mu g{\cdot}L^{-1}$) were recorded in Kamalondo river 60 meter from the GCM-Lubumbashi smelter (Table 1). The highest concentrations of Mn (1,408.136 $\mu g{\cdot}L^{-1}$) and Ag (3.544$\mu g{\cdot}L^{-1}$) were respectively noted Kafubu river 1.36 kilometer downward its confluence with Naviundu river and in Kabulameshi river, and those of Mo (1.49 $\mu g{\cdot}L^{-1}$) and Sn (0.081 $\mu g{\cdot}L^{-1}$) were found in Kafubu river and Tshondo river, respectively (Table 1, Figs. 3-7).

Mean Al and Fe levels of water of all the studied channel, rivers and springs, except the adjusted Adventist spring for Al and both the adjusted Adventist spring and Tshamalale-1 quarter spring for Fe, were much higher than the respective mean Al and Fe concentrations of 49 $\mu g{\cdot}L^{-1}$ and 25 $\mu g{\cdot}L^{-1}$ noted in surface water of Komabangou, a gold mining area in the Tillabéri region, Niger [16]. The mean Pb concentrations in water of all the studied rivers, channel and springs were higher than that (below quantification limit) reported for Komabangou surface water by Tidjani, D. A., et al. [16] and those (< 0.000 $\mu g{\cdot}L^{-1}$) noted in water of Luilu and Musonoie rivers, Kolwezi-Katanga (D.R. Congo) [2], except for both water Pb concentrations at sites KW1 (100 $\mu g{\cdot}L^{-1}$) and KW13 (2,300 $\mu g{\cdot}L^{-1}$) which were higher than those recorded in present study.

Water Cd concentrations found in all the rivers, channel and springs in the present study were in the range of 0 to 39,700 $\mu g{\cdot}L^{-1}$ reported for waters of the upper Lufira hydrographic basin and Tshangalele lake near Likasi (Upper-Katanga province) [1], but they were higher than those reported for Dzindi, Plankenburg and Diep rivers (South Africa) [12]. The Cd concentrations in waters of Tshondo river (2.394 $\mu g{\cdot}L^{-1}$), Kabulameshi river at its confluence with Munua river (2.411 $\mu g{\cdot}L^{-1}$) and Kashobwe river (2.454 $\mu g{\cdot}L^{-1}$) were in the concentration range of 0.2 $\mu g{\cdot}L^{-1}$ to 4.3 $\mu g{\cdot}L^{-1}$ noted for Mvudi river (South Africa) [12], whereas those in Munua river (7.286 $\mu g{\cdot}L^{-1}$), Kafubu river 1.36 km downward its confluence with Naviundu river (7.337 $\mu g{\cdot}L^{-1}$), Lubumbashi river 1.45 km downward the Lubumbashi Slag heap (10.42 $\mu g{\cdot}L^{-1}$) and Kafubu river at its confluence with Lubumbashi river (17.994 $\mu g{\cdot}L^{-1}$) exceeded the concentration range of that metal in Mvudi river and the metal levels of Lufira hydrographic basin and lake Tshangalele waters except that of Shituru effluents (39,700 $\mu g{\cdot}L^{-1}$) [1]. Also, water Pb levels found in the studied springs, channel and some rivers were in the range of below detection limit to 46 $\mu g{\cdot}L^{-1}$ reported for Mvudi river [12], but those found in Kafubu river at its confluence with Lubumbashi river (46.404 $\mu g{\cdot}L^{-1}$), Kabulameshi river at its confluence with Munua river (47.378 $\mu g{\cdot}L^{-1}$), Kashobwe river (59.735 $\mu g{\cdot}L^{-1}$) and Munua river (140.294 $\mu g{\cdot}L^{-1}$) exceeded the concentration range of that metal in Mvudi river. Water U and V levels recorded in the present study (0.015 $\mu g{\cdot}L^{-1}$ to 1.879 $\mu g{\cdot}L^{-1}$ and 0.08 $\mu g{\cdot}L^{-1}$ to 12.063 $\mu g{\cdot}L^{-1}$, respectively) were in the ranges of 0 $\mu g{\cdot}L^{-1}$ to 23 μg·L^{-1} and 0 μg·L^{-1} to 36 μg·L^{-1}, respectively reported for waters of Lufira hydrographic basin and Lake Tshangalele [1]. The metal contamination of rivers, channel and springs which flow through Lubumbashi city is mainly due to effluents from artisanal and industrial processing of ores in Lubumbashi city as well as to atmospheric deposition, run off from contaminated soils and urban waste discharge.

Water pH values of most of the rivers, channel and springs flowing through Lubumbashi city ranged from 4.2 to 6.9 whereas the pH values of six other rivers ranged from 7.2 to 7.8 (Table 1, Fig. 2). The low water pH below the WHO, EPA and EU recommended pH values of 6.5-8.5 in most of the rivers increases metal bioavailability to organisms dwelling in those rivers and the high water pH values reduce metal bioavailability in the six other rivers as alkaline pH plays the role of trapping heavy metals [5, 17-19].

For the WHO guidelines for drinking-water quality, USEPA drinking-water standards and health advisories, and EU drinking-water regulations [13-15], the maximum admissible concentration limits are 200 μg·L^{-1}, 200 μg·L^{-1} and 200 μg·L^{-1}, respectively for Al, 1,300 μg·L^{-1}, 2,000 μg·L^{-1} and no standard, respectively for Ba, 3 μg·L^{-1}, 5 μg·L^{-1} and 5 μg·L^{-1}, respectively for Cd, 50 μg·L^{-1}, 100 μg·L^{-1} and 50 μg·L^{-1}, respectively for Cr, 300 μg·L^{-1}, 300 μg·L^{-1} and 200 μg·L^{-1}, respectively for Fe, 50 μg·L^{-1}, 50 μg·L^{-1} and 50 μg·L^{-1}, respectively for Mn, 10 μg·L^{-1}, 15 μg·L^{-1} and 10 μg·L^{-1}, respectively for Pb, and 30 μg·L^{-1}, 30 μg·L^{-1} and 30 μg·L^{-1}, respectively for U (Table 1).

Mean Al levels above the 200 μg·L^{-1} maximum admissible limit value of the WHO guidelines for drinking-water quality, EPA drinking-water standards and health advisories and EU drinking-water regulations were recorded at various sampling sites. That was the case for Al concentrations in Kashobwe river (5,515.816 μg·L^{-1}), Munua river (3,546.49 μg·L^{-1}), Kabulameshi river at its confluence with Munua river (1,073.125 μg·L^{-1}), Kafubu river at its confluence with Lubumbashi river (990.581 μg·L^{-1}), Lubumbashi river at its confluence with Tshondo river (821.887 μg·L^{-1}), Lubumbashi river 1.45 kilometer downward the Lubumbashi Slag heap (815.918 μg·L^{-1}), Kamama river (614.791 μg·L^{-1}), Tshondo river (565.927 μg·L^{-1}), Kinkalabwamba river (420.362 μg·L^{-1}), Tshibal channel (417.087 μg·L^{-1}), Kafubu river 1.36 kilometer downward its confluence with Naviundu river (343.053 μg·L^{-1}) and Kalubwe river (231.38 μg·L^{-1}). Water Cd concentrations higher than

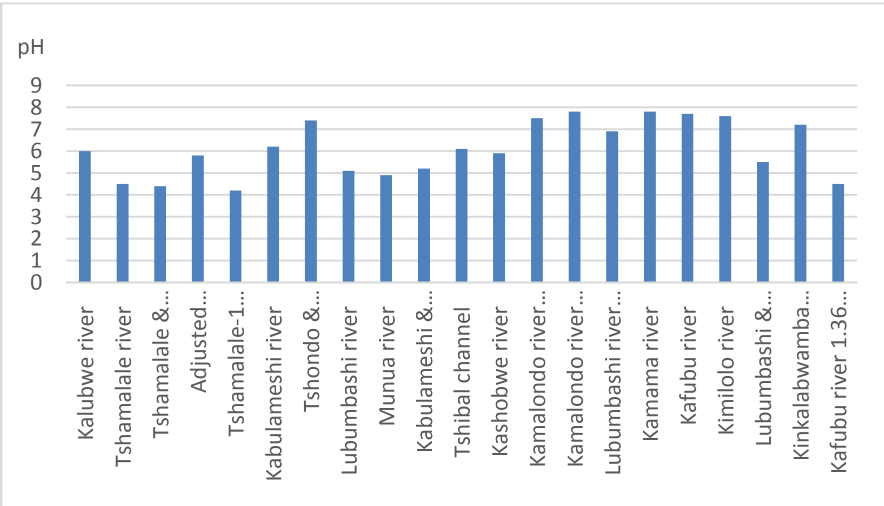

Fig. 2 Mean water pH in the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers in Lubumbashi city during February, March and April 2016.

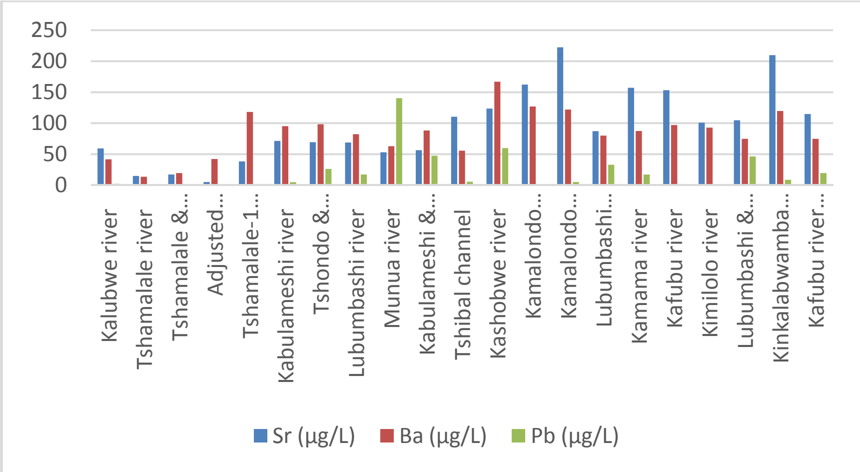

Fig. 3 Concentrations of Sr, Ba and Pb in water samples from the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers (µg·L^{-1}) in Lubumbashi city during February, March and April 2016.

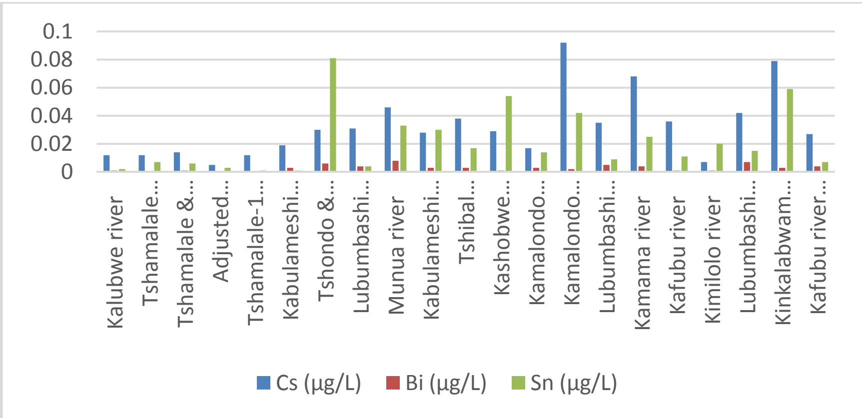

Fig. 4 Mean concentrations of Bi, Cs and Sn in water samples from the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers (µg·L^{-1}) in Lubumbashi city during February, March and April 2016.

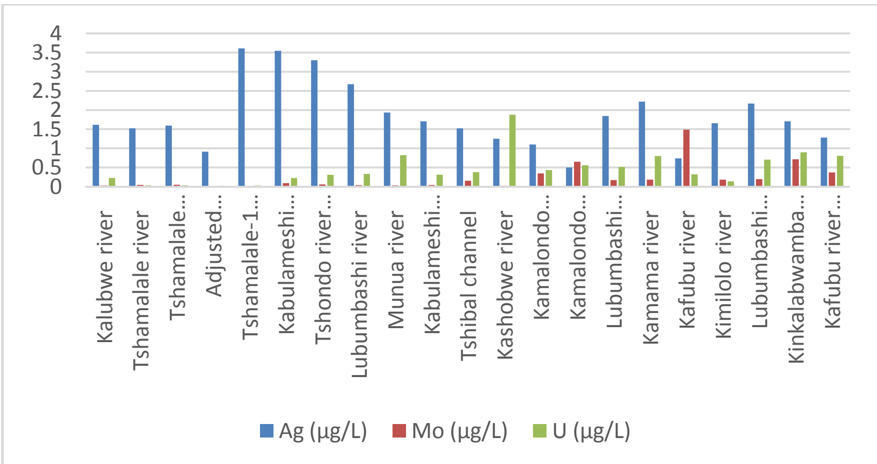

Fig. 5 Mean concentrations of Ag, Mo and U in water samples from the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers (µg·L^{-1}) in Lubumbashi city during February, March and April 2016.

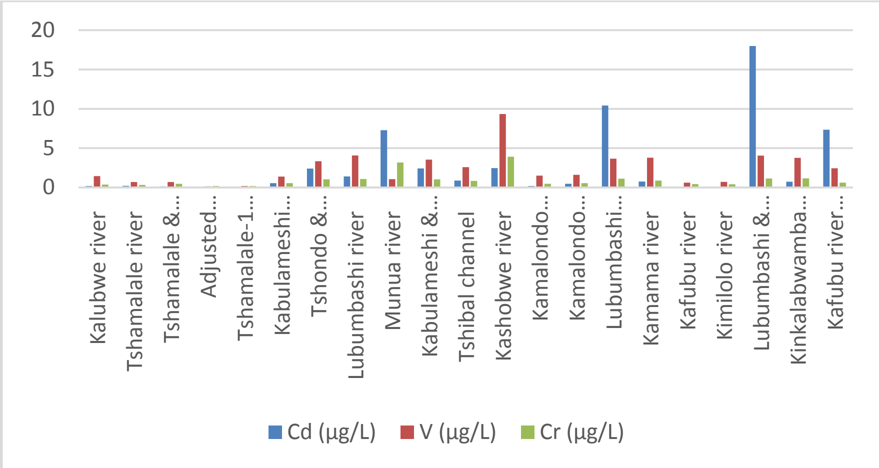

Fig. 6 Mean concentrations of Cd, Cr and V in water samples from the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers (µg·L^{-1}) in Lubumbashi city during February, March and April 2016.

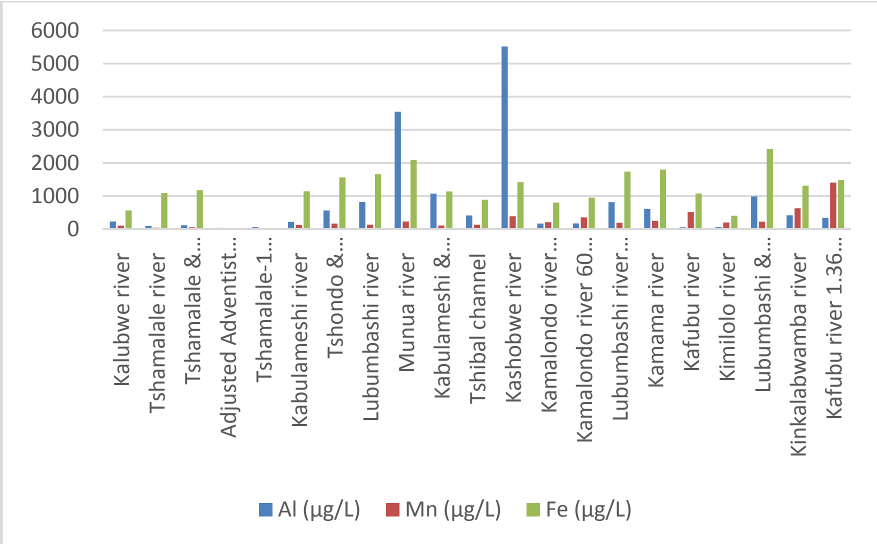

Fig. 7 Concentrations of Al, Fe and Mn in water samples from the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers (µg·L^{-1}) in Lubumbashi city during February, March and April 2016.

the maximum admissible concentration limit of the WHO drinking-water guidelines (3 µg·L^{-1}), EPA drinking-water standards and health advisories and EU drinking-water regulations (5 µg·L^{-1} and 5 µg·L^{-1}, respectively) were noted in water of Kafubu river at its confluence with Lubumbashi river (17.997 µg·L^{-1}), Lubumbashi river 1.45 km downward the Lubumbashi Slag heap (10.42 µg·L^{-1}), Kafubu river 1.36 km downward its confluence with Naviundu (7.337 µg·L^{-1}) and Munua river (7.286 µg·L^{-1}). Water Pb levels above the maximum admissible limit value (10 µg·L^{-1}) of the WHO drinking-water guidelines, EPA drinking-water standards and health advisories and EU drinking-water regulations were found in Munua river (140.294 µg·L^{-1}), Kashobwe river (59.735 µg·L^{-1}), Kabulameshi river at its confluence with Munua river (47.378 µg·L^{-1}), Kafubu river at its confluence with Lubumbashi river (46.404 µg·L^{-1}), Lubumbashi river 1.45 km downward the Lubumbashi slag heap (32.979 µg·L^{-1}), Tshondo river (26.35 µg·L^{-1}), Kafubu river 1.36 km downward its confluence with Naviundu river (19.674 µg·L^{-1}), Lubumbashi river at its confluence with Tshondo river (17.158 µg·L^{-1}) and Kamama river (17.152 µg·L^{-1}). Mn concentrations in water at all the studied sampling sites were higher than the maximum admissible limit value (50 µg·L^{-1}) of the EPA drinking-water standards and health advisories and EU drinking-water regulations, except the Mn concentration values of water in Tshamalale river at its confluence with Kipopo river (41.472 $\mu g \cdot L^{-1}$), adjusted Adventist spring (12.818 $\mu g \cdot L^{-1}$) and Tshamalale-1 quarter spring (10.503 $\mu g \cdot L^{-1}$). However, the highest concentrations of Ba (166.925 $\mu g \cdot L^{-1}$), Cr (3.898 $\mu g \cdot L^{-1}$) and U (1.879 $\mu g \cdot L^{-1}$) recorded in water of Kashobwe river were lower than the respective WHO and USEPA maximum admissible limits of 1,300 $\mu g \cdot L^{-1}$ and 2,000 $\mu g \cdot L^{-1}$ for Ba, 50 $\mu g \cdot L^{-1}$ and 100 $\mu g \cdot L^{-1}$ for Cr and 30 $\mu g \cdot L^{-1}$ for U [13, 14].

The highest mean sediment levels of Ba (547 $mg \cdot kg^{-1} \cdot dw$), Cr (56 $mg \cdot kg^{-1} \cdot dw$) and Fe (108,900 $mg \cdot kg^{-1} \cdot dw$) respectively noted in Kinkalabwamba river [6] were 4,568, 150,042 and 82,992 fold higher than the levels of those metals recorded in water of that river (Table 1), suggesting that sediments are a real sink for trace metals [12, 18-21]. Similarly, the highest mean concentrations of Cd and Pb in sediment of Kafubu river at its confluence with Lubumbashi river (56 $mg \cdot kg^{-1} \cdot dw$ and 342 $mg \cdot kg^{-1} \cdot dw$, respectively) [6] were 3,112 and 7,370 fold higher than the levels of those metals recorded in water of the same river.

The results indicated that waters of the studied channel, rivers and springs in Lubumbashi city were moderately contaminated with Ag, Ba, Bi, Cr, Cs, Mo, Sn, U and V probably originating from local geochemical structure, but they were heavily contaminated with Al, Cd, Fe, Mn and Pb from natural and anthropogenic origins, mainly from abandoned and ongoing mining and ore processing activities in and around Lubumbashi city. Combined with the low water pH in most of the studied rivers, the metal levels of water exceeding the WHO, EU and USEPA drinking-water maximum concentration limits increase the metal risk for aquatic organisms living in those channel and rivers and for the health of people who depend on those waters to meet their water supply, agricultural and recreational needs.

The trace metal contamination of water in the Lubumbashi river basin, Kafubu, Kimilolo and Kinkalabwamba rivers might be partially due to urban and domestic waste discharge into those rivers and channel, to runoff from metal-rich soils and mostly to abandoned and ongoing artisanal and industrial mining and ore processing activities in and around Lubumbashi city. It has been reported that 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 that the exploitation of quartz and brick-making contributes to the remobilization of trace metals through the landscape, soil, air and water [11]. According to Mpundu, M. M., et al. [22], during rainy season, hydromorphic soils in the Lubumbashi city bottom valleys collect waste enriched with trace metals from various plants all around the city, from ore-washing carried out by artisanal mining exploiters in their residential parcels, from malachite jewelry-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. The metal-rich waste discharged in rivers and channels contributes to metal contamination of the receiving rivers or channels.

4. Conclusion

This study was intended to assess trace metal contamination of waters of nine rivers, one channel and two springs of the Lubumbashi river basin as well as three rivers of the Kafubu river basin, all flowing through Lubumbashi city. The results showed mean water pH values ranging from 4.2 to 7.8 and various concentrations of fifteen trace metals including Ag, Al, Ba, Bi, Cd, Cr, Cs, Fe, Mn, Mo, Pb, Sn, Sr, U and V. The highest mean concentrations of Cd and Fe concentrations in water were recorded in Kafubu river at its confluence with Lubumbashi river. Those of Al, Ba, Cr and U were noted in water of Kashobwe river and that of Pb was found in Munua river. Kamalondo river 60 meters from the GCM-Lubumbashi smelter had the highest water Sr and Cs concentrations and Kafubu river 1.36 kilometer downward its confluence with Naviundu river had the highest Mn concentration in water. Finally, the highest concentrations of Mo, Sn and Ag were respectively recorded in Kafubu river, Tshondo river and Kabulameshi river. Trace metal contamination of waters of 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. The levels of some metals exceeded the maximum concentration limits of the WHO guidelines for drinking-water quality [13], USEPA drinking-water standards and health advisories [14] and EU drinking-water regulations [15] and they present a high risk to aquatic organisms living in those waters and to the health of people who depend on those springs, channel and rivers to satisfy their water supply, agricultural and recreational needs.

Authors suggest that (i) the provincial and national governments strictly implement the Congolese Mining Regulations for better environmental protection; (ii) swimming be forbidden in the rivers at heavily contaminated sites; 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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