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Concentrations of Potentially Toxic Elements in Groundwater and Surface Water in Ruashi and Annexe Municipalities of Lubumbashi City, Southeastern Democratic Republic of Congo

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Abstract: Groundwater and surface water contamination by PTE (Potentially Toxic Elements) was assessed in Ruashi and Annexe municipalities of Lubumbashi city. Analyses of seventy water samples collected from six drilled wells, eight spade-sunk wells, one river and one spring in both municipalities in 2017 and 2018 were carried out by ICP-SF-MS (Inductively Coupled Plasma-Sector Field Mass Spectrometry). Twenty PTEs including aluminum, arsenic, barium, bismuth, cadmium, cesium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, strontium, thallium, tungsten, uranium, vanadium and zinc were detected at various concentrations in each one of the samples. Many samples had concentrations and mean concentrations of PTEs, such as aluminum, cadmium, copper, iron, lead, manganese, nickel and zinc, higher than the respective acceptable limits set for drinking water by the EU (European Union), the USEPA (United States Environmental Protection Agency), and the WHO (World Health Organization) standards. Most PTEs being deleterious to human health even at very low concentrations, people who use the groundwater and surface water to meet their water needs in both Ruashi and Annexe municipalities are at risk.

Key words: Contamination, groundwater, PTEs, spring, stream, Ruashi and Annexe municipalities, Lubumbashi city.

1. Introduction

In most parts of the developing countries, many people use groundwater and surface water to meet their water needs for drinking, cooking, bathing and watering their plants. In DRC (Democratic Republic of Congo), the national company (REGIDESO) that provides drinking water to most urban and peri-urban inhabitants and to some rural inhabitants is not able to meet the needs of all its customers [1]. Thus, some people have to find a solution to their water needs by hand sinking themselves a water well in their respective parcels or by paying a specialized company to drill it for them. Unfortunately, groundwater as well as surface water is often contaminated with various chemical contaminants such as PTEs (Potentially Toxic Elements).

PTE contamination of surface water and sediments of various rivers and springs in Lubumbashi city and its neighborhoods has been documented [2-5] and that of groundwater also has been reported [6-9]. The water and sediment contamination has been attributed mainly to industrial and artisanal mining, ore processing and to mismanagement of urbanization and urban waste. Water contamination in Lubumbashi and other parts of the Upper-Katanga province has also been recognized to represent a health risk for the people that use that

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water to meet their water needs and many researchers have reported on adverse health effects of PTE on people in Lubumbashi city and its neighborhoods [10-16]. Other researchers have also reported on human health effects of various PTEs elsewhere in the world [17-24]. No study on PTE contamination of water in Annexe and Ruashi municipalities had been carried out so far. Thus, it was worth finding out whether that water consumed by inhabitants of both municipalities is PTE free or not.

The aim of the present study was to assess PTE contamination of groundwater, spring and stream water in Annexe and Ruashi municipalities of Lubumbashi city in order to find out the chemical quality of that water and to know whether the water presents any threat to the health of inhabitants of both municipalities.

2. Material and Methods

2.1 Study Area, Sampling Campaigns and Sample Pretreatment

Lubumbashi, the capital city of the Upper-Katanga province in the southeastern DRC is located between the longitude of 27°29′00″ East and the latitude of 11°40′11″ at the altitude of 1,230 m. The city has seven administrative municipalities, including Annexe, Kamalondo, Kampemba, Katuba, Kenya, Lubumbashi and Ruashi. The Ruashi municipality is located in the northeastern part of Lubumbashi city and the Annexe municipality is peri-urban and it surrounds the other six municipalities. In 2023, the total population of Lubumbashi city was estimated to 2,988,200 inhabitants [25]. With its area of 747 km^2, the city had thus a population density of 4,000 inhabitants/km^2. In the same time period (2023), the population of Ruashi municipality was estimated to 531,221 inhabitants [25] and that of Annexe municipality to 958,617 inhabitants [25].

In both Ruashi and Annexe municipalities, water samples were collected once a month from eight spade-sunk water wells, six drilled water wells, one spring and one stream in September, October and November 2017, and in February and March 2018. At each sampling campaign, two water subsamples were collected from each sampling site. A total of seventy samples were collected and Fig. 1 illustrates the map of the sampling sites. The water samples were collected in 100 mL polyethylene plastic bottles and acidified with a few drops of concentrated hydrochloric acid. The plastic bottles were beforehand washed with liquid soap and rinsed with double distilled water. Before collecting the samples, the bottles were also rinsed three times with the water to be sampled. Acidified water samples were filtered on 0.45 µm disposable syringe filters (Chromafil, cellulose mixed ester). They were then stored at room temperature until their chemical analyses at the VUB (Brussels Free University) AMGC (Analytical and Environmental Chemistry and Geochemistry) laboratory.

2.2 Analytical Methods

Trace element analysis was carried out by ICP-SF-MS (Inductively Coupled Plasma-Sector Field Mass Spectrometry) (Thermo Scientific Element II). The instrument was equipped with an ESI Fast autosampler, PFA-ST microflow nebulizer, Peltier cooled glass cyclonic spray chamber, quartz injector and torch and Ni cones. Regarding the resolutions used, low resolution was used for Sr, Mo, Cd, Cs, Pb, Bi and U; medium resolution was used for Al, V, Cr, Ni, Cu, Zn, Mn, Fe, Co; high resolution was used for As. Rhodium (1 ppb) was used as internal standard in all resolutions.

Standard solutions were prepared from multielement standard solutions and single element standard solutions. Blanks, standards and QC (Quality Control) samples were reanalysed throughout the procedures. The reference material SW-1 (SPS) was used as QC sample.

2.3 Statistical Analysis

Statistical analysis of the data was performed using R statistical software before being archived by Excel

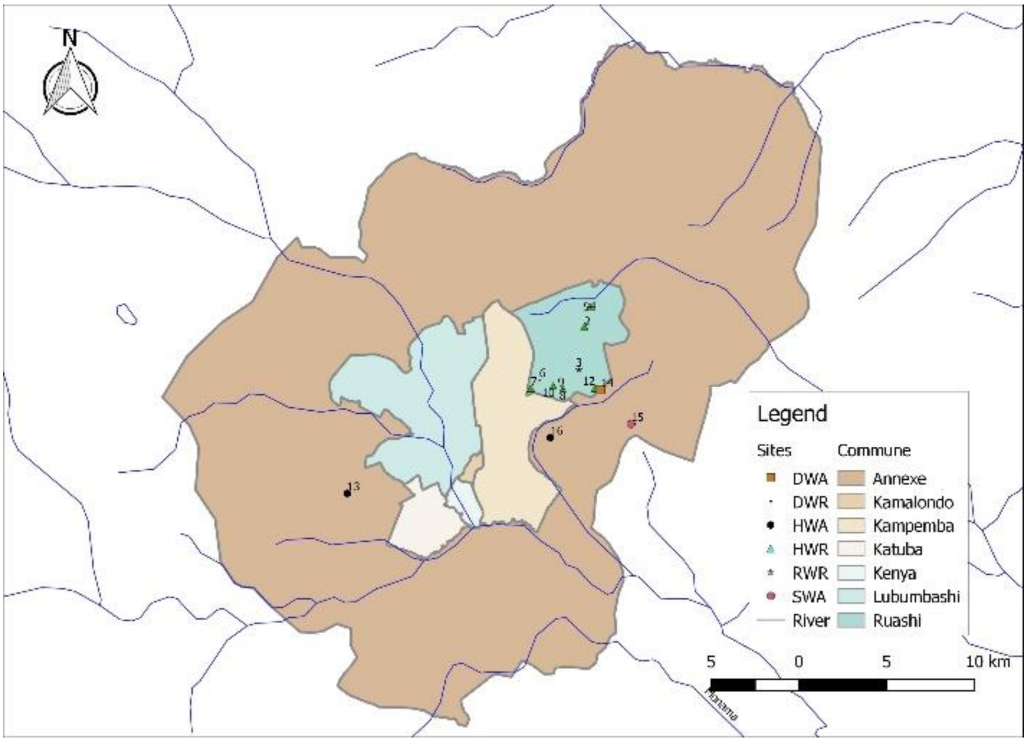

Fig. 1 Map of the water sampling sites in Annexe and Ruashi municipalities of Lubumbashi city.

and Excelstat. With R statistical software, mean PTE concentrations and standard deviations of groundwater and surface water in Ruashi and Annexe municipalities were computed. The R statistical software is an open source of statistics and a data treatment software supported by R Foundation for Statistical Computing. It is part of the GNU package. GNU is a free software distributed according to the terms of general public GNU license available under GNU/Linex, FreeBSD, NetBSD, OpenBSD, MasOS X and Microsoft Windows. The R project was born in 1993 as an Auckland University (New Zealand) research project by Ross Ihaka and Robert Gentleman. In September 2020, R software was ranked 9th by TIOBE Index (issued by TIOBE Software BV based in Eindhoven (Netherlands) which classifies software programming languages and measures their popularity.

For the statistical analysis in the current study, the 4.4.1 version of R software issued on 14 June 2024 was used.

3. Results and Discussion

The results of chemical analyses of the water samples indicate the presence of twenty PTEs detected at various concentrations in all the analyzed samples. The twenty PTEs include aluminum, arsenic, barium, bismuth, cadmium, cesium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, strontium, thallium, tungsten, uranium, vanadium and zinc. They are presented in Table 1 and illustrated in Figs. 2-12. The PTE concentrations were compared with drinking water standards set by the EU (European Union) [26], the USEPA (United States Environmental Protection Agency) [27] and the WHO (World Health Organization) [28] (Table 2).

Among the twenty PTEs found in water in the present study, five of them including bismuth, cesium, cobalt, tungsten and vanadium are the only ones for which international institutions such as the WHO [28], the EU [26], the USEPA [27] or others have not yet set any maximum contaminant limit nor health advisory indicator for drinking water. Concentrations of those PTEs ranged from 0.000 to 1.011 μg/L with the highest mean concentration of 0.172 μg/L for bismuth, from 0.006 to 0.806 μg/L with the highest mean concentration of 0.701 µg/L for cesium, from 0.538 to 434.979 µg/L with the highest mean concentration of 214.942 µg/L for cobalt, from 0.021 to 142 µg/L with the highest mean concentration of 56.605 µg/L for tungsten, and from 0.016 to 2.674 µg/L with the highest mean concentration of 0.97 µg/L for vanadium (Table 1, Figs. 2, 5 and 6, Figs. 9, and 11 and 12). Despite the low concentrations of these PTEs, they might be detrimental to the health of people who use the contaminated water due to possible bioaccumulation and biomagnification of those metals by human organs. Even cobalt which is known to be among the essential trace elements at very low concentrations for normal body function, the toxicity of this metal in humans has been reported [29]. Guo et al. [30] have reported on the changes of essential trace elements in residents of e-waste site and the relationships between elements and hormones of the pituitary-thyroid axis. Other researchers have reported on bismuth toxicity [31-34], tungsten toxicity [35, 36] and vanadium neurotoxicity [37]. Cesium has been reported as being a naturally occurring element found combined with other elements in rocks, soil, and dust in low amounts [38]. Naturally occurring cesium is not radioactive and is referred to as stable cesium. There is only one stable form of cesium naturally present in the environment, ^{133}Cs (read as cesium one-thirty-three). Limited information is available regarding health effects following oral exposure of humans to stable cesium compounds. Symptoms of decreased appetite, nausea, diarrhea, and cardiac arrhythmia have been associated with consumption of cesium chloride [39-43].

For PTEs such as arsenic, barium, chromium, molybdenum, strontium, thallium and uranium, MCLs (Maximum Contaminant Levels) and health advisory indicators have been determined by various international standards for drinking water but the concentrations of these PTEs in water in both municipalities of Lubumbashi city were much lower than their respective MCLs. The concentrations of those PTEs in water in Ruashi and Annexe municipalities ranged from 0.032 to 10.702 µg/L with the highest mean value of 3.665 µg/L for arsenic, from 6.978 to 507.061 µg/L with the highest mean value of 347.241 µg/L for barium, from 0.071 to 2.438 µg/L with the highest mean value of 0.661 µg/L for chromium, from 0.008 to 0.809 µg/L with the highest mean value of 0.318 µg/L for molybdenum, from 2.956 to 177.564 µg/L with the highest mean value of 97.024 µg/L for strontium, from 0.002 to 0.271 µg/L with the highest mean value of 0.121 µg/L for thallium, and from 0.009 to 8.59 µg/L with the highest mean value of 4.237 µg/L for uranium. All those highest PTE concentrations were much lower (Table 1, Figs. 2-5, Figs. 7-10, and Fig. 12) than the respective MCLs and health advisory indicators of 10 µg/L, 2,000 µg/L, 50 µg/L, 40 µg/L, 4,000 µg/L, 2 µg/L, and 30 µg/L set for drinking water (Table 2).

For the other PTE including aluminum, cadmium, copper, iron, manganese, nickel and zinc found in various concentrations in water in this study, MCLs and health advisory indicators have also been determined by various international standards for drinking water (Table 2). In many water samples, mean concentrations of these PTEs were much higher than the respective MCLs or health advisory indicators for drinking water (Table 1, Figs. 4 and 5, Figs. 7-10, and Fig. 12). Aluminum and iron concentrations ranged from 5.732 to 931.481 µg/L with the highest mean concentration of 907.266 µg/L and from 1.588 to 6,458.085 µg/L with the highest mean concentration of 2,875.764 µg/L, respectively. Cadmium and lead concentrations ranged respectively from 0.017 to 385.265 µg/L with the highest mean concentration of 226.884 µg/L and from 0.374 to 16.178 µg/L with the highest mean concentration of 8.835 µg/L. Copper and nickel concentrations ranged respectively from 3.578 to 9,856.15 µg/L with the highest mean concentration of 4,861.74 µg/L and from 0.426 to 96.881 µg/L with the highest mean concentration of 50.007 µg/L. Manganese concentrations ranged from 1.865 to 1,370.736 µg/L with the highest mean concentration of 895.626 µg/L and those of zinc ranged from 4.567 to 49,106.13 µg/L with the highest

Table 1 Concentrations of PTEs in groundwater and surface water (µg/L) in Ruashi and Annexe municipalities of Lubumbashi city.

N samples & conc. value type	Sample code	Sr (µg/L)	Mo (µg/L)	Cd (µg/L)	Cs (µg/L)	Ba (µg/L)	W (µg/L)	Tl (µg/L)	Pb (µg/L)	Bi (µg/L)	U (µg/L)	Al (µg/L)	V (µg/L)	Cr (µg/L)	Mn (µg/L)	Fe (µg/L)	Co (µg/L)	Ni (µg/L)	Cu (µg/L)	Zn (µg/L)	As (µg/L)
(*N* = 4) Conc. range	1DWR	7.898-19.458	0.021-0.043	0.138-0.258	0.044-0.139	95.338-154.75	0.044-0.085	0.022-0.07	2.262-16.178	0.002-0.007	0.027-0.078	37.878-56.448	0.029-0.331	0.269-0.553	39.894-75.016	146.121-277.073	2.883-8.096	4.635-31.973	78.884-393.719	60.562-189.679	0.104-5.777
(*N* = 4) Mean conc.	1DWR	14.337	0.027	0.1748	0.09	128.405	0.0715	0.0455	8.8345	0.005	0.059	47.163	0.135	0.386	53.029	217.978	5.66	13.424	225.075	126.57	2.361
Std. dev.	1DWR	5.963	0.011	0.056	0.052	29.338	0.019	0.027	7.038	0.002	0.023	13.131	0.134	0.121	15.481	55.487	2.747	12.859	169.316	67.798	2.764
(*N* = 6) Conc. range	2HWR	4.981-9.514	0.012-0.02	0.035-0.573	0.157-0.785	133.615-148.562	0.053-0.177	0.035-0.095	0.478-1.661	0.001-0.025	0.039-0.06	195.797-682.825	0.016-2.674	0.151-2.438	102.835-513.798	43.199-1,804.34	7.692-32.657	2.759-8.087	9.051-457.754	25.752-58.288	0.052-2,28
(*N* = 6) Mean conc. value	2HWR	6.597	0.015	0.186	0.29	141.003	0.086	0.051	1.718	0.006	0.084	439.311	0.513	0.661	232.368	374.844	15.805	6.843	93.088	36.621	0.781
Std. dev.	2HWR	1.818	0.003	0.200	0.246	6.78	0.049	0.025	1.805	0.009	0.067	344.381	1.06	0.895	196.267	702.09	12.139	2.013	179.561	11.942	0.893
(*N* = 6) Conc. range	3RWR	42.629-54.103	0.013-0.121	0.029-0.164	0.008-0.018	35.098-51.891	0.021-0.072	0.002-0.006	0.589-3.086	0.001-0.014	0.032-0.062	29.794-40.249	0.031-0.699	0.159-0.312	59.001-157.202	926.146-6,458.085	2.87-5.08	0.465-2.515	8.033-68.167	7.167-36.677	0.307-1.306
(*N* = 6) Mean conc.	3RWR	48.707	0.056	0.078	0.012	45.028	0.044	0.004	1.427	0.172	0.043	35.022	0.371	0.252	102.806	2,875.764	3.926	1.142	24.388	16.269	0.846
Std. dev.	3RWR	5.388	0.047	0.05	0.003	5.854	0.022	0.002	0.89	0.411	0.014	7.393	0.278	0.065	39.547	2,188.653	0.811	0.713	23.799	10.341	0.393
(*N* = 6) Conc. range	4HWR	10.838-18.568	0.008-0.02	0.019-0,382	0.01-0.047	17.274-30.251	0.024-0.076	0.002-0.007	0.533-2.939	0.001-0.027	0.024-0.085	85.017-185.602	0.201-0.845	0.094-0.408	13.234-20.268	107.271-577.515	1.287-3.849	0.565-4.078	5.516-139.122	5.732-50.986	0.184-3.358
(*N* = 6) Mean conc.	4HWR	14.197	0.013	0,119	0.025	23.821	0.052	0.004	1.511	0.007	0.049	135.31	0.493	0.225	16.116	249.761	2.275	1.763	42.73	20.036	0.927
Std. dev.	4HWR	3.285	0.005	0.136	0.014	4.735	0.019	0.002	1.014	0.01	0.022	71.124	0.254	0.126	3.205	166.992	1,165	1,385	54.57	16.306	1.268
(*N* = 6) Conc. range	5DWR	22.444-177.564	0.02-0.387	0.047-9.323	0.046-0.271	42.437-133.012	0.103-0.185	0.018-0.076	1.955-15.353	0.002-0.01	0.08-1.205	19.954-21.753	0.078-0.793	0.259-0.428	15.174-111.131	146.545-5,178.246	1.13-13.301	1.519-13.207	56.509-297.193	8.876-1,419.014	0.947-3.105
(*N* = 4) Mean conc.	5DWR	97.024	0.189	2.394	0.158	80.443	0.136	0.033	6.241	0.005	0.62	21.753	0.403	0.348	54.582	1,450.537	5.095	5.658	144.428	380.234	1.971
Std. dev.	5DWR	86.077	0.185	4.62	0.126	45.389	0.035	0.029	6.303	0.004	0.494	1.272	0.374	0.087	46.633	2,485.634	5.574	5.191	108.795	693.15	1.101
(*N* = 4) Conc. range	6DWR	77.979-87.938	0.012-0.058	0.056-385.265	0.028-0.09	48.27-329.666	0.07-2.508	0.008-0.067	1.406-7.604	0.002-0.019	0.032-8.59	20.472-76.442	0.171-0.308	0.197-0.463	7.434-1,370.736	93.615-381.78	2.265-434.979	3.782-96.881	3,366-9,856.15	18.837-4,9106.13	0.063-9.265
(*N* = 4) Mean conc.	6DWR	80.654	0.051	378.767	0.095	48.697	2.436	0.042	4.489	0.009	4.237	48.457	0.207	0.337	684.118	216.959	214.942	50.007	4,861.743	2,4196.981	3.665
Std. dev.	6DWR	4.096	0.022	218.702	0.032	132.483	1.353	0.024	3.087	0.007	4.849	39.577	0.067	0.117	766.991	146.276	245.551	52.785	5,565.293	2,7919.643	4.445
(*N* = 4) Conc. range	7HWR	11.92-81.675	0.009-0.023	0.081-1.181	0.022-0.073	25.06-331.923	0.063-0.105	0.004-0.069	0.549-4.688	0.001-0.022	0.036-0.07	34.258-66.068	0.234-0.838	0.228-0.856	11.258-28.381	85.226-205.505	2.031-4.812	1.081-5.881	14.881-148.059	17.404-156.518	0.123-10.702
(*N* = 4) Mean conc.	7HWR	34.168	0.016	0.37	0.044	133.247	0.081	0.022	1.924	0.009	0.05	50.163	0.476	0.413	18.684	152.923	2.875	3.335	60.053	57.912	2.872
Std. dev.	7HWR	32.644	0.006	0.541	0.024	143.67	0.021	0.031	1.871	0.009	0.016	15.905	0.291	0.298	7.414	53.861	1.313	2.366	59.77	66.332	5.223
(*N* = 4) Conc. range	8HWR	4.338-7.683	0.008-0.019	0.064-0.238	0.025-0.104	22.794-351.933	0.077-0.11	0.022-0.123	0.7-3.354	0.001-0.007	0.08-0.102	52.45-230.058	0.344-1.208	0.189-0.567	54.574-549.344	1.588-244.008	5.084-21.239	1.506-3.108	75.5-344.419	18.98-59.448	0.078-0.176
(*N* = 4) Mean conc.	8HWR	5.562	0.012	0.157	0.066	190.084	0.088	0.076	2.068	0.004	0.094	141.254	0.939	0.364	319.577	98.916	15.49	2.47	163.215	39.892	0.126
Std. dev.	8HWR	1.473	0.005	0,083	0.038	180.02	0.015	0.055	1.192	0.003	0.01	125.588	0.406	0.159	246.888	118.64	7.415	0.689	124.581	17.595	0.044
(*N* = 4) Conc. range	9DWR	4.157-6.937	0.01-0.012	0.111-0.185	0.302-0.727	78.296-314.66	0.134-0.29	0.049-0.117	0.565-3.294	0.004-0.019	0.032-0.08	28.378-33.274	0.117-0.157	0.209-0.398	42.427-168.517	36.912-421.984	6.809-14.314	7.697-10.324	14.207-477.663	48.789-178.091	0.09-8.843

(*N* = 4) Mean conc.	9DWR	5.545	0.011	0.153	0.504	195.819	0.219	0.082	1.976	0.011	0.054	30.825	0.138	0.276	105.571	209.725	10.435	8.89	212.558	113.735	3.379
Std. dev.	9DWR	1.502	0.001	0.031	0.23	134.138	0.066	0.036	1.274	0.006	0.025	3.463	0.02	0.088	69.393	192.263	5.657	3.595	232.157	72.183	4.191
(*N* = 6) Conc. range	10HWR	6.858-11.076	0.01-0.017	0.05-0.466	0.591-0.806	308.885-384.382	0.232-0.374	0.102-0.141	0.597-6.115	0.001-0.04	0.064-0.79	883.051-931.481	0.051-2.673	0.071-1.4	161.874-304.731	16.017-905.585	11.379-16.973	7.996-14.628	10.237-189.564	35.334-93.051	0.032-4.944
(*N* = 4) Mean conc.	10HWR	8.479	0.011	0.17	0.701	334.338	0.281	0.12	2.463	0.009	0.312	907.266	0.822	0.525	206.501	307.945	13.509	10.878	57.822	57.431	1.528
Std. dev.	10HWR	1.938	0.003	0.154	0.095	31.726	0.052	0.018	2.462	0.016	0.298	34.245	1.143	0.581	67.238	387.526	2.49	2.69	69.861	20.144	2.05
(*N* = 4) Conc. range	11DWR	19.655-133.111	0.016-0.809	0.153-0.402	0.032-0.104	96.077-194.591	0.048-142	0.011-0.022	0.49-3.4	0-0.003	0.024-0.486	5.732-25.874	0.045-0.548	0.076-0.483	14.347-29.086	5.26-1,004.373	0.684-15.806	1.383-4.661	18.452-114.297	9.9-81.226	0.994-5.316
(*N* = 4) Mean conc.	11DWR	73.365	0.318	0.257	0.067	137.824	56.605	0.016	2.518	0.002	0.264	15.803	0.255	0.275	16.794	498.165	6.028	3.093	66.883	56.964	2.547
Std. dev.	11DWR	62.001	0.375	0.105	0.04	49.569	69.409	0.005	1.366	0.002	0.252	14.243	0.251	0.183	8.656	550.476	7.086	1.394	54.37	31.971	2.021
(*N* = 6) Conc. range	12HWR	4.269-6.888	0.007-0.014	0.056-0.387	0.02-0.039	211.826-570.061	0.057-0.188	0.017-0.0271	1.304-3.296	0.001-0.015	0.067-0.164	256.395-329.715	0.156-1.835	0.113-0.657	399.442-1,134.871	91.126-518.721	15.977-34.658	1.737-3.619	61.182-189.818	33.838-74.475	0.15-0.206
(*N* = 6) Mean conc.	12HWR	5.689	0.011	0.21	0.031	347.241	0.11	0.121	2.018	0.006	0.107	293.055	0.97	0.389	677.53	308.728	24.828	2.724	113.896	51.938	0.176
Std. dev.	12HWR	1.059	0.003	0.135	0.007	156.691	0.058	0.11	0.941	0.006	0.033	51.845	0.694	0.235	331.767	165.788	7.172	0.809	52.674	14.967	0.023
N samples & conc. value type	Sample code	Sr (μg/L)	Mo (μg/L)	Cd (μg/L)	Cs (μg/L)	Ba (μg/L)	W (μg/L)	Tl (μg/L)	Pb (μg/L)	Bi (μg/L)	U (μg/L)	Al (μg/L)	V (μg/L)	Cr (μg/L)	Mn (μg/L)	Fe (μg/L)	Co (μg/L)	Ni (μg/L)	Cu (μg/L)	Zn (μg/L)	As (μg/L)
(*N* = 4) Conc. range	13HWA	2.956-3.208	0.014-0.018	0.104-0.11	0.018-0.022	8.296-8.654	0.067-0.088	0.009-0.01	1.091-1.097	0.002-0.002	0.039-0.046	68.836-80.283	0.267-0.29	0.196-0.303	18.817-19.347	114.133-129.207	2.18-2.531	1.101-1.164	8.686-10.686	16.66-17.342	0.113-0.121
(*N* = 4) Mean conc.	13HWA	3.082	0.016	0.107	0.02	8.475	0.078	0.01	1.094	0.002	0.043	74.56	0.279	0.25	19.082	121.67	2.356	1.133	9.686	17.001	0.117
Std. dev.	13HWA	0.178	0.003	0.004	0.003	0.253	0.015	0.001	0.004	0	0.005	8.094	0.016	0.076	0.375	10.659	0.248	0.045	1.414	0.482	0.006
(*N* = 4) Conc. range	14DWA	3.073-4.67	0.019-0.087	0.017-0.092	0.006-0.02	6.978-37.943	0.053-1.113	0.001-0.003	2.031-2.399	0.001-0.004	0.009-0.016	8.647-27.554	0.064-0.1	0.177-0.418	1.865-3.635	20.64-59.564	0.538-0.912	0.426-0.845	8.134-17.979	8.767-18.748	0.045-0.08
(*N* = 4) Mean conc.	14DWA	3.906	0.049	0.042	0.016	29.748	0.371	0.002	2.151	0.002	0.012	17.247	0.084	0.328	2.606	35.468	0.716	0.64	13.453	12.857	0.059
Std. dev.	14DWA	0.79	0.028	0.034	0.007	15.187	0.504	0.001	0.168	0.001	0.004	8.209	0.017	0.11	0.779	18.156	0.155	0.205	4.085	4.554	0.015
(*N* = 4) Conc. range	15SWA	67.808-108.299	0.05-0.169	0.018-0.099	0.026-0.046	204.848-229.894	0.067-3.139	0.004-0.006	0.374-1.393	0.001-0.004	0.126-0.245	22.04-49.468	0.413-0.718	0.143-1.124	3.657-7.411	24.29-112.411	0.575-0.811	0.902-1.365	3.522-7.827	4.587-23.071	0.066-0.174
(*N* = 4) Mean conc.	15SWA	93.51	0.101	0.051	0.04	216.11	1.286	0.005	0.843	0.003	0.201	33.037	0.64	0.553	5.709	66.801	0.675	1.157	5.573	13.357	0.105
Std. dev.	15SWA	17.708	0.054	0.038	0.009	11.69	1.499	0.001	0.539	0.001	0.053	13.115	0.152	0.447	1.817	42.183	0.1	0.234	2.35	8.107	0.048
(*N* = 2) Conc. range	16HWA	13.809-18.126	0.013-0.014	0.121-0.158	0.184-0.204	150.871-199.824	0.149-0.193	0.023-0.028	2.949-5.559	0-0.001	0.567-0.584	513.712-657.738	0.079-0.165	1.073-1.408	813.468-977.783	341.6-647.86	7.586-8.044	3.003-3.123	12.43-13.13	26.679-30.43	0.044-0.048
(*N* = 2) Mean conc.	16HWA	15.968	0.014	0.14	0.194	175.348	0.171	0.026	4.254	0.001	0.576	585.725	0.122	1.241	895.626	494.73	7.815	3.063	12.78	28.555	0.046
Std. dev.	16HWA	3.053	0.001	0.026	0.014	34.615	0.031	0.004	1.846	0.001	0.012	101.842	0.061	0.237	116.188	216.559	0.324	0.085	0.495	2.652	0.003

Conc.: PTEs concentration; DWA: drilled water wells in Annexe municipality; DWR: drilled water wells in Ruashi municipality; HWA: hand-sunk water wells in Annexe municipality; HWR: hand-sunk water wells in Ruashi municipality; *N*: number of analyzed samples; RWR: River water in Ruashi municipality; Std. dev.: standard deviation; SWA: Spring water in Annexe municipality.

Table 2 PTEs acceptable MCLs and health advisories set by the European Union, the United States Environmental Protection Agency, and the World Health Organization standards for drinking water.

Drinking water standards	Sr (μg/L)	Mo (μg/L)	Cd (μg/L)	Cs (μg/L)	Ba (μg/L)	W (μg/L)	Tl (μg/L)	Pb (μg/L)	Bi (μg/L)	U (μg/L)	Al (μg/L)	V (μg/L)	Cr (μg/L)	Mn (μg/L)	Fe (μg/L)	Co (μg/L)	Ni (μg/L)	Cu (μg/L)	Zn (μg/L)	As (μg/L)
2020 EU-MCLs	ND	ND	5	ND	ND	ND	ND	5	ND	30	200*	ND	50	50	50*	ND	20	2,000	ND	10
2018 USEPA-MCLs	4,000**	40**	5	ND	2,000	ND	2	15	ND	30	50-200**	ND	100	300**	300**	ND	100**	1,300	2,000**	10
2017 WHO-MCLs	ND	ND	3	ND	ND	ND	ND	10	ND	30	ND	ND	50	50	ND	ND	70	2,000	ND	10

*: Drinking Water Health Advisory Indicators set by the European Union; **: Drinking Water Health Advisory Indicators set by the United States Environmental Protection Agency; EU: European Union; MCLs: Drinking water acceptable maximum contaminant levels; ND: non-available data; USEPA: United States Environment Protection Agency; WHO: World Health Organization.

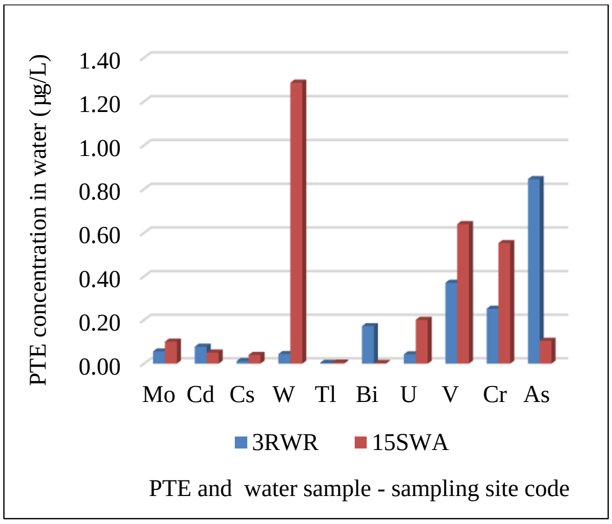

Fig. 2 Low mean concentrations of various PTEs in spring and river water samples (μg/L) in Ruashi and Annexe municipalities of Lubumbashi city.

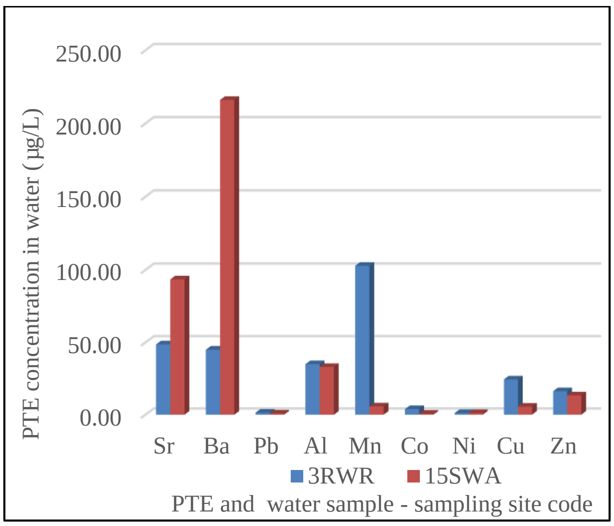

Fig. 3 High mean concentrations of various PTEs in spring and river water samples (μg/L) in Ruashi and Annexe municipalities of Lubumbashi city.

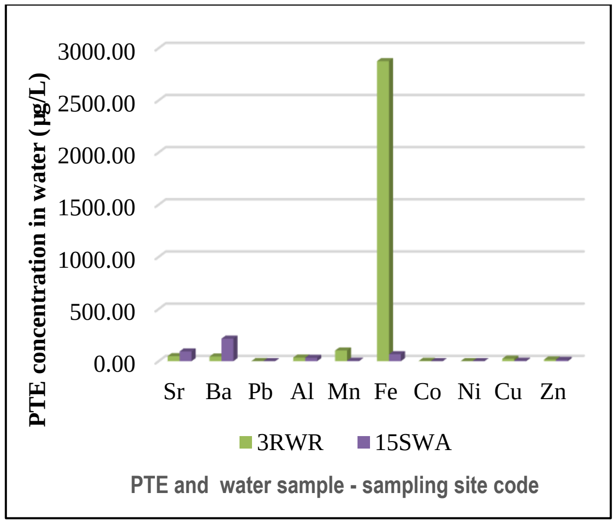

Fig. 4 Very high mean concentrations of various PTEs in spring and river water samples (μg/L) in Ruashi and Annexe municipalities of Lubumbashi city.

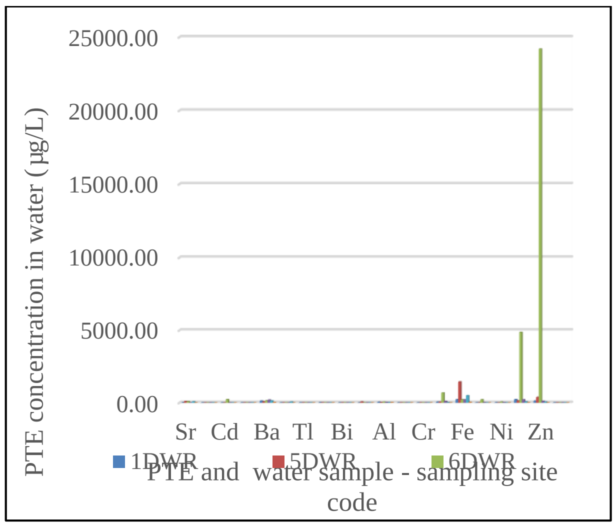

Fig. 5 Mean concentrations of all PTEs detected in water samples (μg/L) from drilled water wells in Ruashi and Annexe municipalities of Lubumbashi city.

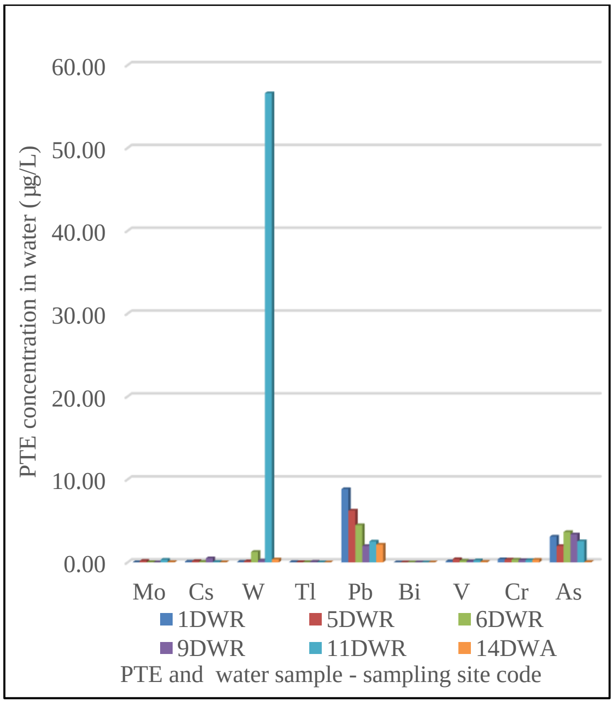

Fig. 6 Low mean concentrations of various PTEs in water samples (µg/L) from drilled water wells in Ruashi and Annexe municipalities of Lubumbashi city.

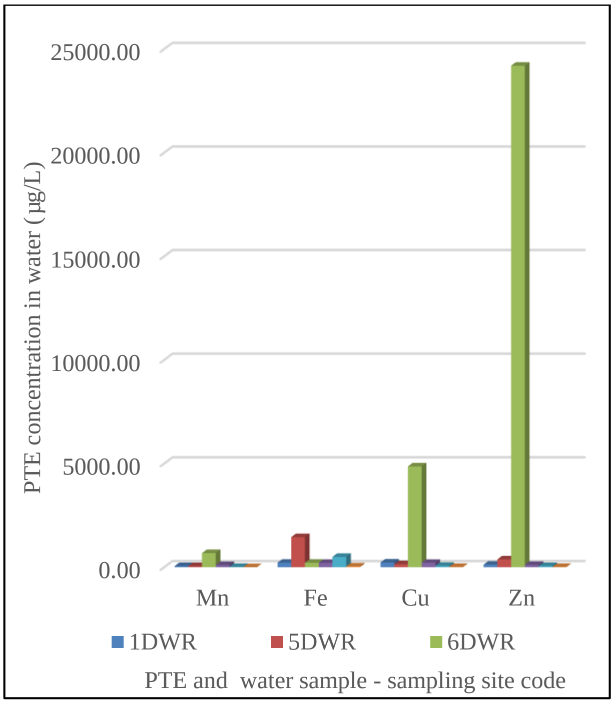

Fig. 8 Very high mean concentrations of various PTEs in water samples (µg/L) from drilled water wells in Ruashi and Annexe municipalities of Lubumbashi city.

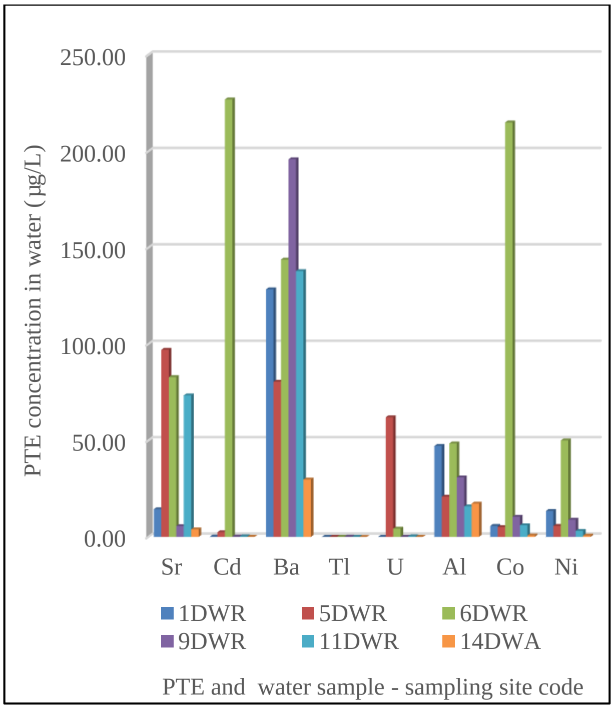

Fig. 7 High mean concentrations of various PTEs in water samples samples (µg/L) from drilled water wells in Ruashi and Annexe municipalities of Lubumbashi city.

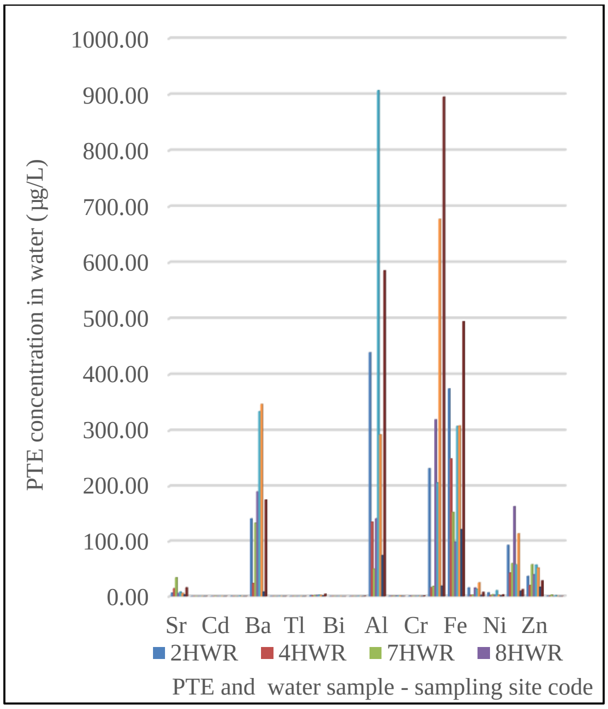

Fig. 9 Mean concentrations of all PTEs detected in water samples (µg/L) from spade-sunk water wells in Ruashi and Annexe municipalities of Lubumbashi city.

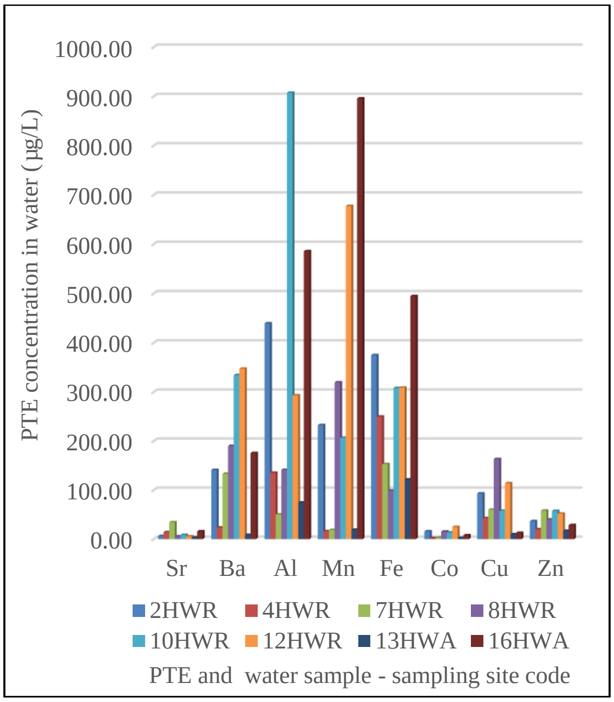

Fig. 10 High mean concentrations of various PTEs in water samples (µg/L) from spade-sunk water wells in Ruashi and Annexe municipalities of Lubumbashi city.

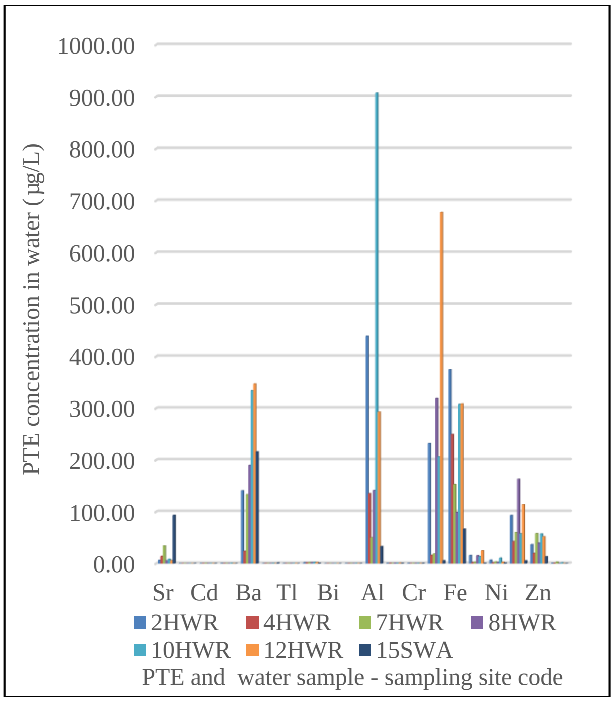

Fig. 12 Concentrations of all PTEs detected in water samples (µg/L) from spring and spade-sunk water wells in Ruashi and Annexe municipalities of Lubumbashi city.

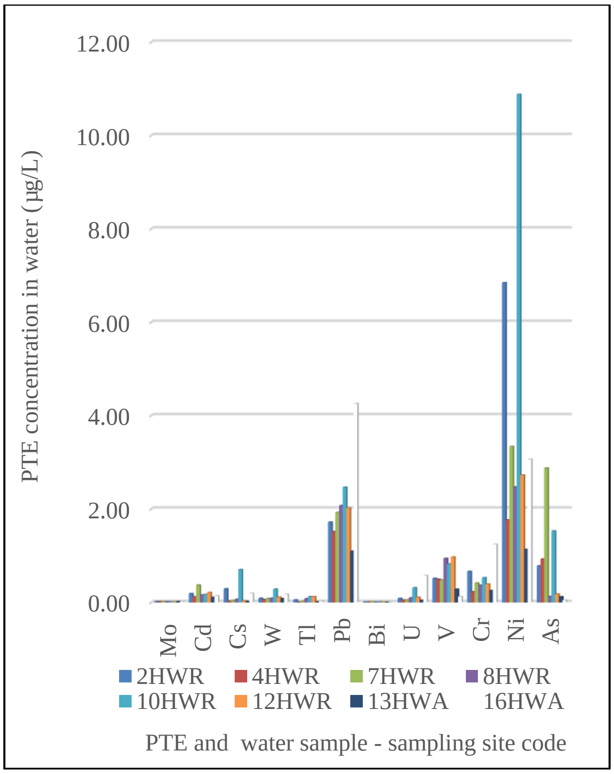

Fig. 11 Low mean concentrations of various PTEs in water samples (µg/L) from spade-sunk water wells in Ruashi and Annexe municipalities of Lubumbashi city.

mean concentration of 24,196.98 µg/L. The highest concentrations of arsenic and lead in the present study were much lower than those (65.458 µg/L and 38.162 µg/L) respectively reported for groundwater in Kamalondo, Kampemba and Lubumbashi communes but the highest mean concentration of cadmium found in this study was much higher than that (116.89 µg/L) noted in those communes [7].

The highest concentrations of arsenic, cadmium and lead found in the present study were much lower than those (21.262 µg/L, 379.579 µg/L, and 19.752 µg/L) respectively reported for groundwater in Katuba and Kenya municipalities [8].

Also, the highest concentrations and mean concentrations of copper, iron, manganese, nickel and zinc found in water in Ruashi and Annexe municipalities were lower than those (9,753.56 µg/L and 9,655.88 µg/L of copper, 6,392.32 µg/L and 3,297.18 µg/L of iron, 2,229.49 µg/L and 1,639.41 µg/L of manganese, 108.516 µg/L and 101.733 µg/L of nickel, and 49,053.03 µg/L and 48,976.54 µg/L of zinc) noted in groundwater in

Katuba and Kenya municipalities [8]. However, they were higher than the acceptable drinking water MCLs and health advisories set by the EU [26], the USEPA [27] and the WHO [28]. It has been reported that groundwater pollution is a result of natural and anthropogenic activities, and that while the elevated levels of various inorganic constituents could be attributed to natural processes, such as geological weathering and aquifer characteristics, many times, anthropogenic activities also substantially pollute the groundwater [44]. According to the same researchers, extensive groundwater mining, the hydraulic connection between groundwater and other surface water bodies, and leaching underground buried infrastructure also contribute to groundwater quality.

The PTE contamination of water in Ruashi and Annexe municipalities might eventually be due to interaction between rock and groundwater, to atmospheric deposition, and mainly to anthropogenic activities, such as mining and ore processing activities in both municipalities.

4. Conclusion

PTEs contamination of water in Ruashi and Annexe municipalities of Lubumbashi city was assessed in order to find out the chemical quality of that water and to know whether the water presents any threat to the health of inhabitants of both municipalities. Twenty PTEs including aluminum, arsenic, barium, bismuth, cadmium, cesium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, strontium, thallium, tungsten, uranium, vanadium and zinc were detected at various concentrations in each one of the seventy water samples collected from six drilled wells, eight spade-sunk wells, one river and one spring in both municipalities and analyzed by Inductively Coupled Plasma-Sector Field Mass Spectrometry. Many samples had concentrations and mean concentrations of PTE, such as aluminum, cadmium, copper, iron, lead, manganese, nickel and zinc, higher than the respective acceptable limits and health advisory indicators set for drinking water by international standards. Most PTEs being deleterious to human health even at very low concentrations, people who use the groundwater and surface water in both Ruashi and Annexe municipalities to meet their water needs are at risk.

Authors suggest that the provincial and national Governments strictly implement the Congolese Mining Rule to push the mining and ore processing companies which operate in Lubumbashi city to treat their chimneys and waste water in order to reduce PTE contents of their smoke and waste water before releasing them in the nature. The national Government should also substantially finance REGIDESO, the Congolese water supply company to allow it to provide suitable drinking water to all inhabitants of Lubumbashi city.

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References

[1] UNEP (United Nations Environmental Program). 2011. *Water Issues in the Democratic Republic of the Congo—Challenges and Opportunities* (Technical Report). Nairobi: United Nations Environmental Program. https://wedocs.unep.org/handle/20.500.11822/22067.

[2] Muhaya, B. B., Kayembe, M. W. K., Kunyonga, C. Z., Mulongo, S. C., and Cuma, F. M. 2017. "Assessment of Trace Metal Contamination of Sediments in the Lubumbashi River Basin, Kafubu, Kimilolo and Kinkalabwamba Rivers in Lubumbashi City, Democratic Republic of Congo." *Journal of Environmental Science and Engineering A* 6 (4): 167-77. https://doi.org/10.17265/2162-5298/2017.04.001.

[3] Muhaya, B. B., Kayembe, M. W. K., Mulongo, S. C., Kunyonga, C. Z., and Mushobekwa, F. Z. 2017. "Trace Metal Contamination of Water in the Lubumbashi River

Basin, Kafubu, Kimilolo and Kinkalabwamba Rivers in Lubumbashi City, Democratic Republic of Congo." *Journal of Environmental Science and Engineering B* 6 (6): 301-11. https://doi.org/10.17265/2162-5263/2017.06.002.

[4] Muhaya, B. B., Mulongo, S. C., Kunyonga, C. Z., Mushobekwa, F. Z., and Kayembe, M. W. K. 2017. "Trace Metal Contamination of Water in Naviundu River Basin, Luano and Ruashi Rivers and Luwowoshi Spring in Lubumbashi City, Democratic Republic of Congo." *Journal of Environmental Science and Engineering A* 6 (7): 329-36. https://doi.org/10.17265/2162-5298/2017.07.001.

[5] Muhaya, B. B., Kunyonga, C. Z., Mulongo, S. C., Mushobekwa, F. Z., and Bisimwa, A. M. 2017. "Trace Metal Contamination of Sediments in Naviundu River Basin, Luano and Ruashi Rivers and Luwowoshi Spring in Lubumbashi City, Democratic Republic of Congo." *Journal of Environmental Science and Engineering B* 6 (9): 456-64. https://doi.org/10.17265/2162-5263/2017.09.003.

[6] Muhaya, B. B., Numbi, R. M., Lubala, F. T., Mugisho, J. B., and Tshibanda, D. K. 2015. "Heavy Metal Contamination of Well Water in the Kipushi Mining Town (Democratic Republic of Congo)." *Journal of Environmental Science and Engineering B* 4 (8): 403-18. https://doi.org/10.17265/2162-5263/2015.08.001.

[7] Muhaya, B. B., Mulongo, S. C., Kunyonga, C. Z., Mpomangan, W. A., and Kalonda, M. E. 2021. "Assessment of Trace Metal Levels of Groundwater in Lubumbashi, Kampemba and Kamalondo Communes of Lubumbashi City, Democratic Republic of Congo." *Journal of Environmental Science and Engineering A* 10 (1): 9-25. https://doi.org/10.17265/2162-5298/2021.01.002.

[8] Muhaya, B. B., and Badarhi, B. B. 2022. "Trace Metal Contamination of Groundwater and Human Health Risk in Katuba and Kenya Municipalities of Lubumbashi City, Southeastern Democratic Republic of Congo." *African Journal of Environmental Science and Technology* 16 (3): 91-110. https://doi.org/10.5897/AJEST2021.3087.

[9] Muhaya, B. B., and Badarhi, B. B. 2023. "Trace Metal Levels of Groundwater, Surface Water and Sediments in Kinsevere Industrial Zone and Its Surroundings, Southeastern Republic of Congo." *Journal of Environmental Science and Engineering A* 12 (5): 163-75. https://doi.org/10.17265/2162-5298/2023.05.001.

[10] Mudekereza, M. A., Gray, K., Tamubango, K. H., and Numbi, L. 2016. "Eléments Traces dans le serum des enfants malnutris et bien nourris vivants à Lubumbashi et Kawama dans un contexte d'un environnement de pollution minière." *Pan African Medical Journal* 24 (1): 11. https://doi.org/10.11604/pamj.2016.24.11.9236. (in French)

[11] Mudekereza, M. A., Chenge, B. G., Tamubango, K. H., Bakari, A. S., Kakoma, S. J. B., Wembonya, O. S., and Luboya, N. O. 2021. "Les métaux lourds plus polluant dans la malnutrition chez l'enfant de moins de 5 ans à Lubumbashi." *Revue Africaine de Médecine et de Santé Publique* 4 (1): 21-5. file:///C:/Users/admin/AppData/Local/Temp/les-metaux-lourds-plus-polluant-dans-la-malnutrition-des-enfants-de-moins-de-5-ans-a-lubumbashi.pdf. (in French)

[12] Mukendi, M. R. A., Banza, L. N. C., Mukeng, C. A. K., Ngwe, T. M. J., Mwembo, N.-A.-N. A., and Kalenga, M. K. P. 2018. "Exposition de l'homme aux éléments traces métalliques et altération du sperme: étude menée dans les zones minières au Haut-Katanga en République Démocratique du Congo." *The Pan African Medical Journal* 30: 35. https://doi.org/10.11604/pamj.2018.30.35.13694. (in French)

[13] Obadia, M. P., Kayembe-Kitenge, T., Haufroid, V., Banza, L. N. C., and Nemery, B. 2018. "Preeclampsia and Blood Lead (and Other Metals) in Lubumbashi, DR Congo." *Environmental Research* 167: 468-71. https://doi.org/10.1016/j.envres.2018.07.032.

[14] Cham, L. C., Chuy, K. D., Tamubango, H., Chenge, M. F., Kaniki, A., Mwembo, T. A., and Kalenga, M. K. 2020. "Eléments traces métalliques chez les accouchées et les nouveau-nés résidant aux environs des sites d'exploitation minière dans la ville de Lubumbashi, République Démocratique du Congo." *IOSR Journal of Dental and Medical Sciences* 10 (8 series 10): 50-60. https://doi.org/10.9790/0853-1908105060. (in French)

[15] Malamba-Lez, D., Tshala-Katumbay, D., Bito, V., Rigo, J. M., Kipenge, K. R., Ngoy, Y. E., Katchunga, P., Koba-Bora, B., and Ngoy-Nkulu, D. 2021. "Concurrent Heavy Metal Exposures and Idiopathic Dilated Cardiomyopathy: A Case-Control Study from the Katanga Mining Area of the Democratic Republic of Congo." *International Journal of Environmental Research and Public Health* 18: 4956. https://doi.org/10.3390/ijerph18094956.

[16] Ngoy, M. J., Mukalay, W. M. A., Laurence, R., Banza, L. N. C., Koba, B. B., Bilonda, M. E., Musa, O. P., and Okitundu, L. E.-A. D. 2021. "Caractéristiques électro-neurologiques des adultes diabétiques et non diabétiques à Lubumbashi, milieu exposé aux éléments traces métalliques, République Démocratique du Congo." *Revue d'Epidémiologie et de Santé Publique* 69 (1): 68-9. https://doi.org/10.1016/j.respe.2021.04.117. (in French)

[17] Osorio-Rico, L., Santamaria, A., and Galvan-Arzate, S. 2017. "Thallium Toxicity: General Issues, Neurotoxicological Symptoms, and Neurotoxic Mechanisms." *Advances in Neurobiology* 18: 345-53. https://doi.org/10.1007/978-3-319-60189-2_17.

[18] Smith, A. H., Marshall, G., Roh, T., Ferreccio, C., Liaw, J., and Steinmaus, C. 2018. "Lung, Bladder, and Kidney Cancer Mortality 40 Years after Arsenic Exposure Reduction." *Journal of the National Cancer Institute* 110 (3): 241-9. https://doi.org/10.1093/jnci/djx201.

[19] Browar, A. W., Koufos, E. B., Wei, Y., Leavitt, L. L.,

Prozialeck, W., and Edwards, J. R. 2018. "Cadmium Exposure Disrupts Periodontal Bone in Experimental Animals: Implications for Periodontal Disease in Humans." *Toxics* 6 (2): 32-41. https://doi.org/10.3390/toxics6020032.

[20] Khandare, A. L., Validandi, V., Rajendran, A., Singh, T. G., Thingnganing, L., Kurella, S., Nagaraju, R., Dheeravath, S., Vaddi, N., Kommu, S., and Maddela, Y. 2020. "Health Risk Assessment of Heavy Metals and Strontium in Groundwater Used for Drinking and Cooking in 58 Villages of Prakasam District, Andhra Prakadesh, India." *Environmental Geochemistry and Health* 42: 3675-701. https://doi.org/10.1007/s10653-020-00596-1.

[21] Mirzaee, M., Semnani, S., Roshandel, G., Nejabat, M., Hesari, Z., and Joshaghani, H. 2020. "Strontium and Antimony Serum Levels in Healthy Individuals Living in High- and Low-Risk Areas of Esophageal Cancer." *Journal of Clinical Laboratory Analysis* 34 (7): e23269. https://doi.org/10.1002/jcla.23269.

[22] Li, X., Fan, Y., Zhang, Y., Huang, X., Huang, Z., Yu, M., Xu, Q., Han, X., Lu, C., and Wang, X. 2021. "Association between Selected Urinary Heavy Metals and Asthma in Adults: A Retrospective Cross-Sectional Study of the US National Health and Nutrition Examination Survey." *Environmental Science and Pollution Research* 28: 5833-41. https://doi.org/10.1007/s11356-020-10906-w.

[23] Nuvolone, D., Petri, D., Aprea, M. C., Bertelloni, S., Voller, F., and Aragoni, I. 2021. "Thallium Contamination of Drinking Water: Health Implications in a Residential Cohort Study in Tuscany (Italy)." *International Journal of Environmental Research and Public Health* 18 (8): 4058. https://doi.org/10.3390/ijerph18084058.

[24] Hopkins, C. D., Wessel, C., Chen, O., El-Kersh, K., Cave, M. C., Cai, L., and Huang, J. 2023. "Potential Roles of Metals in the Pathogenesis of Pulmonary and Systemic Hypertension." *International Journal of Biological Sciences* 19 (16): 5036-54. https://doi.org/10.7150/ijbs.85590.

[25] Lubumbashi City Population Office. 2024. *The Demography of Lubumbashi City in 2024*.

[26] EU (European Union). 2020. *Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water intended for Human Consumption (Recast) (Text with EEA Relevance)*. Official Journal of the European Union. https://eur-lex.europa.eu/eli/dir/2020/2184/oj.

[27] USEPA (United States Environmental Protection Agency). 2018. *2018 Edition of the Drinking Water Standards and Health Advisories Tables* (EPA 822-F-18-001). U.S. Washington, DC: Office of Water, Environmental Protection Agency. https://www.epa.gov/sites/production/files/2018-03/documents/dwtable2018.pdf.

[28] WHO (World Health Organization). 2017. *Guidelines for Drinking-Water Quality* (4th ed.). Geneva: World Health Organization. https://www.who.int/publications/i/item/9789241549950.

[29] Leyssens, L., Vinck, B., Van Der Straeten, C., Wuyts, F., and Maes, L. 2017. "Cobalt Toxicity in Humans—A Review of the Potential Sources and Systemic Health Effects." *Toxicology* 387: 43-56. https://doi.org/10.1016/j.tox.2017.05.015.

[30] Guo, C., Qian, Y., Yan, L., Li, Z., Liu, H., Li, X., Wang, Z., Zhu, X., Wang, Z., Wang, J., and Wie, Y. 2021. "The Changes of Essential Trace Elements in Residents from E-Waste Site and the Relationships between Elements and Hormones of the Hypothalamic-Pituitary-Thyroid (HPT) Axis." *Ecotoxicology and Environmental Safety* 2021: 112513. https://doi.org/10.1016/j.ecoenv.2021.112513.

[31] Bradley, B., Singleton, M., and Lin Wan Po, A. 1989. "Bismuth Toxicity—A Reassessment." *Journal of Clinical and Pharmaceutical Therapy* 14 (6): 423-41. https://doi.org/10.1111/j.1365-2710.1989.tb00268.x.

[32] Borbinha, C., Serrazina, F., Salavisa, M., and Viana-Baptista, M. 2019. "Bismuth Encephalopathy—A Rare Complication of Long-Standing of Bismuth Subsalicylate." BMC *Neurology* 19 (1): 212. https://doi.org/10.1086/s12883-019-1437-9.

[33] Wang, R., Li, H., and Sun, H. 2019. "Bismuth: Environmental Pollution and Health Effects." *Encyclopedia of Environmental Health* 2018: 415-23. https://doi.org/10.1016/B978-0-409548-9-11870-6.

[34] Polepenko, L. E., Janini, A. C. P., Gomes, B. P. F. A., de-Jesus-Soarez, A., and Marciano, M. A. 2022. "Effects of Bismuth Exposure on Human Kidney—A Systemic Review." *Antibiotics* 11 (12): 1741. https://doi.org/10.3390/antibiotics11121741.

[35] Bolt, A. M., and Mann, K. K. 2016. "Tungsten: An Emerging Toxicant, Alone or in Combination." *Current Environmental Health Reports* 3: 405-15. https://link.springer.com/article/10.1007/s40572-016-0106-z.

[36] Wasel, O., and Freeman, J. L. 2018. "Comparative Assessment of Tungsten Toxicity in the Absence or Presence of Other Metals." *Toxics* 6 (4): 66. https://doi.org/10.3390/toxics60640066.

[37] Ngwa, H. A., Ay, M., Jin, H., Anantharan, V., and Kanthasamy, A. G. 2017. "Neurotoxicity of Vanadium." *Advances in Neurobiology* 18: 287-301. https://doi.org/10.1007/978-3-319-60189-2-14.

[38] ATSDR (Agency for Toxic Substances and Disease Registry). 2004. *Cesium: Cas #7440-46-2*. United States Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry, Division of Toxicology. https://www.atsdr.cdc.gov/toxfaqs/tfacts157.pdf.

[39] Bangh, S., Houlihan, R., Anderson, D., et al. 2001. "Prolonged QT and Polymorphic VT with Chronic Cesium Use." *Journal of Toxicology, Clinical Toxicology* 39 (5): 556. https://www.ncbi.nlm.nih.gov/books/NBK594659.

[40] Harik, N. S., Stowe, C. D., and Seib, P. M. 2002. "Cesium Induced Prolonged QT Syndrome." *Journal of Investigative Medicine* 50 (1): 141A. https://eurekamag.com/research/034/548/034548709.php.

[41] Saliba, W., Erdogan, O., and Niebauer, M. 2003. "Case Reports: Polymorphic Ventricular Tachycardia in a Woman Taking Cesium Chloride." *Pacing and Clinical Electrophysiology* 24 (4): 515-7. https://doi.org/10.1046/j.1460-9592.2001.00515.x.

[42] NCBI (National Center for Biotechnology Information), 2004. *Toxicological Profile for Cesium*. https://www.ncbi.nlm.nih.gov/books/NBK594667/#ch3.s2.

[43] O'Brien, C. E., Harik, N., James, L. P., Seib, P. M., and Stowe, C. D. 2012. "Cesium-Induced QT-Interval Prolongation in an Adolescent." *Pharmacotherapy* 28 (8): 1059-65. https://doi.org/10.1592/phco.28.8.1059.

[44] Kurwadkar, S., Kanel, S. R., and Nakarmi, A. 2020. "Groundwater Pollution: Occurrence, Detection, and Remediation of Organic and Inorganic Pollutants." *Water Environment Research* 92: 1659-68. https://doi.org/10.1002/wer.1415.