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Assessment of Trace Metal Levels of Groundwater in Lubumbashi, Kampemba and Kamalondo Communes of Lubumbashi City, Democratic Republic of Congo

Bamba Bukengu Muhaya[1], Sonia Catherine Mulongo[2], Clarisse Zoza Kunyonga[3], Alexis Woot Mpomanga[4] and Emery Mutombo Kalonda[1]

1. Department of Chemistry, Faculty of Science, University of Lubumbashi, P.O. Box 1825, Lubumbashi, Democratic Republic of Congo

2. Department of Geology, Faculty of Science, University of Lubumbashi, P.O. Box 1825, Lubumbashi, Democratic Republic of Congo

3. Department of Process Chemistry, Higher School of Industrial Engineers, University of Lubumbashi, P.O. Box 1825, Lubumbashi, Democratic Republic of Congo

4. Department of Geography and Environmental Science, Faculty of Science, University of Lubumbashi, P.O. Box 1825, Lubumbashi, Democratic Republic of Congo

Abstract: Trace metal levels of groundwater in Lubumbashi, Kampemba and Kamalondo communes of Lubumbashi city were assessed from October 2016 to February 2017. Two hundred forty water samples collected from twenty-two spade-sunk wells and twelve drilled wells in these three communes of Lubumbashi city were analyzed for their metal contents using ICP-SF-MS (Inductively Coupled Plasma-Sector Field Mass Spectrometry). Twenty trace elements including strontium, molybdenum, cadmium, cesium, barium, tungsten, thallium, lead, bismuth, uranium, aluminum, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc and arsenic were recorded at varying concentrations in all the water samples and were compared with the WHO (World Health Organization), US EPA (Environmental Protection Agency) and EU (European Union) drinking water MCLs (Maximum Concentration Limits) for cadmium, barium, thallium, lead, uranium, aluminum, chromium, manganese, iron, nickel, copper, zinc and arsenic. Mean cadmium, lead, aluminum, manganese, iron, nickel, zinc and arsenic levels respectively exceeded the WHO, US EPA and EU drinking water MCLs in 6.66%, 3.38%, 26.67%, 5.02%, 30.03%, 3.38%, 1.64% and 5.02% of the samples with the highest mean levels of 116.89 μg/L for cadmium, 38.162 μg/L for lead, 2,712.5 μg/L for aluminum, 1,242.68 μg/L for manganese, 17,325.98 μg/L for iron, 64.647 μg/L for nickel, 9,900.72 μg/L for zinc and 65.458 μg/L for arsenic. Mean water pH values ranged from 4.7 to 11.1 with 19.17% of the groundwater samples having mean pH values outside the WHO drinking water pH optimum range values of 6.5-8.5, including 5.02% of the water samples which were acidic (mean pH values ranging from 4.7 to 6.4) and 14.15% which were alkaline (mean pH values ranging from 8.6 to 11.1). With such physicochemical and trace metal contamination status of groundwater in the three communes of Lubumbashi city, there is a high risk to the health of people who use that water to meet their drinking water needs.

Key words: Drinking water, groundwater, EPA standards, EU regulations, pH, trace metals, Lubumbashi city, WHO guidelines.

1. Introduction

In many developing countries, such as the DRC (Democratic Republic of Congo), millions of people do not have access to safe drinking water, especially those who live in rural areas and most of the poor people living in urban areas. They largely depend on surface water and groundwater to meet their domestic water needs [1-3]. In the DRC Copperbelt, which includes the Upper-Katanga and Lualaba provinces, and in other eastern provinces such as Ituri, Maniema, North-Kivu, South-Kivu and Tanganyika, atmosphere, soils, surface water and sediments, and groundwater are severely contaminated with trace metals as a result of abandoned and ongoing artisanal and industrial

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

mining and ore processing activities [3-13].

In Lubumbashi, the capital city of the Upper-Katanga province, active and abandoned mines, ore processing plants, tailings, dumps and industrial wastelands are likely to generate trace metal contamination of surface water [9, 11, 12, 14], sediments [10, 13] and groundwater [3]. The use of surface and groundwater contaminated with trace metals may present environmental and public health risk in the city, depending on the contamination status. Currently, drinking water supply by the Congolese Water Supply Company (REGIDESO) does no longer cover all parcels in the city, mainly because of rapid growth of the urban population, neglected infrastructures, low investment return and low financial viability of the public services in charge of water, degradation of watersheds increasing the costs of water treatments [15] and unplanned urbanization. Thus, spade-sunk and drilled wells as well as rivers constitute the main sources of drinking water for a large part of the city population.

The objective of this study was to assess trace metal contamination of groundwater in the Lubumbashi, Kampemba and Kamalondo communes of Lubumbashi city, and to compare the results with WHO (World Health Organization), US EPA (Environmental Protection Agency) and EU (European Union) drinking water MCLs (Maximum Concentration Limits) to highlight health impacts of the consumption of that water in the city.

2. Material and Methods

2.1 Description of the Study Area

Lubumbashi, the capital city of the Upper-Katanga province is located at the altitude of 1,230 m between the latitude of 11°40′11″ and the longitude of 27°29′00″ East in South-Eastern DRC, at less than 50 km from the DRC-Zambia border. Lubumbashi city has seven administrative communes including Lubumbashi, Kampemba and Kamalondo communes (Fig. 1), as well as Katuba, Kenya, Ruashi and Annex communes. According to Wikipedia [16], the population of Lubumbashi city was estimated to 2,786,397 inhabitants, including 397,761 inhabitants in Lubumbashi commune, 524,218 inhabitants in Kampemba commune and 51,582 inhabitants in Kamalondo commune in 2015. With an area of 747 km^2, the city had a density of 3,730 inhabitants/km^2 in 2015.

2.2 Sampling Campaign

Water samples were monthly collected from twenty-one spade-sunk and twelve drilled wells in Lubumbashi commune from October 2016 to February 2017 and Kampemba and Kamalondo communes in November 2016, January and February 2017. At each sampling campaign, two water samples were collected from each well. The depth of hand-dug wells ranged from 2 to 18 m and that of drilled wells ranged from 30 to 90 m.

2.3 Analytical Methods

2.3.1 Sample Pretreatment

Collected water samples were filtered on 0.45 µm disposable syringe filters (Chromafil, cellulose mixed ester) and acidified with concentrated hydrochloric acid after determining the pH of the water samples.

2.3.2 Trace Metal Analysis

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 (Elemental Scientific Incorporation) Fast autosampler, PFA-ST (Perfluoroalkoxy Series Type) MicroFlow nebulizer, Peltier cooled glass cyclonic spray chamber, quartz injector and torch and Ni cones. Regarding the resolutions used, low resolution was used for strontium, molybdenum, cadmium, cesium, lead, bismuth and uranium; medium resolution was used for aluminium, vanadium, chromium, nickel, copper, zinc, manganese, iron, cobalt; high resolution was used for arsenic. Rhodium (1 ppb) was used as internal standard in all resolutions.

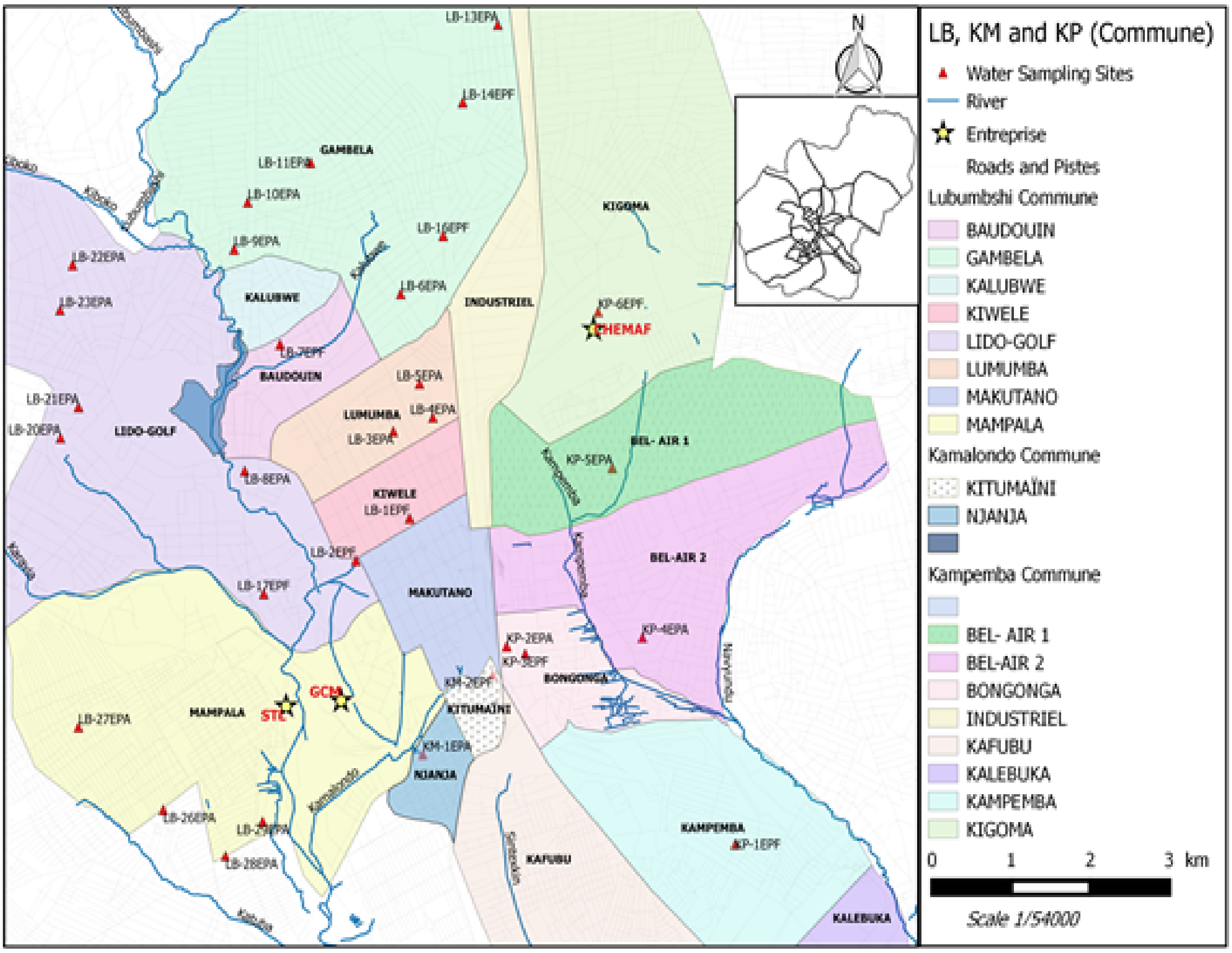

Fig. 1 Map of groundwater sampling locations in Lubumbashi, Kampemba and Kamalondo communes of Lubumbashi city from October 2016 to February 2017.

Standard solutions were prepared from multi-element 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.

3. Results and Discussion

Mean pH values and trace metal levels of groundwater recorded in Lubumbashi, Kampemba and Kamalondo communes of Lubumbashi city are presented in Table 1 and illustrated in Figs. 2-7. The WHO Guidelines for Drinking-Water Quality [17], United States EPA Standards and Health Advisories [18], and EU (Drinking Water) Regulations and Indicator Parameters [19] are given in Table 2. Mean water pH values ranged from 4.7 to 11.1 with 19.17% of the groundwater samples having mean pH values outside the WHO drinking water pH optimum range values of 6.5-8.5, including 5.02% of the water samples which were acidic (mean pH values ranging from 4.7 to 6.4) and 14.15% which were alkaline (mean pH values ranging from 8.6 to 11.1). This implies that the acidic or alkaline water from some of the sampled wells did not conform to the physicochemical quality of water for human consumption. Very low pH of water makes available for bioaccumulation of the metals dissolved in the water. The alkaline conditions (very high pH) of groundwater in Lubumbashi city are probably due to the roach hosting the groundwater as that roach is made

Table 1 Minimum, maximum, mean and SD (Standard Deviation) values of pH and trace metal levels of groundwater (μg/L) in Lubumbashi, Kampemba and Kamalondo communes of Lubumbashi city from October 2016 to February 2017.

Sampling site	Data type	pH value	Sr88 (μg/L)	Mo98 (μg/L)	Cd114 (μg/L)	Cs133 (μg/L)	Ba138 (μg/L)	W183 (μg/L)	Tl205 (μg/L)	Pb208 (μg/L)	Bi209 (μg/L)	U238 (μg/L)	Al27 (μg/L)	V51 (μg/L)	Cr52 (μg/L)	Mn55 (μg/L)	Fe56 (μg/L)	Co59 (μg/L)	Ni60 (μg/L)	Cu63 (μg/L)	Zn66 (μg/L)	As75 (μg/L)
LB-3EPA	Range	4.7-7.7	6.564-33.245	0.012-0.063	0.192-1.744	0.014-0.14	29.258-740.24	0.068-2.992	0.004-0.409	1.285-8.226	0.002-0.024	0.022-2.492	732.27-2,712.5	0.134-1.61	0.345-1.558	17.734-314.55	42.824-361.21	2.626-16.28	1.594-4.549	15.758-28.248	34.931-69.203	0.,063-6.472
	Mean±SD	6.3±1.3	18.085±9.689	0.026±0.021	0.742±0.617	0.079±0.054	485.63±327.14	1.546±1.245	0.256±0.185	5.091±2.905	0.01±0.009	1.554±1.058	1,722.38±1,400.24	0.628±0.57	0.683±0.521	204.31±135.31	140.84±128.48	10.877±6.42	3.023±1.075	19.941±5.017	53.836±12.468	1.697±2.74
LB-4EPA	Range	7.5-8.1	29.282-80.635	0.029-0.073	0.153-1.197	0.034-0.211	31.095-58.261	0.081-0.377	0.007-0.015	1.306-5.737	0.002-0.02	0.072--0.214	434.74-434.74	0.275-4.026	0.223-2.247	31.07-422.69	1,037.78-7,110.14	9.063-17.175	1.276-8.886	34.485-65.739	57.665-287.83	0.287-2.543
	Mean±SD	7.8±0.3	65.761±24.573	0.058±0.02	0.474±0.493	0.111±0.075	42.053±11.575	0.191±0.129	0.011±0.004	4.03±1.956	0.01±0.008	0.116±0.066	434.74±0	1.382±1.771	1.207±0.918	264.87±171.92	4,129.25±3,205.19	13.046±4.019	3.336±3.703	43.476±14.884	145.46±106.43	1.331±1.023
LB-5EPA	Range	5.3-8.3	5.171-50.134	0.01-0.141	0.045-0.781	0.039-0.118	55.607-167.88	0.139-0.539	0.015-0.05	0.803-2.186	0.001-0.015	0.087-0.492	198.3-304.99	0.066-1.248	0.143-1.332	53.495-169.64	55.197-674.78	1.122-5.532	1.188-2.397	7.332-19.332	9.732-30.205	0.049-5.627
	Mean±SD	7.3±1.2	16.683±18.872	0.038±0.058	0.244±0.305	0.071±0.035	96.328±49.764	0.269±0.165	0.032±0.016	1.284±0.546	0.007±0.006	0.281±0.166	251.65±75.437	0.451±0.539	0.446±0.506	108.28±55.195	254.99±253.46	3.804±1.973	1.779±0.531	11.586±4.884	20.435±9.001	1.915±2.297
LB-6EPA	Range	6.6-8.4	40.971-68.543	0.016-0.041	0.116-1.606	0.008-0.125	27.981-127.12	0.055-0.756	0.007-0.075	0.559-38.162	0.002-0.017	0.06-1.162	40.277-96.723	0.325-27.363	0.236-10.014	38.17-472.05	162.48-8,585.14	0.717-26.2	0.939-7.788	4.298-217.25	12.793-248.09	0.11-29.854
	Mean±SD	7.4±0.7	54.621±10.967	0.027±0.012	0.708±0.775	0.04±0.048	77.765±35.84	0.227±0.297	0.034±0.025	8.399±16.641	0.008±0.006	0.299±0.483	68.5±39.913	5.991±11.954	2.327±4.302	167.69±173.7	2,016.66±3,685.75	6.794±10.982	2.657±2.908	51.888±92.866	67.085±101.66	6.688±12.986
LB-8EPA	Range	6.9-8.4	5.97-88.187	0.012-0.07	0.131-1.029	0.028-0.594	59.597-144.04	0.075-0.81	0.017-0.081	1.081-10.081	0.002-0.013	0.093-1.298	386.17-386.17	0.208-13.789	0.183-4.43	87.631-1,242.68	231.83-17,325.98	2.96-12.075	1.133-5.605	9.509-39.499	8.542-655.88	0.113-5.772
	Mean±SD	7.7±0.6	36.839±33.064	0.027±0.025	0.433±0.356	0.197±0.231	91.157±34.453	0.272±0.311	0.035±0.027	3.794±3.703	0.008±0.004	0.491±0.478	386.17±0	3.794±5.773	1.446±1.737	471.57±451.93	4,537.83±7,383.39	7.553±3.226	3.256±1.586	20.692±11.288	183.78±272.81	1.753±2.328
LB-10EPA	Range	7.3-7.3	4.855-7.531	0.01-0.022	0.086-0.14	0.067-0.188	40.9-56.65	0.062-0.227	0.013-0.033	0.611-5.02	0.001-0.033	0.137-0.527	1,645.59-1,645.59	0.284-0.994	0.44-1.189	111.52-144.23	121.43-1,101.5	4.457-4.589	2.969-3.984	24.037-26.723	26.86-59.296	0.147-5.379
	Mean±SD	7.3±0	6.193±1.892	0.016±0.008	0.113±0.038	0.128±0.086	48.775±11.137	0.145±0.117	0.023±0.014	2.816±3.118	0.017±0.023	0.332±0.276	1,645.59±0	0.639±0.502	0.815±0.53	127.87±23.126	611.47±693.01	4.523±0.093	3.477±0.718	25.38±1.899	43.078±22.936	2.763±3.7
LB-11EPA	Range	6.6-9	2.297-4.488	0.009-0.042	0.053-0.129	0.025-0.095	14.596-39.748	0.033-0.119	0.006-0.02	0.747-4.923	0.001-0.012	0.038-0.275	347.86-818.6	0.278-1.001	0.266-1.013	5.933-200.87	104.23-954.64	1.829-4.793	1.005-3.671	7.161-19.302	8.964-37.699	0.118-65.458
	Mean±SD	7.7±1.0	3.321±1.108	0.018±0.016	0.089±0.033	0.053±0.031	26.653±10.295	0.08±0.036	0.011±0.006	2.542±1.856	0.007±0.006	0.138±0.102	583.23±332.86	0.589±0.354	0.598±0.35	85.384±83.847	371.46±395.53	2.964±1.333	2.115±1.14	13.244±6.827	26.605±13.158	16.497±32.641
LB-12EPA	Range	7.7-8	25.671-27.535	0.046-0.061	0.058-0.082	0.013-0.02	38.378-73.54	0.089-0.319	0.002-0.008	1.372-3.887	0.004-0.016	0.02-0.039	16.649-16.649	0.35-0.381	0.434-0.549	2.823-30.248	20.956-220.93	0.701-1.742	1.431-2.999	8.902-19.157	46.146-49.423	0.265-0.455
	Mean±SD	7.9±0.2	26.603±1.318	0.054±0.011	0.07±0.017	0.017±0.005	55.959±24.863	0.204±0.163	0.005±0.004	2.63±1.778	0.01±0.008	0.03±0.013	16.649±0	0.366±0.022	0.492±0.081	16.536±19.392	120.94±141.4	1.222±0.736	2.215±1.109	14.03±7.251	47.785±2.317	0.36±0.134
LB-20EPA	Range	6.5-8.7	6.046-87.443	0.008-0.083	0.085-0.194	0.015-0.029	7.842-142.56	0.062-0.121	0.015-0.024	0.39-1.183	0.001-0.021	0.032-0.421	74.297-74.297	0.225-0.302	0.198-0.407	25.299-88.547	146.94-335.9	1.048-3.349	0.694-2.855	3.761-20.661	8.15-22.459	0.113-8.635
	Mean±SD	7.6±1.1	37.171±43.947	0.035±0.042	0.126±0.059	0.023±0.007	71.656±67.636	0.092±0.03	0.019±0.005	0.75±0.402	0.008±0.011	0.164±0.222	74.297±0	0.252±0.043	0.297±0.105	54.666±31.865	237.17±94.77	2.508±1.269	1.597±1.124	9.881±9.364	13.422±7.863	3.075±4.818
LB-21EPA	Range	7.5-8.7	2.14-43.947	0.012-0.024	0.049-0.642	0.011-0.018	22.881-118.76	0.032-0.137	0.005-0.019	0.897-1.747	0.003-0.007	0.028-0.064	56.61-79.829	0.087-0.438	0.254-0.411	11.119-70.321	43.629-215.62	0.38-5.474	0.801-7.257	3.463-12.302	4.772-36.214	0.064-1.699
	Mean±SD	8±0.5	35.974±61.129	0.017±0.005	0.208±0.29	0.015±0.003	66.301±50.549	0.077±0.046	0.014±0.006	1.324±0.349	0.005±0.002	0.046±0.015	68.22±16.418	0.192±0.165	0.331±0.078	32.365±27.225	120.86±87.188	2.787±2.089	3.622±2.69	7.959±3.628	19.567±13.319	0.597±0.771
LB-22EPA	Range	6.8-8.6	3.377-43.866	0.013-0.057	0.014-0.257	0.015-0.109	5.159-34.07	0.015-0.151	0.006-0.02	0.824-2.755	0.001-0.002	0.022-0.29	50.199-869.46	0.271-1.157	0.527-1.606	11.425-87.328	62.867-494.04	0.363-3.057	0.515-2.002	2.802-16.58	6.359-40.209	0.085-0.558
	Mean±SD	7.4±1.0	17.479±22.87	0.028±0.025	0.12±0.124	0.07±0.049	21.896±14.986	0.076±0.069	0.014±0.007	1.517±1.075	0.001±0.001	0.139±0.137	459.83±579.3	0.579±0.501	0.947±0.578	43.66±39.222	208.16±247.59	1.549±1.376	1.206±0.749	9.49±6.898	20.576±17.563	0.248±0.269
LB-23EPA	Range	7.7-8.1	2.022-95.315	0.009-0.023	0.074-1.785	0.02-0.073	6.751-42.726	0.047-0.207	0.007-0.027	0.571-3.931	0.001-0.011	0.032-0.095	59.3-147.45	0.214-0.551	0.169-0.816	9.352-125.61	87.66-461.58	1.29-12.047	0.921-20.002	9.474-75.853	11.721-92.688	0.063-14.846
	Mean±SD	8±0.2	33.331±43.83	0.014±0.007	0.648±0.804	0.038±0.025	20.799±15.708	0.103±0.074	0.019±0.008	1.886±1.466	0.005±0.004	0.057±0.027	103.38±44.076	0.349±0.146	0.445±0.272	51.609±52.502	215.43±174.09	4.877±5.07	7.339±8.954	32.269±30.829	39.703±37.486	5.025±6.945
LB-24EPA	Range	6.8-9.5	94.304-128.36	0.013-0.089	0.004-0.445	0.002-0.031	87.705-141.52	0.036-35.31	0.002-0.018	0.004-2.844	0-0.005	0.033-0.43	4.721-83.741	0.112-0.556	0.044-0.339	0.039-80.762	0.339-263.61	0.075-2.731	0.446-1.144	0.58-24.912	0.601-28.609	0.069-2.84
	Mean±SD	7.8±1.0	106.91±13.55	0.051±0.027	0.216±0.177	0.016±0.012	114.76±22.595	8.875±15.263	0.008±0.006	1.276±1.094	0.003±0.002	0.147±0.164	44.231±39.51	0.351±0.17	0.242±0.116	33.566±30.559	120.5±95.206	1.172±0.967	0.901±0.275	10.156±9	13.384±10.214	0.891±1.136

Table 1 to be continued

LB-25EPA	Range	7.4-11.1	12.345-95.592	0.012-0.046	0.004-0.455	0.002-0.132	9.614-158.57	0.054-30.794	0.002-0.029	0.005-3.031	0-0.009	0.032-0.063	4.255-89.894	0.107-0.782	0.041-1.664	0.037-80.868	0.293-241.85	0.07-3.671	0.421-3.984	0.576-60.64	0.628-52.662	0.059-0.374
	Mean±SD	8.6±2.1	46.118±43.788	0.024±0.019	0.195±0.233	0.049±0.072	85.529±74.519	10.308±17.741	0.012±0.015	1.528±1.513	0.005±0.005	0.043±0.017	47.075±60.556	0.454±0.338	0.919±0.82	31.895±43.048	128.96±121.55	2.081±1.837	2.429±1.824	25.942±31.1	31.733±27.469	0.244±0.164
LB-27EPA	Range	6.6-10.1	2.254-53.453	0.008-0.055	0.068-0.15	0.057-0.174	17.303-261.89	0.043-15.776	0.016-0.028	0.36-3.335	0.002-0.009	0.023-0.099	172.16-311.34	0.136-1.292	0.239-1.702	42.463-128.21	57.409-417.72	1.657-4.064	3.215-4.933	10.689-42.706	11.456-62.442	0.651-27.472
	Mean±SD	8.1±1.5	15.756±25.14	0.03±0.022	0.108±0.035	0.121±0.058	82.323±119.83	3.998±7.852	0.022±0.005	2.104±1.251	0.005±0.003	0.055±0.032	241.75±98.412	0.788±0.48	0.99±0.598	71.164±38.641	223.63±168.53	2.507±1.065	4± 0.725	26.103±13.193	45.585±23.122	7.878±13.097
LB-28EPA	Range	8-8.5	27.871-151.43	0.016-0.036	0.045-0.179	0.049-0.121	147.92-317.07	0.049-0.316	0.02-0.04	0.278-2.443	0.001-0.004	0.083-0.671	117.24-180.27	0.251-0.558	0.292-0.574	65.491-135.66	61.653-195.99	1.688-2.322	1.85-4.848	4.679-25.204	7.046-38.317	0.209-0.541
	Mean±SD	8.2±0.3	79.493±64.238	0.025±0.01	0.116±0.067	0.088±0.036	254.05±92.448	0.145±0.148	0.03±0.01	1.587±1.152	0.002±0.002	0.281±0.338	148.76±44.57	0.398±0.154	0.416±0.144	89.736±39.792	135.75±68.234	2.042±0.323	3.768±1.666	16.855±10.785	24.678±16.013	0.429±0.191
LB-29EPA	Range	8-9.2	70.459-213.4	0.054-0.118	0.065-0.699	0.006-0.036	93.698-306.13	0.052-0.388	0.003-0.004	0.636-2.215	0.001-0.017	0.174-1.385	67.262-515.89	0.347-0.935	0.172-0.999	34.268-391.24	126.67-377.64	3.688-16.851	0.889-2.599	22.435-31.761	22.846-28.439	0.424-0.791
	Mean±SD	8.6±0.6	164.07±81.105	0.091±0.033	0.315±0.338	0.017±0.016	223.49±113.8	0.165±0.193	0.003±0.001	1.503±0.801	0.007±0.009	0.868±0.625	291.58±317.23	0.717±0.322	0.569±0.414	230.36±181.07	221±136.6	8.499±7.261	1.636±0.875	27.378±4.688	25.39±2.831	0.565±0.198
LB-31EPA	Range	7.8-10.1	203.72-253.62	0.021-0.025	0.116-0.236	0.012-0.083	59.91-77.8	0.038-0.084	0.016-0.023	1.085-2.54	0.002-0.013	0.506-0.638	159.13-159.13	0.686-2.336	0.262-0.867	14.105-152.04	78.493-722.84	0.56-2.106	0.415-0.839	8.165-15.305	10.23-11.678	0.273-3.443
	Mean±SD	8.7±1.3	226.84±25.148	0.023±0.002	0.179±0.06	0.049±0.036	67.276±9.354	0.062±0.023	0.02±0.004	1.714±0.747	0.008±0.006	0.551±0.075	159.13±0	1.741±0.916	0.626±0.321	88.532±69.614	496.12±362.12	1.399±0.781	0.597±0.218	10.991±3.795	11.017±0.732	1.495±1.705
KM-1EPA	Range	7.8-8.9	125.65-135.53	0.04-0.107	0.402-0.715	0.055-0.132	124.13-198.48	0.041-0.26	0.064-0.083	1.576-6.824	0.002-0.012	0.159-0.307	194.35-286.62	0.569-0.785	0.217-0.663	57.33-287.94	111.65-877.53	3.708-13.151	0.453-2.303	16.145-76.831	46.554-117.02	0.567-6.203
	Mean±SD	8.4±0.6	130.77±4.949	0.075±0.034	0.539±0.16	0.083±0.043	151.91±40.58	0.167±0.113	0.076±0.01	4.246±2.625	0.006±0.005	0.209±0.085	240.49±65.25	0.701±0.116	0.469±0.228	140.59±127.97	382.26±429.53	7.187±5.189	1.388±0.925	42.678±31.052	76.264±36.505	2.46±3.242
KP-3EPA	Range	6.4-7.8	85.006-174.72	0.017-0.082	0.09-52.585	0.004-0.25	31.319-87.344	0.075-0.148	0.002-0.042	0.56-3.864	0.002-0.002	0.301-0.586	45.038-407.13	0.17-0.784	0.181-0.852	3.76-599.94	45.913-1,634.9	0.136-27.641	0.339-4.06	2.226-50.805	33.711-5,109.37	0.094-7.324
	Mean±SD	7.1±0.7	127.77±45.006	0.047±0.033	17.614±30.286	0.121±0.123	65.472±29.964	0.122±0.041	0.023±0.02	1.679±1.893	0.002±0	0.398±0.163	226.08±256.04	0.483±0.307	0.41±0.383	241.75±315.75	700±830.88	12.203±14.059	1.883±1.939	19.333±27.290	1,726.59±2,929.57	2.55±4.135
KP-4EPA	Range	7.2-8.5	18.519-31.246	0.021-0.078	0.113-0.628	0.041-0.094	122.73-181.17	0.076-0.165	0.045-0.051	0.524-2.745	0.002-0.005	0.065-0.157	113.05-324.44	0.182-1.038	0.315-0.985	31.464-203.28	56.329-2,280.95	7.179-16.523	4.587-6.88	5.317-41.928	16.551-124.609	0.074-0.723
	Mean±SD	7.8±0.7	24.476±6.402	0.043±0.03	0.287±0.295	0.06±0.03	156.68±30.346	0.112±0.047	0.047±0.003	1.53±1.125	0.003±0.002	0.119±0.048	218.75±149.48	0.753±0.494	0.571±0.362	146.01±99.199	801.88±1,280.93	11.561±4.699	5.91±1.186	29.724±21.137	57.707±58.449	0.335±0.342
KP-5EPA	Range	7.3-8.2	56.289-290.98	0.062-0.321	0.081-0.199	0.047-0.078	65.521-114.47	0.096-0.246	0.088-0.107	0.634-0.884	0.003-0.006	0.085-0.327	37.941-43.715	0.963-2.486	0.561-0.692	24.847-87.039	41.999-150.02	1.003-3.001	0.727-1.316	9.078-19.217	13.951-20.052	0.191-2.195
	Mean±SD	7.8±0.5	178.39±117.63	0.226±0.143	0.155±0.065	0.058±0.018	86.772±25.104	0.155±0.08	0.098±0.01	0.779±0.13	0.004±0.002	0.193±0.123	40.828±4.083	1.781±0.768	0.606±0.074	51.111±32.203	92.363±54.377	1.732±1.103	0.98±0.303	12.781±5.595	16±3.509	0.902±1.121
LB-1EPF	Range	7.1-9.3	5.459-80.683	0.015-0.091	0.035-0.356	0.014-0.356	16.626-65.721	0.078-0.206	0.008-0.017	1.169-2.218	0.001-0.016	0.151-0.501	44.404-56.254	0.052-2.431	0.332-0.701	17.331-218.57	74.408-353.92	0.573-15.193	0.668-3.038	5.124-634.8	14.007-75.05	0.067-4.412
	Mean±SD	8.1±0.8	45.573±34.201	0.038±0.032	0.119±0.136	0.104±0.143	27.108±21.594	0.113±0.053	0.012±0.003	1.722±0.473	0.006±0.006	0.232±0.151	50.329±8.379	0.56±1.046	0.503±0.147	73.801±81.857	164.47±112.24	3.666±6.447	1.274±1.002	138.46±277.57	39.234±22.236	1.622±2.141
LB-2EPF	Range	7.2-9.6	11.859-131.27	0.009-0.547	0.025-1.68	0.005-0.094	101.58-175.05	0.034-0.141	0.001-0.009	0.469-3.015	0.001-0.017	0.047-0.403	11.823-22.454	0.194-0.457	0.179-0.552	2-53.067	18.3-212.12	0.148-27.334	0.488-4.67	7.14-154.17	11.393-968.29	0.267-6.265
	Mean±SD	8.2±0.9	78.473±42.69	0.127±0.235	0.408±0.715	0.032±0.037	146.53±30.669	0.079±0.049	0.003±0.003	1.44±1.022	0.006±0.007	0.15±0.144	17.139±7.517	0.296±0.119	0.331±0.141	149±21.513	112.99±81.926	5.811±12.034	1.879±1.658	45.864±60.929	382.13±377.85	1.484±2.673
LB-7EPF	Range	6.7-9.4	4.31-57.106	0.012-0.046	0.036-0.815	0.134-1.431	58.429-104.16	0.022-0.401	0.02-0.048	0.501-1.121	0.001-0.034	0.017-0.494	11.58-34.426	0.005-0.118	0.152-0.796	156.13-380.16	74.287-9,174.63	4.231-8.896	4.046-7.923	2.578-13.278	13.254-203.48	0.015-3.832
	Mean±SD	7.8±1.0	20.469±21.152	0.02±0.015	0.202±0.343	0.615±0.502	76.539±19.423	0.121±0.158	0.032±0.011	0.699±0.258	0.008±0.015	0.121±0.209	23.003±16.155	0.039±0.046	0.362±0.269	289.12±89.701	5,691.81±4,117.9	7.522±1.898	5.999±1.766	7.656±3.852	107.1±77.258	1.315±1.581
LB-14EPF	Range	6.2-8.5	3.118-46.62	0.01-0.038	0.036-0.864	0.016-0.417	22.771-93.336	0.033-0.136	0.005-0.031	1.038-1.822	0.002-0.049	0.024-0.125	70.882-95.984	0.044-1.339	0.237-1.13	63.695-161.87	639.83-1,913.9	1.545-31.872	0.883-8.509	6.216-27.594	8.663-335.29	0.027-18.189
	Mean±SD	7.5±0.8	15.173±18.809	0.024±0.012	0.219±0.361	0.115±0.17	44.452±27.886	0.079±0.044	0.014±0.01	1.418±0.294	0.013±0.02	0.058±0.04	83.433±17.75	0.383±0.538	0.607±0.37	132.92±40.173	1,181.86±542.58	9.726±12.806	5.306±2.774	13.738±8.24	154.08±130.89	4.813±7.713
LB-15EPF	Range	7.3-8.5	1.257-3.128	0.009-0.075	0.032-0.05	0.047-0.127	20.584-37.629	0.053-0.13	0.005-0.025	0.721-1.386	0.002-0.019	0.006-0.067	14.137-38.54	0.09-0.138	0.31-0.49	5.285-91.225	23.042-273.01	0.572-3.031	3.982-9.711	5.827-20.05	26.896-113.45	0.037-3.615
	Mean±SD	8± 0.6	2.504±1.08	0.032±0.037	0.042±0.009	0.093±0.041	31.466±9.451	0.093±0.039	0.013±0.01	1.037±0.334	0.01±0.009	0.033±0.031	26.339±17.256	0.108±0.026	0.396±0.09	41.355±44.601	106.9±143.86	1.654±1.256	7.784±3.293	13.129±7.119	66.938±43.639	1.234±2.062
LB-16EPF	Range	7.6-8	1.965-5.462	0.014-0.028	0.023-0.096	0.022-0.067	25.814-60.141	0.022-0.109	0.005-0.016	0.614-3.596	0.004-0.031	0.016-0.034	37.109-66.632	0.047-0.121	0.253-0.634	11.879-17.541	42.7-77.504	0.512-3.929	5.185-8.519	9.168-45.244	51.801-129.29	0.088-0.594

Table 1 to be continued

	Mean±SD	7.8±0.2	4.121±1.886	0.02±0.007	0.056±0.037	0.038±0.025	46.414±18.166	0.075±0.047	0.012±0.006	1.91±1.529	0.013±0.015	0.024±0.009	51.871±20.876	0.074±0.041	0.416±0.196	14.34±2.903	56.123±18.717	2.508±1.78	7.239±1.797	22.18±20.029	93.55±39.092	0.271±0.281
LB-17EPF	Range	7.2-8	5.149-95.294	0.019-0.498	0.049-13.336	0.026-0.137	58.687-195.87	0.061-0.118	0.014-0.035	1.786-14.963	0.002-0.004	0.03-0.341	38.456-38.456	0.081-0.172	0.142-0.524	133.5-618.39	50.998-146.487	2.983-3.977	3.471-6.225	11.967-284.42	36.399-1,602.786	0.871-25.19
	Mean±SD	7.7±0.4	62.635±49.938	0.33±0.27	8.791±7.573	0.084±0.056	124.86±68.719	0.081±0.032	0.024±0.011	7.97±6.626	0.003±0.001	0.2±0.157	38.456±0	0.136±0.049	0.308±0.196	309.56±302.72	93.389±48.637	3.335±0.557	5.099±1.444	164.12±138.99	887.33±791.93	9.367±13.716
LB-30EPF	Range	7.1-8	75.549-77.313	0.047-0.168	0.048-11.83	0.141-1.201	83.777-193.38	0.106-0.337	0.036-0.052	0.774-11.468	0.004-0.02	0.242-0.501	119.76-119.76	0.115-0.385	0.439-0.691	292.95-554.75	34.047-310.61	3.661-4.036	3.716-4.548	5.225-199.02	16.371-1,248.31	0.101-4.079
	Mean±SD	7.7±0.5	76.412±0.883	0.089±0.068	4.015±6.768	0.818±0.588	126.64±58.574	0.259±0.133	0.043±0.008	4.383±6.136	0.01±0.009	0.412±0.147	119.76±0	0.218±0.146	0.6± 0.14	394.39±140.49	146.77±145.19	3.8±0.205	4.11±0.418	71.287±110.64	431.78±707.17	1.8±2.051
KM-2EPF	Range	6.4-8.7	86.294-90.829	0.024-0.034	9.563-18.721	0.088-0.107	50.266-105.98	0.259-0.533	0.03-0.043	0.815-5.842	0.001-0.003	0.636-1.131	241.53-654.79	0.061-0.232	0.283-0.697	221.3-388.24	44.073-88.748	37.597-54.026	51.823-64.647	14.777-28.386	885.94-1,854.68	0.118-2.007
	Mean±SD	7.3±1.2	88.251±2.331	0.031±0.006	14.751±4.699	0.098±0.01	72.057±29.773	0.438±0.155	0.037±0.007	3.319±2.514	0.002±0.001	0.898±0.249	448.16±292.22	0.123±0.095	0.47±0.21	297.63±84.382	61.486±23.911	45.768±8.215	57.505±6.535	20.564±7.029	1,408.47±488.86	0.786±1.059
KP-1EPF	Range	7.9-8.8	83.167-126.95	0.036-0.142	0.077-116.89	0.008-0.277	36.762-87.322	0.256-0.296	0.003-0.029	0.326-1.253	0.002-0.004	0.387-0.388	21.358-21.358	0.221-0.768	0.201-1.612	8.102-226.64	93.704-931.18	2.906-52.617	2.152-6.745	5.303-23.436	36.5-9,900.72	1.287-3.184
	Mean±SD	8.3±0.5	97.763±25.28	0.107±0.061	39.016±67.44	0.187±0.155	70.469±29.191	0.269±0.023	0.012±0.015	0.944±0.535	0.003±0.001	0.387±0.001	21.358±0	0.586±0.316	1.142±0.815	80.949±126.17	535.18±420.59	19.476±28.701	3.683±2.652	17.392±10.469	3,324.57±5,695.11	1.919±1.095
KP-2EPF	Range	7.6-8	25.754-29.598	0.022-0.043	0.03-0.061	0.011-0.013	45.485-56.367	0.03-0.106	0.004-0.006	0.565-0.625	0.003-0.003	0.12-0.132	27.788-27.788	0.228-0.392	0.634-1.234	14.607-15.826	19.586-65.253	1.43-15.826	7.726-8.74	6.825-18.927	26.119-39.7	0.374-2.983
	Mean±SD	7.7±0.2	28.317±2.219	0.036±0.012	0.04±0.018	0.012±0.001	49.112±6.283	0.081±0.044	0.005±0.001	0.585±0.035	0.003±0	0.124±0.007	27.788±0	0.337±0.095	1.034±0.346	15.013±0.704	43.746±22.949	2.365±0.809	8.402±0.585	14.893±6.987	35.173±7.841	1.244±1.506
KP-6EPF	Range	6.5-8.1	11.386-18.123	0.027-0.045	0.093-0.121	0.019-0.026	21.832-35.148	0.026-0.237	0.006-0.019	0.392-1.152	0.002-0.006	0.043-0.74	23.082-43.842	0.129-0.569	0.377-1.254	13.042-18.968	63.386-127.58	1.346-3.578	1.739-3.29	3.084-29.669	14.144-23.325	0.124-0.554
	Mean±SD	7.4±0.8	13.989±3.62	0.035±0.009	0.109±0.014	0.022±0.004	28.594±6.66	0.109±0.112	0.014±0.007	0.748±0.382	0.003±0.002	0.278±0.4	33.462±14.68	0.422±0.254	0.852±0.443	15.017±3.421	91.135±32.97	2.322±1.142	2.568±0.781	20.022±14.716	18.241±4.67	0.394±0.235

EPA: water sampling of a hand-dug well; EPF: water sampling of a drilled well; KM: Kamalondo commune; KP: Kampemba commune; LB: Lubumbashi commune; Range: minimum and maximum; SD: standard deviation.

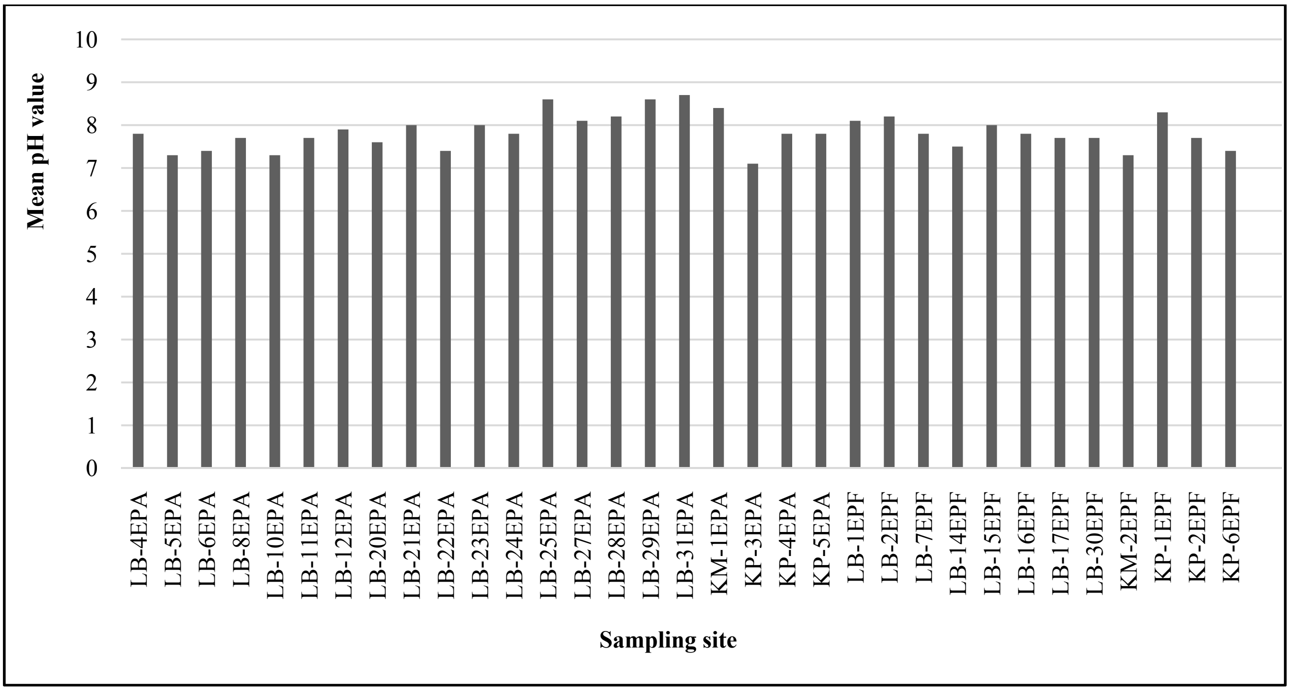

Fig. 2 Mean values of water pH of hand-dug and drilled wells in Lubumbashi, Kamalondo and Kampemba communes of Lubumbashi city from October 2016 to February 2017.

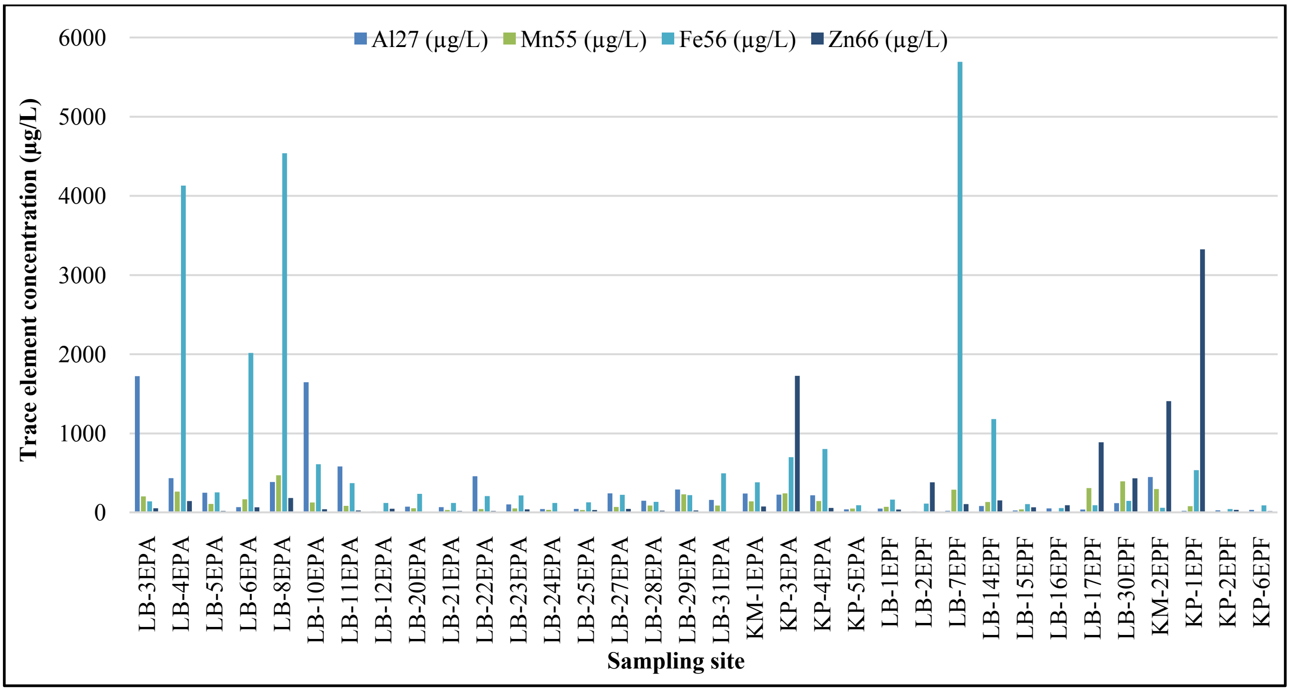

Fig. 3 Mean concentrations of aluminum, manganese, iron and zinc in groundwater (µg/L) of hand-dug and drilled wells in Lubumbashi, Kamalondo and Kampemba communes of Lubumbashi city from October 2016 to February 2017.

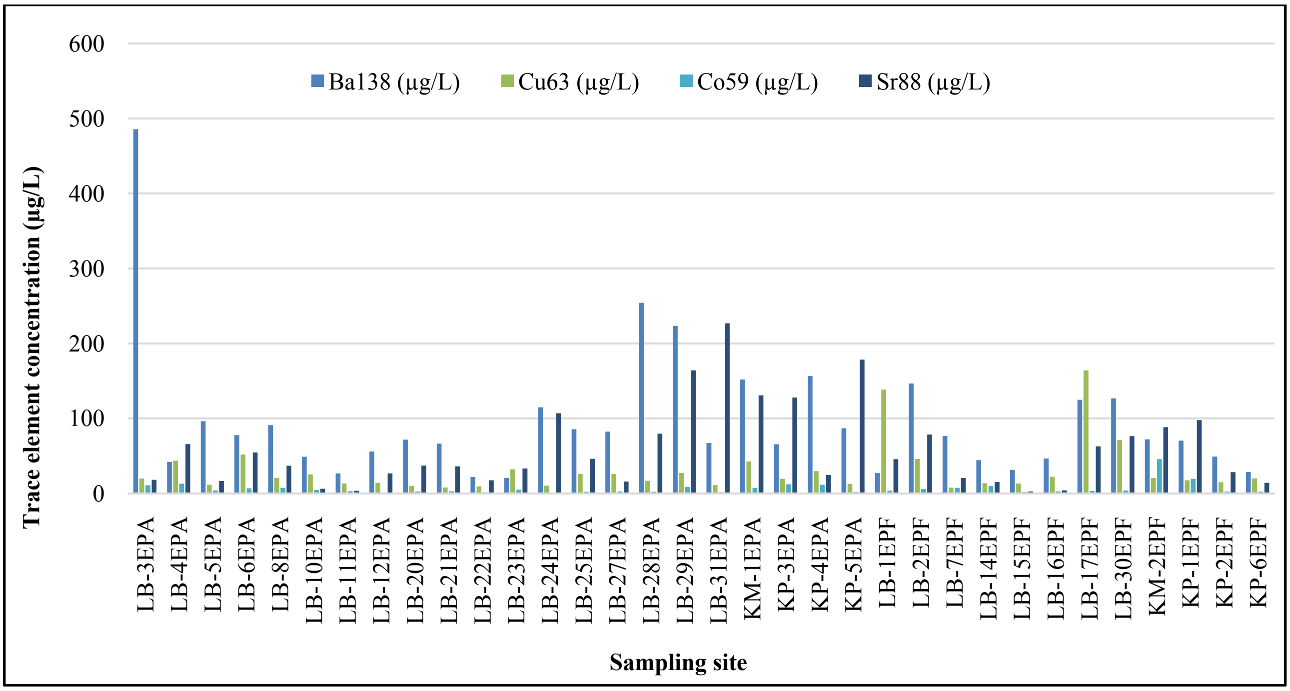

Fig. 4 Mean concentrations of barium, cobalt, copper and strontium in groundwater (µg/L) of hand-dug and drilled wells in Lubumbashi, Kamalondo and Kampemba communes of Lubumbashi city from October 2016 to February 2017.

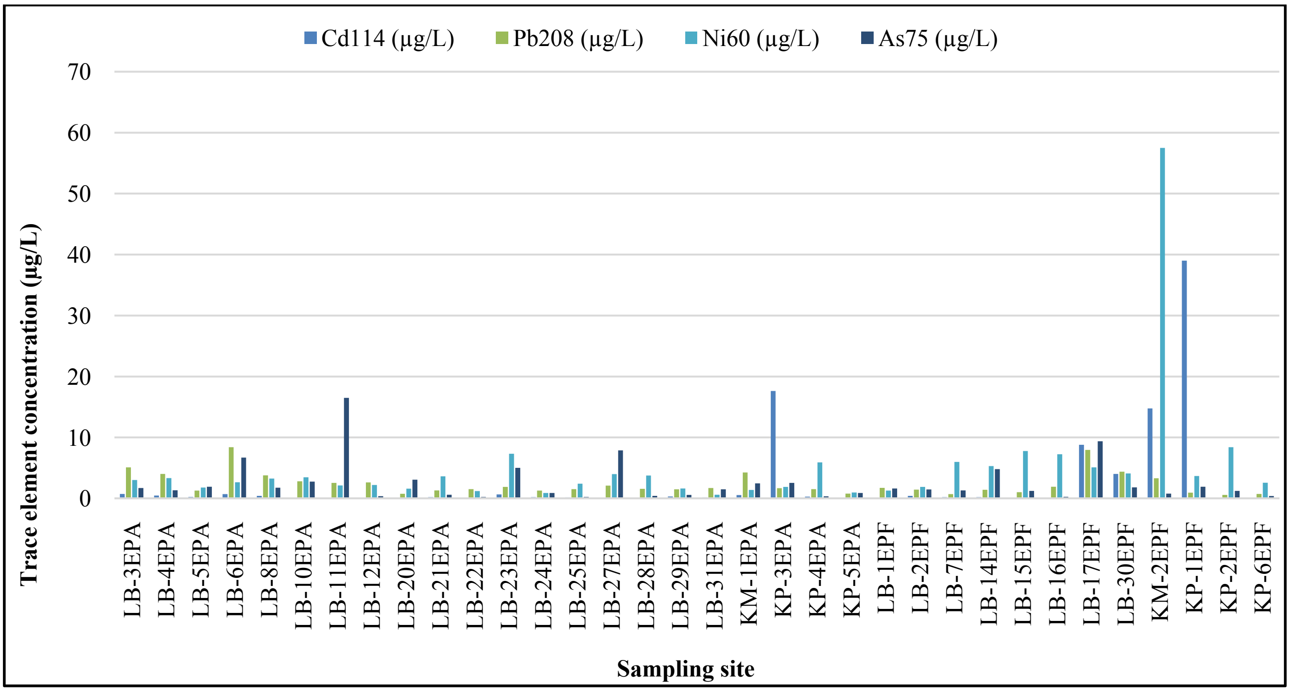

Fig. 5 Mean concentrations of cadmium, lead, nickel and arsenic in groundwater (µg/L) of hand-dug and drilled wells in Lubumbashi, Kamalondo and Kampemba communes of Lubumbashi city from October 2016 to February 2017.

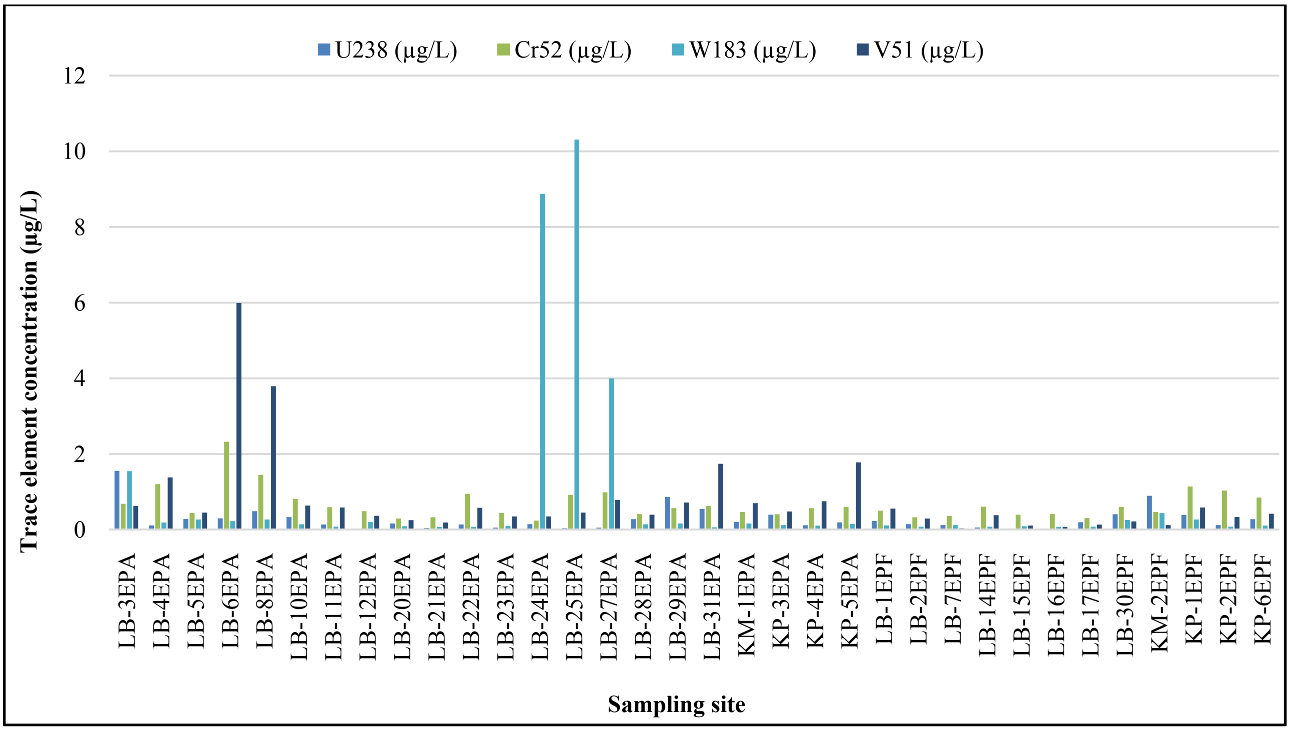

Fig. 6 Mean concentrations of uranium, chromium, tungsten and vanadium in groundwater (µg/L) of hand-dug and drilled wells in Lubumbashi, Kamalondo and Kampemba communes of Lubumbashi city from October 2016 to February 2017.

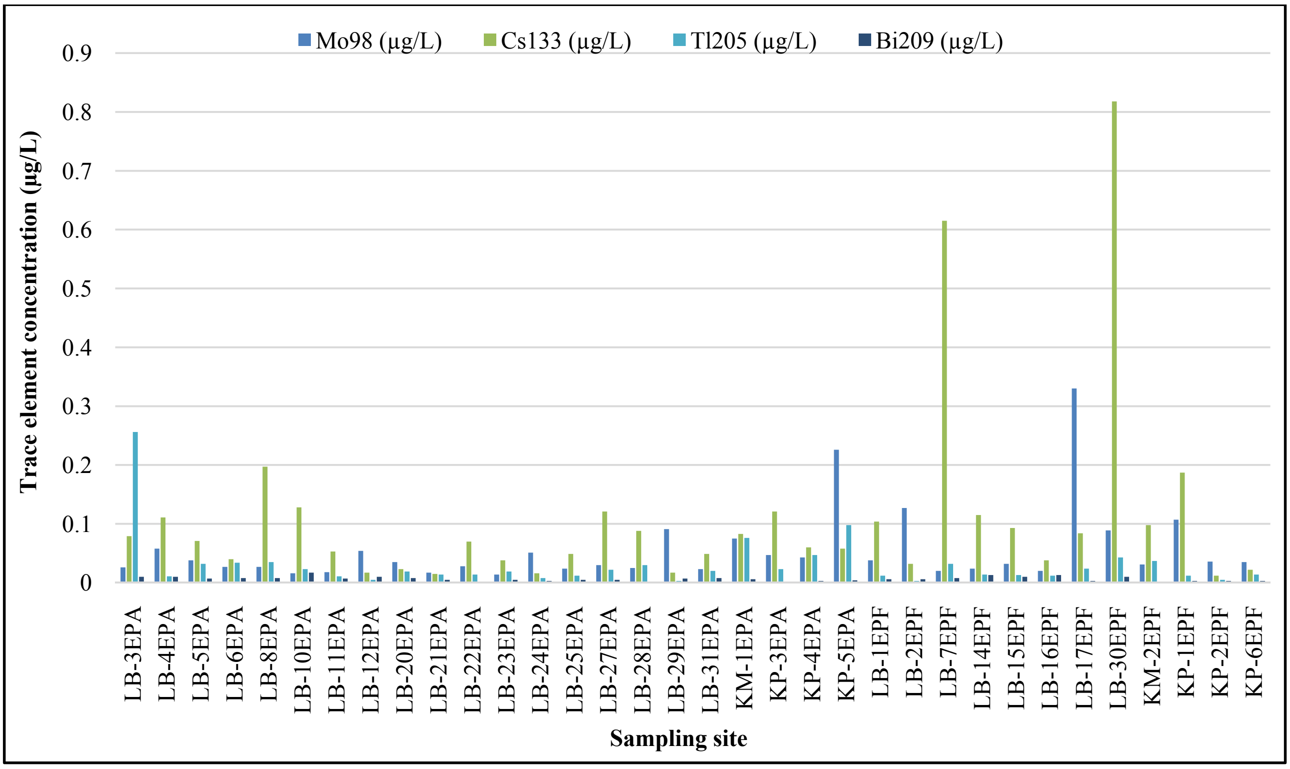

Fig. 7 Mean concentrations of molybdenum, cesium, thallium and bismuth in groundwater (µg/L) of hand-dug and drilled wells in Lubumbashi, Kamalondo and Kampemba communes of Lubumbashi city from October 2016 to February 2017.

Table 2 WHO Guidelines for Drinking-Water Quality, United States EPA Standards and Health Advisories, and EU (Drinking Water) Regulations and Indicator Parameters.

Guidelines, Standards, Regulations	Optimum pH values	Sr88 (μg/L)	Mo98 (μg/L)	Cd114 (μg/L)	Cs133 (μg/L)	Ba138 (μg/L)	W183 (μg/L)	Tl205 (μg/L)	Pb208 (μg/L)	Bi209 (μg/L)	U238 (μg/L)	Al27 (μg/L)	V51 (μg/L)	Cr52 (μg/L)	Mn55 (μg/L)	Fe56 (μg/L)	Co59 (μg/L)	Ni60 (μg/L)	Cu63 (μg/L)	Zn66 (μg/L)	As75 (μg/L)
WHO	6.5-8.5	Na	Na	3	Na	1,300	Na	Na	10	Na	30	Na	Na	50	Na	Na	Na	70	2,000	Na	10
US EPA	6.5-8.5*	4,000*	40*	5	Na	2,000	Na	2	15	Na	30	50-200*	Na	100	300*	300*	Na	100*	1,300	2,000*	10
EU	6.5-9.5	Na	Na	5	Na	Na	Na	Na	10	Na	30	200**	Na	50	50**	200**	Na	20	2,000	Na	10

EU: European Union (Drinking Water) Regulations and Indicator Parameters, 2014; Na: no available data; US EPA: United States Environmental Protection Agency 2018 Drinking Water Standards and Health Advisories; WHO: World Health Organization Guidelines for Drinking-Water Quality, 2017; *: United States Environmental Protection Agency 2018 Drinking Water Health Advisories; **: European Union (Drinking Water) Indicator Parameters, 2014.

of dolomite (calcium and magnesium carbonate) which is very rich in calcium. During wet season in Lubumbashi city, from November to March, the level of groundwater goes up and brings with it deep alkaline solutions which make the well water alkaline to very alkaline. According to Roadcap et al. [20], where alkaline groundwater discharges in springs, atmospheric CO_2 dissolves into the water and thick layers of calcite form. Calcite precipitated at the springs is rich in a number of heavy metals, suggesting that metals can move through the system as particulate matter.

Twenty trace elements including strontium (Sr), molybdenum (Mo), cadmium (Cd), cesium (Cs), barium (Ba), tungsten (W), thallium (Tl), lead (Pb), bismuth (Bi), uranium (U), aluminum (Al), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn) and arsenic (As) were noted at varying concentrations in all the water samples and were compared with the WHO, US EPA and EU drinking water permissible MCLs for cadmium, barium, thallium, lead, uranium, aluminum, chromium, manganese, iron, nickel, copper, zinc and arsenic (Table 1).

Trace element levels of water samples from hand-dug wells in the three communes of Lubumbashi city presented the following ranges: 2.022-290.98 μg/L for strontium, 0.008-0.321 μg/L for molybdenum, 0.004-52.585 μg/L for cadmium, 0.002-0.594 μg/L for cesium, 5.159-740.24 μg/L for barium, 0.015-35.31 μg/L for tungsten, 0.002-0.409 μg/L for thallium, 0.004-38.162 μg/L for lead, 0.000-0.033 μg/L for bismuth, 0.020-2.492 μg/L for uranium, 4.255-2,712.5 μg/L for aluminum, 0.066-27.363 μg/L for vanadium, 0.041-10.014 μg/L for chromium, 0.037-1,242.68 μg/L for manganese, 0.293-17,325.98 μg/L for iron, 0.07-27.641 μg/L for cobalt, 0.218-20.002 μg/L for nickel, 0.576-217.25 μg/L for copper, 0.601-5,109.37 μg/L for zinc and 0.049-65.458 μg/L for arsenic.

In water samples from drilled wells, the ranges of trace metal levels were 1.257-131.27 μg/L for strontium, 0.009-0.547 μg/L for molybdenum, 0.023-116.89 μg/L for cadmium, 0.005-1.431 μg/L for cesium, 16.626-195.87 μg/L for barium, 0.022-0.533 μg/L for tungsten, 0.001-0.052 μg/L for thallium, 0.326-14.963 μg/L for lead, 0.001-0.049 μg/L for bismuth, 0.006-1.131 μg/L for uranium, 11.58-654.79 μg/L for aluminum, 0.047-2.431 μg/L for vanadium, 0.09-1.612 μg/L for chromium, 2-618.39 μg/L for manganese, 18.3-9,174.63 μg/L for iron, 0.148-54.026 μg/L for cobalt, 0.418-64.647 μg/L for nickel, 3.084-634.8 μg/L for copper, 8.663-9,900.72 μg/L for zinc and 0.027-25.19 μg/L for arsenic.

The highest mean concentrations of barium, thallium, uranium, chromium and copper recorded in the groundwater samples were 740.24 μg/L, 0.409 μg/L, 2.492 μg/L, 10.014 μg/L and 655.88 μg/L, respectively in hand-dug wells and 195.87 μg/L, 0.052 μg/L, 1.131 μg/L, 1.612 μg/L and 634.8 μg/L, respectively in drilled wells. Thus, none of the groundwater samples contained mean barium, thallium, uranium, chromium and copper levels above the WHO US EPA, and EU permissible MCLs for drinking water.

On the other hand, mean cadmium, lead, aluminum, manganese, iron, nickel, zinc and arsenic levels exceeding the WHO, U.S.EPA and EU drinking water permissible MCLs were respectively noted in 6.66%, 3.38%, 26.67%, 5.02%, 30.03%, 3.38%, 1.64% and 5.02% of all the samples with the highest mean levels of 116.89 µg/L for cadmium, 38.162 µg/L for lead, 2,712.5 µg/L for aluminum, 1,242.68 µg/L for manganese, 17,325.98 µg/L for iron, 64.647 µg/L for nickel, 9,900.72 µg/L for zinc and 65.458 µg/L for arsenic. Trace metal concentrations in water of spade-sunk and drilled wells in the three communes of Lubumbashi city are much higher than those reported for water of similar wells in Kipushi mining city [3]. They are also much higher than those noted by Jeje and Oladepo [21] for hand-dug and drilled wells in Ife North local government area of Osun State, Nigeria. Trace metal contamination of groundwater in Lubumbashi city is also much higher than that reported for groundwater around dumpsite in Igando, Nigeria by Akoteyon [22], except that copper levels of groundwater in Lubumbashi city and those in Igando were respectively below and above the WHO drinking water MCL for that metal.

The recorded cadmium, lead, aluminum, chromium, manganese, iron, nickel, copper and zinc contamination of hand-dug and drilled wells in Lubumbashi city was much higher than that noted for water of similar wells in Kipushi mining town where the highest mean trace metal levels of water were 9 µg/L for cadmium, 28 µg/L for lead, 1,106 µg/L for aluminum, 8 µg/L for chromium, 135 µg/L for manganese, 491 µg/L for iron, 14 µg/L for nickel, 143 µg/L for copper, and 2,170 µg/L for zinc [3]. With the highest mean molybdenum and cobalt levels of 2 µg/L and 94 µg/L, respectively noted for well water in Kipushi mining city, the well water contamination with both metals in Lubumbashi city was lower than that reported by the same researchers for well water in Kipushi. The recorded levels of those metals in water from hand-dug and drilled wells in Lubumbashi city were also higher than those reported by Jeje and Oladepo [21] for Ife North local Government area of Osun State in Nigeria. Also, the mean concentrations of lead, cadmium, copper and chromium in groundwater in the present study were much higher than those below detection limits reported for groundwater around a dumpsite in Igando (Nigeria) in wet season [22]. According to this author, only iron concentrations in all the sampling locations of Igando groundwater exceeded the WHO drinking water MCL during the dry season and only in about 46.7% of the sampling locations during the rainy season, whereas lead, zinc and copper concentrations exceeded the WHO MCLs in dry season only. The highest cadmium, lead, manganese, cobalt, zinc and arsenic levels of groundwater recorded in Lubumbashi city are higher than those reported by Nriagu et al. [23] for groundwater in Ulaanbaatar, Mongolia but the highest uranium level of Lubumbashi city groundwater was much lower than the 57 µg/L noted in Ulaanbaatar groundwater.

Of the twenty trace metals recorded in groundwater in the three communes of Lubumbashi city, only cobalt, copper, iron, manganese, molybdenum and zinc are essential for human body and they play an important biological role at low concentrations in the body, whereas excessive concentrations or deficiency of these metals in the body are known to induce some dysfunction of the body. D. G. Barceloux and D. D. Barceloux [24] have reported that vanadium is probably an essential trace element, but a vanadium-deficiency disease has not been identified in humans. The other trace metals noted in groundwater in Lubumbashi city have no known biological importance for human body and most of them are even toxic to humans, even at low concentrations. Cadmium, lead, arsenic, uranium, chromium and nickel are those which have the most negative health impacts on humans even at low concentrations.

Cadmium and cadmium compounds are known to be carcinogenic and ingestion of very high cadmium concentrations severely irritates the stomach, leading to vomiting and diarrhea. Long-term exposure to low cadmium concentrations leads to the accumulation of that metal in the kidneys and possible kidney disease, damage of lungs and weakening of bones [25]. Also, Browar et al. [26] have reported that cadmium is an environmental contaminant that damages the kidney, the liver, and bones and they supported the possibility of cadmium being a contributing factor to the development of periodontal disease in humans.

Lead has been recognized to be a general and cumulative metabolic poison [27]. Children are particularly sensitive to lead exposure due to high gastro-intestinal absorption and permeable blood-brain barrier [28]. Martin and Griswold [25] reported that lead is a probable carcinogen for man and that long-term exposure to lead may result in reduced performance to some tests that measure the functions of the nervous system, weakness of fingers, wrists and ankles, light increase of blood pressure and anemia. According to the authors, exposure to high lead levels may cause severe damage to brain, kidneys and ultimate death. Exposure to high lead levels may cause abortion to pregnant women and may damage the organs responsible for sperm production in men. Other studies have linked lead exposure, even at low concentrations, to an increase of arterial pressure as well as a weak intelligence quotient in children and a disorder in attention [29-31].

Arsenic is a toxic metalloid that is ubiquitous in the environment and affects global health problems due to its carcinogenicity [32]. In most populations, the main source of arsenic exposure is drinking water [32-37]. In drinking water, chronic exposure to arsenic is associated with increased risks of various cancers including those of skin, lung, bladder, kidney, and liver, as well as numerous other non-cancer illnesses including gastrointestinal and cardiovascular diseases, diabetes, reproductive and developmental problems, and neurologic and cognitive problems [33, 34, 36, 38, 39]. Prenatal exposure to inorganic arsenic causes adverse pregnancy outcomes and children's health problems. During pregnancy, high-level exposure to arsenic in drinking water causes pregnancy complications, including fetal loss and premature delivery [40], and low-level exposure to arsenic affects uterus and placental growth results in progeny birth weight [41, 42]. Other studies have reported that woman exposure to chronic arsenic in drinking water increases adverse pregnancy outcomes including premature delivery, spontaneous abortion, stillbirth and neonatal death in Chile [43], northeastern Taiwan [44], and Bangladesh [45]. In males, inorganic arsenic is associated with reproductive dysfunctions through declined testosterone synthesis, apoptosis and necrosis [46, 47]. Also, Y. J. Kim and J. M. Kim [32] have reported that oral exposure to inorganic arsenic in drinking water causes dysfunction of spermatogenesis, reductions of testosterone and gonadotrophins, and disruptions of steroidogenesis, and that the crucial mechanisms of arsenic-induced reproductive toxicity may be associated with hormonal regulation and function, binding to sperm, and regulation of steroidogenesis as well as direct effects of testicular component cells. Recently, a few epidemiologic studies have shown that arsenic exposure significantly induces infertility and low sperm quality, as well as erectile dysfunction in men [48-50].

Uranium exposure in drinking water from various wells in Ulaanbaartar, Mongolia has been associated with nephrotoxicity, high blood pressure, bone dysfunction and likely reproductive impairment in human populations [23]. Arzuaga, et al. [51] reported that uranium exposure is associated with alterations in normal bone functions and that available studies suggest that upon absorption uranium directly affects bone development and maintenance by inhibiting osteoblast differentiation and normal functions, and indirectly by disrupting renal production of vitamin D. And according to Corlin, et al. [52], there is a strong toxicological evidence for renal and reproductive effects as well as DNA (Deoxyribo Nucleic Acid) damage but the epidemiological evidence of these effects in people exposed to uranium in drinking water is limited.

Mean concentrations of chromium and nickel in groundwater in Lubumbashi city ranged from 0.041 µg/L to 10.014 µg/L and from 0.339 µg/L to 64.647 µg/L, respectively. Those chromium concentrations were much lower than the WHO, EU and US EPA permissible MCLs of that metal in drinking water whereas mean concentrations of nickel exceeded the EU permissible MCL at sampling sites LB-23EPA (20,002 µg/L) and KM-2EPF (64.647 µg/L). The highest mean concentration of chromium in Lubumbashi city groundwater was higher than that (8 µg/L) recorded in groundwater in Kipushi mining city [3] and those (3.17 µg/L and 3.898 µg/L) respectively noted in Munua river and Tshibal channel in Lubumbashi city [11], as well as that (8.185 µg/L) noted in CHEMAF hydrometallurgical plant effluent [12]. The groundwater of Lubumbashi city is also much more contaminated with chromium than groundwater resources of Asadabad plain, Iran where the mean concentration of 0.044 ± 0.016 µg/L was reported by Ghobadi and Jahangard [53], and the groundwater of Agbor and Owa Communities of Nigeria where cadmium, chromium and arsenic were not detected [54]. Minnesota Pollution Control Agency [55] has reported that the primary sources of copper, chromium, nickel and zinc are rocks, and that concentrations of these metals in groundwater are usually well below the amount that could potentially occur (based on solubility); consequently, concentration of these metals in geologic materials generally limits their concentration in groundwater. According to that Agency [55], copper, hexavalent chromium, nickel and zinc can contaminate shallow groundwater as a result of human activity. The Agency [55] also reported that drinking water standards were exceeded once each for nickel and zinc in wells sampled for the Groundwater Monitoring and Assessment Program Statewise Baseline Network of 954 wells. Oakley and Korte [56] have reported increased nickel concentrations in groundwater and municipal tap water (100-2,500 µg/L) in polluted areas and areas in which natural nickel was mobilized and that certain stainless-steel well materials were identified as the source of increased nickel concentrations in groundwater wells in Arizona, USA, with mean nickel levels of 8-395 µg/L. According to those authors, in some cases, nickel levels were in the range of 1-5 mg/L. The major target organ for nickel induced general toxicity is kidney for oral exposure, and additional organs are the cardiovascular system, the immune system and blood [57, 58].

Although no WHO or EU MCLs in drinking water have been set for other non-essential trace metals for human life such as strontium, cesium, tungsten, thallium and bismuth, these trace elements are considered toxic to humans [59-65]. The highest concentrations recorded in groundwater in Lubumbashi commune were 253.62 µg/L for strontium, 1.431 µg/L for cesium, 35.31 µg/L for tungsten, 0.409 µg/L for thallium and 0.049 µg/L for bismuth; those noted in groundwater in Kamalondo and Kampemba communes were respectively 135.53 µg/L and 290.98 µg/L for strontium, 0.098 µg/L and 0.277 µg/L for cesium, 0.26 µg/L and 0.256 µg/L for tungsten, 0.083 µg/L and 0.107 µg/L for thallium, and 0.012 µg/L and 0.006 µg/L for bismuth.

The trace metal contamination of groundwater in Lubumbashi city might be from natural and anthropogenic origins, mainly from abandoned and ongoing mining and ore processing activities in the city and its neighborhood. It may also be partially from infiltration of surface water and runoff of rainwater through metal contaminated soils to the groundwater during rainy season, as well as from atmospheric fallout during dry season (especially that all the studied hand-dug wells are not well protected and the tools used for withdrawing water from the wells are open and left in the air), as well as from an interconnexion between surface water and groundwater. Muhaya et al. [11] and Muhaya et al. [12] assessed trace metal contamination of water of various rivers in Lubumbashi city and reported high contamination of the water with mean Cd, Pb, Al, Fe and Mn levels exceeding the WHO, US EPA and EU drinking water MCLs of those metals in many rivers. According to the authors, the highest mean concentrations of Cd, Pb, Mn and Fe in water of some rivers in Lubumbashi city were 17.99 µg/L, 472.29 µg/L, 29,714.59 µg/L and 14,258.9 µg/L, respectively. Due to interconnexion between the surface water and groundwater, such high trace metal contamination of riverine water in Lubumbashi city may explain the recorded high trace metal contamination of groundwater in that city.

4. Conclusion

Trace metal contaminations and pH of groundwater in Lubumbashi, Kampemba and Kamalondo communes of Lubumbashi city were investigated in two hundred forty-six water samples collected from twenty-one spade-sunk wells and twelve drilled wells from October 2016 to February 2017. Recorded mean pH values and levels of twenty trace metals of the water samples, including strontium, molybdenum, cadmium, cesium, barium, tungsten, thallium, lead, bismuth, uranium, aluminum, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc and arsenic, were compared to the WHO guidelines for drinking water quality, US EPA drinking water standards and EU (drinking water) regulations. Water of many wells in the three communes of Lubumbashi city being too acidic or alkaline and highly contaminated with cadmium, lead, manganese, iron, nickel, zinc, arsenic and other trace metals, it is unsuitable for human consumption and presents a high risk for the health of people who use it to meet their drinking water needs.

Authors recommend that further research be carried out to compare seasonal variation of metal contamination of the groundwater. They also suggest that the provincial and national governments forbid the consumption of water from very contaminated wells, enhance financing and better management of the Congolese Water Supply Company (REGIDESO) in order to provide all Lubumbashi city inhabitants with safe drinking water, and strictly implement the Congolese Mining Regulations for better environmental and public health protection.

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