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Trace metal contamination of groundwater and human health risk in Katuba and Kenya municipalities of Lubumbashi city, Southeastern Democratic Republic of Congo

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Trace metal contamination of groundwater was assessed in Katuba and Kenya municipalities of Lubumbashi city in 2016 and 2017 to determine whether water was suitable or unsuitable for human consumption. Two hundred and four groundwater samples collected from twenty spade-sunk and four drilled wells in both municipalities were analyzed for their trace metal contents using a sector field inductively coupled plasma mass spectrometry Thermo Element II. Nineteen trace elements including strontium, molybdenum, cadmium, cesium, barium, tungsten, thallium, lead, bismuth, uranium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc and arsenic were recorded at varying concentrations in all samples. Arsenic, cadmium, lead, nickel and copper levels of groundwater exceeded the World Health Organization acceptable limits for drinking water, respectively in 14.44, 8.89, 6.67, 0 and 0%, of samples from Katuba and in 0, 16.67, 25, 16.67 and 16.67% of samples from Kenya municipality. In Katuba, 55.56% of the groundwater samples were acidic (pH 4.7-6.4) in dry season and 61.11% were very alkaline (pH 8.6-11.2) in rainy season. In Kenya municipality, 33.33% of the samples were acidic (pH 5.5-6.2) in rainy season. With such physicochemical and trace metal contamination status of the groundwater in both municipalities, water of many wells is unsuitable for human consumption and presents a health risk to people who use it to meet their drinking water needs.

Key words: Groundwater, pH, trace metals, Lubumbashi city.

INTRODUCTION

In developing countries, such as the Democratic Republic of Congo where access to tap water is limited, many people depend on groundwater and surface water for drinking and domestic use. Groundwater usually contains very low levels of trace metals depending upon the composition and the dissolution of the rock which is in

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interaction with the aquifer (Vetrimurugan et al., 2017). In urban and peri-urban areas, groundwater and surface water may be metal polluted as a result of anthropogenic activities, such as mining and industrial activities, intensive agriculture, waste mismanagement, unplanned urbanization, etc.

Lubumbashi, the capital city of the Upper-Katanga province in the Southeastern Democratic Republic of Congo (DRC) is located in a region having rich ore deposits of certain metals and which tend to have those metals in groundwater due to naturally occurring rock-water interaction. In the city, active and abandoned mines, ore processing plants, tailings, dumps and industrial wastelands are likely to generate trace metal contamination of soils (Kashimbo, 2016; Muhaya et al., 2016), surface water (Muhaya et al., 2017a, b), sediments (Muhaya et al., 2017c, d) and groundwater (Muhaya et al., 2021). 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. Many researchers have reported on adverse effects of trace metals on the health of people in Lubumbashi (Mudekereza et al., 2016, 2021; Mukendi et al., 2018; Obadia et al., 2018; Cham et al., 2020; Malamba-Lez et al., 2021; Ngoy et al., 2021). Most inhabitants of Katuba and Kenya municipalities have no access to tap water. Spade-sunk (hand-dug) and drilled wells are their main source of water for drinking, cooking, bathing, cleaning and watering of plants and domestic animals but no study on the quality of water has been published so far. It was necessary to conduct the current study because of active and abandoned mining and ore processing history of Lubumbashi city, the various reports on adverse health effects of trace metals in the city, the use of private groundwater wells as the main source of drinking water for most inhabitants of Katuba and Kenya municipalities, and no similar study has been reported so far.

The aim of this study was to assess trace metal contamination of groundwater used for drinking in Katuba and Kenya municipalities of Lubumbashi city to determine whether the water was suitable or unsuitable for human consumption and to suggest actions to be taken to reduce the contamination.

MATERIALS AND METHODS

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 (Figure 1). The city of Lubumbashi comprises seven municipalities/communes including Annex, Kamalondo, Kampemba, Lubumbashi and Ruashi, as well as Katuba and Kenya where groundwater samples were collected (Figure 1).

In 2019, the municipalities of Katuba and Kenya encompassed 445,544 inhabitants and 153,966 inhabitants, respectively (Lubumbashi City Report, 2020). Katuba comprises nine administrative quarters/areas including Bana Katanga, Bukama, North Kaponda, South Kaponda, Kisale, Lufira, Musumba, N'sele and Upemba while Kenya includes three quarters, namely Lualaba, Luapula and Luvua.

The total population of Lubumbashi city was estimated to 2,988,200 inhabitants in 2019 (Lubumbashi City Report, 2020). Thus, with its area of 747 km^2 the city had a population density of 4,000 inhabitants/km^2 in 2019.

Sampling campaign

Groundwater samples were collected once a month from seventeen spade-sunk (hand-dug) wells and one drilled well at two sites of each of the nine administrative areas/quarters of Katuba municipality in May and October 2016 (dry season), November 2016, January and March 2017 (rainy season), and from three hand-dug wells and three drilled wells at two sites of each of the three administrative areas of Kenya municipality in December 2016 and February 2017 (rainy season).

At each sampling campaign, two groundwater samples were collected from each well. The depth of hand-dug wells ranged from 2 to 15 m and that of drilled wells ranged from 20 to 60 m.

Analytical methods

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.

Trace metal analysis

Trace element analysis was carried out by Inductively Coupled Plasma-Sector Field Mass Spectrometry (ICP-SF-MS) (Thermo Scientific Element II).

The instrument was equipped with an Elemental Scientific Incorporation (ESI) 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 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.

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

Statistical analysis

The data were statistically processed by R statistical software before being filed by Excel and Excelstat. With the R software, the means and standard deviations of trace element concentrations in the well water of Katuba and Kenya municipalities were calculated. The correlations that would exist between metals and the influence of the seasons on the metal concentrations in the media were verified.

R statistical software is an open source of statistics and a data

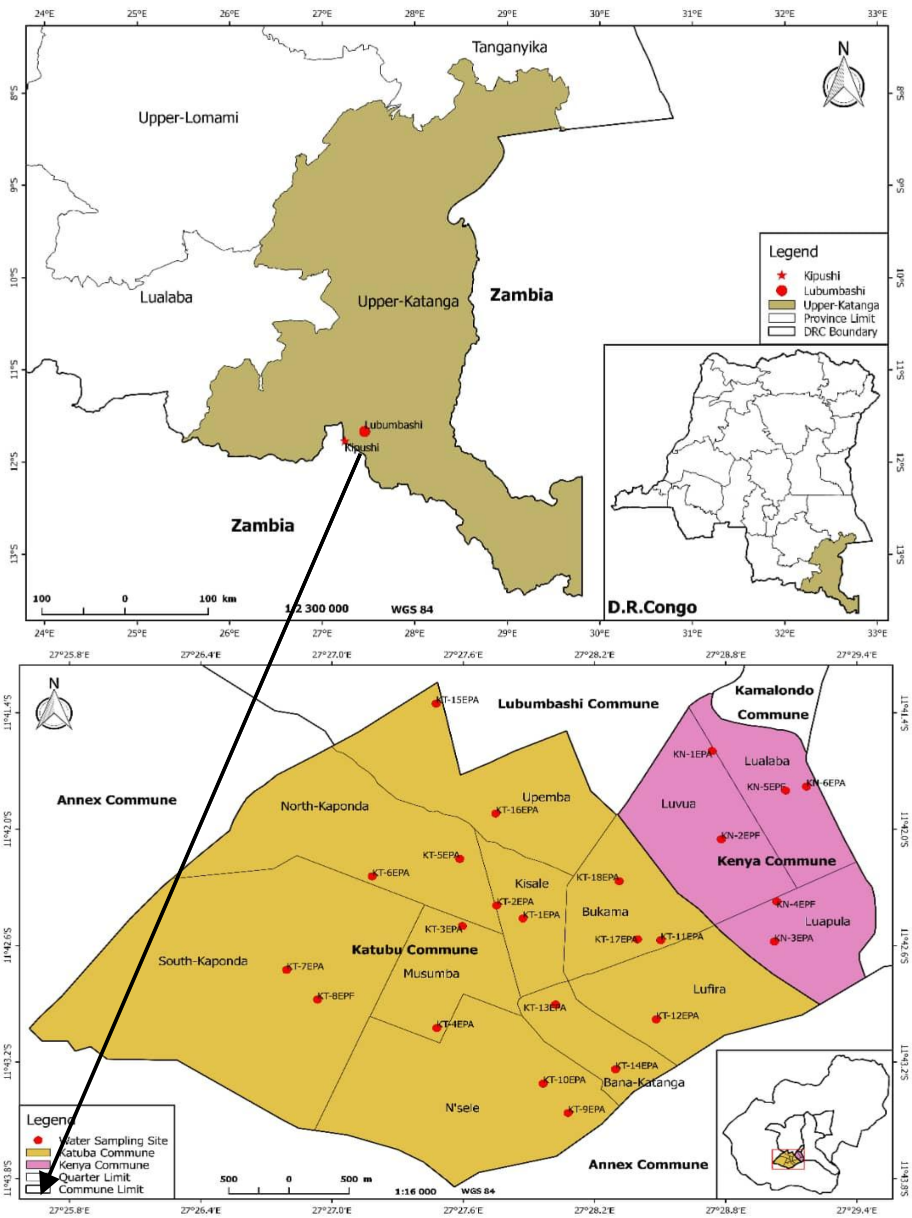

Figure 1. Location of the Upper-Katanga province and Lubumbashi city in the southeastern Democratic Republic of Congo, and the sampling sites in Katuba and Kenya municipalities (communes).

science software supported by the R Foundation for Statistical Computing. It is part of the list of GNU packages. GNU is a free software distributed under the terms of the GNU General Public License and available under GNU/Linux, FreeBSD, NetBSD, OpenBSD, MacOS X and Microsoft Windows. For this study, the version 3.0 released in April 2013 was used.

RESULTS AND DISCUSSION

Trace metal levels and pH values of groundwater recorded in Katuba and Kenya municipalities of Lubumbashi city found in this study are presented in Tables 1 and 2 and Figures 2 to 4. Nineteen trace elements including strontium (Sr), molybdenum (Mo), cadmium (Cd), cesium (Cs), barium (Ba), tungsten (W), thallium (Tl), lead (Pb), bismuth (Bi), uranium (U), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn) and arsenic (As) were recorded at varying concentrations in all groundwater samples.

From the data shown in Table 1, it was noted that during the rainy season in Katuba municipality, the

Table 1. Groundwater pH values and trace metal levels (µg/L) in Katuba municipality in May and October 2016 (dry season) and in November 2016, January and March 2017 (rainy season), and Kenya municipality in December 2016 and February 2017 (rainy season).

Sampling period	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)
Dry s.	KT-1EPA	Range	6.4-7	140.177-188.278	0.025-0.053	0.091-0.053	0.041-0.069	288.2-212.085	0.05-0.099	0.024-0.029	0.706-1.105	0.005-0.023	0.081-0.112
Dry s.	KT-1EPA	Mean	6.7	164.228	0.039	0.199	0.055	250.143	0.075	0.027	0.906	0.014	0.097
Dry s.	KT-1EPA	SD	0.4	34.013	0.02	0.153	0.02	53.821	0.035	0.004	0.282	0.013	0.022
Dry s.	KT-2EPA	Range	6.3-6.8	237.247-245.294	0.021-0.047	0.068-1.33	0.147-0.183	162.516-174.182	0.057-0.105	0.082-0.099	0.578-1.54	0.004-0.011	0.095-0.165
Dry s.	KT-2EPA	Mean	6.5	241.271	0.034	0.699	0.165	168.349	0.081	0.091	1.059	0.008	0.13
Dry s.	KT-2EPA	SD	0.4	5.69	0.018	0.892	0.025	8.249	0.034	0.012	0.68	0.005	0.049
Dry s.	KT-3EPA	Range	6.3-6.8	159.807-216.165	0.019-0.067	0.054-0.487	0.034-0.078	178.544-233.486	0.079-0.107	0.013-0.028	0.398-1.213	0.003-0.018	0.074-0.154
Dry s.	KT-3EPA	Mean	6.5	187.986	0.043	0.271	0.056	206.015	0.093	0.021	0.806	0.011	0.114
Dry s.	KT-3EPA	SD	0.4	39.851	0.034	0.306	0.031	38.85	0.02	0.011	0.576	0.011	0.057
Dry s.	KT-4EPA	Range	6.7-6.8	375.77-386.027	0.128-0.414	0.052-0.402	0.015-0.048	169.932-206.661	0.073-0.102	0.027-0.037	0.263-1.219	0.002-0.012	0.371-0.566
Dry s.	KT-4EPA	Mean	6.8	380.899	0.271	0.227	0.032	188.297	0.088	0.032	0.741	0.007	0.469
Dry s.	KT-4EPA	SD	0.1	7.253	0.202	0.247	0.023	25.971	0.021	0.007	0.676	0.007	0.138
Dry s.	KT-5EPA	Range	6.2-6.8	61.162-61.647	0.047-0.047	0.044-0.815	0.034-0.063	96.147-104.504	0.036-0.067	0.015-0.016	0.68-1.362	0.001-0.019	0.065-0.094
Dry s.	KT-5EPA	Mean	6.5	61.404	0.047	0.43	0.049	100.326	0.052	0.016	1.021	0.01	0.08
Dry s.	KT-5EPA	SD	0.4	0.343	0	0.545	0,021	5,909	0.022	0.001	0.482	0.013	0.021
Dry s.	KT-6EPA	Range	4.7-6.3	71.002-74.5	0.025-0.051	0.21-1.115	0.261-1.311	237.323-483.548	0.103-0.568	0.159-0.193	2.494-8.763	0.02-0.067	0.147-0.986
Dry s.	KT-6EPA	Mean	5.5	72.751	0.038	0.663	0.786	360.436	0.336	0.176	5.629	0.044	0.567
Dry s.	KT-6EPA	SD	1.1	2.473	0.018	0.64	0.742	174.107	0.329	0.024	4.433	0.033	0.593
Dry s.	KT-7EPA	Range	5.1-5.9	33.277-69.359	0.016-0.083	0.174-0.899	0.023-0.153	22.157-38.394	0.043-0.155	0.017-0.023	0.954-1.632	0.002-0.096	0.045-0.207
Dry s.	KT-7EPA	Mean	5.5	51.318	0.050	0.537	0.088	30.276	0.099	0.02	1.293	0.049	0.126
Dry s.	KT-7EPA	SD	0.6	25.514	0.047	0.513	0.092	11.481	0.079	0.004	0.479	0.066	0.115
Dry s.	KT-8EPF	Range	6.8-7.8	66.312-69.423	0.126-0.182	0.348-0.704	0.019-0.042	15.909-24.913	0.054-0.123	0.005-0.007	0.549-2.133	0.002-0.03	0.099-0.131
Dry s.	KT-8EPF	Mean	7.3	67.867	0.154	0.526	0.031	20.411	0.089	0.006	1.341	0.016	0.115
Dry s.	KT-8EPF	SD	0.7	2.199	0.039	0.252	0.016	6.367	0.049	0.001	1.12	0.02	0.023
Dry s.	KT-9EPA	Range	6.8-7.5	178.282-186.186	0.031-0.039	0.067-0.264	0.013-0.118	55.518-76.119	0.045-0.152	0.005-0.014	2.094-9.234	0.001-0.013	0.641-0.719
Dry s.	KT-9EPA	Mean	7.2	182.234	0.035	0.166	0.066	65.819	0.099	0.01	5.664	0.007	0.68
Dry s.	KT-9EPA	SD	0.5	5.589	0.006	0.139	0.074	14.567	0.076	0.006	5.049	0.008	0.055
Dry s.	KT-10EPA	Range	6-6	19.773-24.772	0.019-0.076	0.312-0.380	0.084-0.17	80.847-144.611	0.034-0.122	0.021-0.027	0.522-2.34	0.001-0.029	0.098-0.176
Dry s.	KT-10EPA	Mean	6	22.273	0.048	0.346	0.127	112.729	0.078	0.024	1.431	0.015	0.137
Dry s.	KT-10EPA	SD	0	3.535	0.04	0.048	0.061	45.088	0.062	0.004	1.286	0.02	0.055
Dry s.	KT-11EPA	Range	4.9-5.6	123.970-487.60	0.16-0.38	6.98-7.10	0.072-0.079	91.25-133.789	0.058-0.084	0.049-0.083	0.413-1.331	0.01-0.012	1.06-1.10
Dry s.	KT-11EPA	Mean	5.3	305.785	0.27	7.040	0.076	112.52	0.071	0.066	0.872	0.011	1.080
Dry s.	KT-11EPA	SD	0.5	257.125	0.156	0.085	0.005	30.08	0.018	0.024	0.649	0.001	0.028

Table 1. Contd.

Dry s.	KT-12EPA	Range	6.7-6.9	159.353-209.894	0.023-0.076	0.075-0.227	0.046-0.148	137.937-181.43	0.05-0.092	0.019-0.055	0.557-1.967	0.001-0.017	0.882-0.974
Dry s.	KT-12EPA	Mean	6.8	184.624	0.05	0.151	0.097	159.684	0.071	0.037	1.262	0.009	0.928
Dry s.	KT-12EPA	SD	0.1	35.738	0.037	0.107	0.072	30.754	0.03	0.025	0.997	0.011	0.065
Dry s.	KT-13EPA	Range	5.1-6	56.531-65.661	0.024-0.035	0.083-0.233	0.049-0.302	80.436-157.765	0.313-0.632	0.085-0.137	1.032-2.224	0.024-0.005	0.911-1.321
Dry s.	KT-13EPA	Mean	5.6	61.096	0.03	0.158	0.176	119.101	0.473	0.111	1.628	0.015	1.116
Dry s.	KT-13EPA	SD	0.6	6.456	0.008	0.106	0.179	54.68	0.226	0.037	0.843	0.018	0.29
Dry s.	KT-14EPA	Range	5.6-5.9	58.906-133.545	0.021-0.031	0.273-0.402	0.03-0.122	212.171-365.036	0.119-0.13	0.02-0.02	0.486-1.559	0.004-0.009	0.082-0.11
Dry s.	KT-14EPA	Mean	5.8	96.226	0.026	0.338	0.076	288.604	0.125	0.02	1.023	0.007	0.096
Dry s.	KT-14EPA	SD	0.2	52.778	0.007	0.091	0.065	108.092	0.008	0	0.759	0.004	0.02
Dry s.	KT-15EPA	Range	5.8-5.9	216.375-247.752	0.029-0.115	0.593-0.677	0.063-0.156	100.751-130.111	0.237-0.355	0.055-0.061	5.156-6.164	0.02-0.016	0.103-0.155
Dry s.	KT-15EPA	Mean	5.9	232.064	0.072	0.635	0.11	115.431	0.296	0.058	5.66	0.018	0.129
Dry s.	KT-15EPA	SD	0.1	22.187	0.061	0.059	0.066	20.761	0.083	0.004	0.713	0.003	0.037
Dry s.	KT-16EPA	Range	6.5-6.7	110.043-114.18	0.027-0.138	0.379-0.634	0.04-0.117	156.264-179.427	0.056-0.246	0.032-0.037	3.722-6.802	0.01-0.023	0.253-0.34
Dry s.	KT-16EPA	Mean	6.6	112.112	0.083	0.507	0.079	167.846	0.151	0.035	5.262	0.017	0.297
Dry s.	KT-16EPA	SD	0.1	2.925	0.078	0.18	0.054	16.379	0.134	0.004	2.178	0.009	0.062
Dry s.	KT-17EPA	Range	6.3-6.7	174.838-259.652	0.036-0.038	0.57-1.467	0.018-0.134	71.194-95.971	0.049-0.115	0.024-0.035	1.501-6.307	0.002-0.013	0.17-0.327
Dry s.	KT-17EPA	Mean	6.5	217.245	0.037	1.019	0.076	83.583	0.082	0.03	3.904	0.008	0.249
Dry s.	KT-17EPA	SD	0.3	59.973	0.001	0.634	0.082	17.52	0.047	0.008	3.398	0.008	0.111
Dry s.	KT-18EPA	Range	6.7-6.8	288.844-390.794	0.173-0.945	1.231-4.47	0.355-0.625	55.288-152.252	0.134-0.26	0.104-0.113	9.016-14.253	0.01-0.075	0.384-0.517
Dry s.	KT-18EPA	Mean	6.8	339.819	0.559	2.851	0.49	103.77	0.197	0.109	11.635	0.043	0.451
Dry s.	KT-18EPA	SD	0	72.09	0.546	2.29	0.191	68.564	0.089	0.006	3.703	0.046	0.094
Rainy s.	KT-1EPA	Range	8.1-10.4	116.944-180.383	0.034-0.16	0.031-0.286	0,039-0.06	137.985-243.05	0.092-0.159	0.018-0.025	0.063-1.415	0.002-0.011	0.043-0.303
Rainy s.	KT-1EPA	Mean	9.2	157.732	0.084	0.131	0.047	195.887	0.133	0.022	0.913	0.005	0.153
Rainy s.	KT-1EPA	SD	1.1	35.396	0.067	0.136	0.012	53.349	0.036	0.004	0.74	0.005	0.135
Rainy s.	KT-2EPA	Range	8.1-10.3	193.263-241.318	0.017-0.42	0.194-0.794	0.023-0.161	52.062-87.651	0.083-0.3	0.043-0.096	0.016-1.67	0.001-0.014	0.117-0.339
Rainy s.	KT-2EPA	Mean	9.2	209.857	0.162	0.53	0.082	75.438	0.217	0.062	0.968	0.006	0.196
Rainy s.	KT-2EPA	SD	1.1	27.260	0.224	0.306	0.071	20.251	0.117	0.03	0.855	0.007	0.124
Rainy s.	KT-3EPA	Range	8.4-10.7	155.676-173.887	0.051-0.117	0.093-0.385	0.034-0.063	73.06-183.801	0.087-0.249	0.022-0.048	1.589-6.824	0.002-0.035	0.089-0.179
Rainy s.	KT-3EPA	Mean	9.7	163.878	0.085	0.275	0.049	111.113	0.169	0.039	4.493	0.014	0.147
Rainy s.	KT-3EPA	SD	1.2	9.239	0.033	0.159	0.015	62.973	0.081	0.014	2.664	0.019	0.051
Rainy s.	KT-4EPA	Range	8.3-10.7	331.77-423.209	0.189-3.758	0.06-0.356	0.011-0.269	69.122-227.428	0.335-0.918	0.02-0.139	0.006-1.844	0.002-0.011	0.446-1.352
Rainy s.	KT-4EPA	Mean	9.6	391.701	1.422	0.238	0.099	167.311	0.539	0.063	0.999	0.005	0.841
Rainy s.	KT-4EPA	SD	1.2	51.925	2.024	0.157	0.147	85.746	0.328	0.066	0.928	0.005	0.464
Dry s.	KT-12EPA	Range	6.7-6.9	159.353-209.894	0.023-0.076	0.075-0.227	0.046-0.148	137.937-181.43	0.05-0.092	0.019-0.055	0.557-1.967	0.001-0.017	0.882-0.974
Dry s.	KT-12EPA	Mean	6.8	184.624	0.05	0.151	0.097	159.684	0.071	0.037	1.262	0.009	0.928
Dry s.	KT-12EPA	SD	0.1	35.738	0.037	0.107	0.072	30.754	0.03	0.025	0.997	0.011	0.065

Table 1. Contd.

Dry s.	KT-13EPA	Range	5.1-6	56.531-65.661	0.024-0.035	0.083-0.233	0.049-0.302	80.436-157.765	0.313-0.632	0.085-0.137	1.032-2.224	0.024-0.005	0.911-1.321
Dry s.	KT-13EPA	Mean	5.6	61.096	0.03	0.158	0.176	119.101	0.473	0.111	1.628	0.015	1.116
Dry s.	KT-13EPA	SD	0.6	6.456	0.008	0.106	0.179	54.68	0.226	0.037	0.843	0.018	0.29
Dry s.	KT-14EPA	Range	5.6-5.9	58.906-133.545	0.021-0.031	0.273-0.402	0.03-0.122	212.171-365.036	0.119-0.13	0.02-0.02	0.486-1.559	0.004-0.009	0.082-0.11
Dry s.	KT-14EPA	Mean	5.8	96.226	0.026	0.338	0.076	288.604	0.125	0.02	1.023	0.007	0.096
Dry s.	KT-14EPA	SD	0.2	52.778	0.007	0.091	0.065	108.092	0.008	0	0.759	0.004	0.02
Dry s.	KT-15EPA	Range	5.8-5.9	216.375-247.752	0.029-0.115	0.593-0.677	0.063-0.156	100.751-130.111	0.237-0.355	0.055-0.061	5.156-6.164	0.02-0.016	0.103-0.155
Dry s.	KT-15EPA	Mean	5.9	232.064	0.072	0.635	0.11	115.431	0.296	0.058	5.66	0.018	0.129
Dry s.	KT-15EPA	SD	0.1	22.187	0.061	0.059	0.066	20.761	0.083	0.004	0.713	0.003	0.037
Dry s.	KT-16EPA	Range	6.5-6.7	110.043-114.18	0.027-0.138	0.379-0.634	0.04-0.117	156.264-179.427	0.056-0.246	0.032-0.037	3.722-6.802	0.01-0.023	0.253-0.34
Dry s.	KT-16EPA	Mean	6.6	112.112	0.083	0.507	0.079	167.846	0.151	0.035	5.262	0.017	0.297
Dry s.	KT-16EPA	SD	0.1	2.925	0.078	0.18	0.054	16.379	0.134	0.004	2.178	0.009	0.062
Dry s.	KT-17EPA	Range	6.3-6.7	174.838-259.652	0.036-0.038	0.57-1.467	0.018-0.134	71.194-95.971	0.049-0.115	0.024-0.035	1.501-6.307	0.002-0.013	0.17-0.327
Dry s.	KT-17EPA	Mean	6.5	217.245	0.037	1.019	0.076	83.583	0.082	0.03	3.904	0.008	0.249
Dry s.	KT-17EPA	SD	0.3	59.973	0.001	0.634	0.082	17.52	0.047	0.008	3.398	0.008	0.111
Dry s.	KT-18EPA	Range	6.7-6.8	288.844-390.794	0.173-0.945	1.231-4.47	0.355-0.625	55.288-152.252	0.134-0.26	0.104-0.113	9.016-14.253	0.01-0.075	0.384-0.517
Dry s.	KT-18EPA	Mean	6.8	339.819	0.559	2.851	0.49	103.77	0.197	0.109	11.635	0.043	0.451
Dry s.	KT-18EPA	SD	0	72.09	0.546	2.29	0.191	68.564	0.089	0.006	3.703	0.046	0.094
Rainy s.	KT-1EPA	Range	8.1-10.4	116.944-180.383	0.034-0.16	0.031-0.286	0,039-0.06	137.985-243.05	0.092-0.159	0.018-0.025	0.063-1.415	0.002-0.011	0.043-0.303
Rainy s.	KT-1EPA	Mean	9.2	157.732	0.084	0.131	0.047	195.887	0.133	0.022	0.913	0.005	0.153
Rainy s.	KT-1EPA	SD	1.1	35.396	0.067	0.136	0.012	53.349	0.036	0.004	0.74	0.005	0.135
Rainy s.	KT-2EPA	Range	8.1-10.3	193.263-241.318	0.017-0.42	0.194-0.794	0.023-0.161	52.062-87.651	0.083-0.3	0.043-0.096	0.016-1.67	0.001-0.014	0.117-0.339
Rainy s.	KT-2EPA	Mean	9.2	209.857	0.162	0.53	0.082	75.438	0.217	0.062	0.968	0.006	0.196
Rainy s.	KT-2EPA	SD	1.1	27.260	0.224	0.306	0.071	20.251	0.117	0.03	0.855	0.007	0.124
Rainy s.	KT-3EPA	Range	8.4-10.7	155.676-173.887	0.051-0.117	0.093-0.385	0.034-0.063	73.06-183.801	0.087-0.249	0.022-0.048	1.589-6.824	0.002-0.035	0.089-0.179
Rainy s.	KT-3EPA	Mean	9.7	163.878	0.085	0.275	0.049	111.113	0.169	0.039	4.493	0.014	0.147
Rainy s.	KT-3EPA	SD	1.2	9.239	0.033	0.159	0.015	62.973	0.081	0.014	2.664	0.019	0.051
Rainy s.	KT-4EPA	Range	8.3-10.7	331.77-423.209	0.189-3.758	0.06-0.356	0.011-0.269	69.122-227.428	0.335-0.918	0.02-0.139	0.006-1.844	0.002-0.011	0.446-1.352
Rainy s.	KT-4EPA	Mean	9.6	391.701	1.422	0.238	0.099	167.311	0.539	0.063	0.999	0.005	0.841
Rainy s.	KT-4EPA	SD	1.2	51.925	2.024	0.157	0.147	85.746	0.328	0.066	0.928	0.005	0.464
Rainy s.	KT-5EPA	Range	8.6-11.2	70.898-75.056	0.048-0.167	0.064-0.296	0.032-0.036	114.25-128.315	0.068-0.164	0.013-0.04	0.007-1.624	0.001-0.008	0.056-1.435
Rainy s.	KT-5EPA	Mean	10.1	73.115	0.095	0.148	0.035	122.409	0.11	0.025	0.795	0.004	0.54
Rainy s.	KT-5EPA	SD	1.3	2.093	0.064	0.128	0.002	7.298	0.049	0.014	0.809	0.004	0.776
Rainy s.	KT-6EPA	Range	6.9-8.9	46.309-95.162	0.035-0.043	0.305-0.607	0.069-0.207	143.095-257.21	0.098-0.135	0.016-0.079	1.588-3.15	0.005-0.015	0.079-0.162
Rainy s.	KT-6EPA	Mean	7.8	65.346	0.038	0.437	0.121	185.605	0.112	0.044	2.516	0.009	0.113
Rainy s.	KT-6EPA	SD	1	26.150	0.004	0.155	0.075	62.373	0.02	0.032	0.822	0.005	0.044

Table 1. Contd.

Rainy s.	KT-7EPA	Range	7.3-9.8	52.68-74.03	0.015-0.021	0.143-1.237	0.023-0.203	17.86-43.143	0.082-0.277	0.010-0.034	0.981-14.161	0-0.026	0.034-0.271
Rainy s.	KT-7EPA	Mean	8.7	66.71	0.018	0.633	0.103	26.482	0.153	0.021	5.938	0.009	0.128
Rainy s.	KT-7EPA	SD	1.3	12.154	0.003	0.556	0.092	14.432	0.108	0.012	7.172	0.015	0.126
Rainy s.	KT-8EPF	Range	9-11	165.707-187.83	0.117-0.416	0.12-1.013	0.006-0.024	13.1-83.512	0.057-0.101	0.003-0.005	0.5-4.929	0.001-0.004	0.159-0.999
Rainy s.	KT-8EPF	Mean	10	176.591	0.222	0.471	0.015	53.926	0.089	0.004	2.682	0.002	0.583
Rainy s.	KT-8EPF	SD	1	11.066	0.168	0.476	0.009	36.541	0.011	0.001	2.215	0.002	0.420
Rainy s.	KT-9EPA	Range	8.9-11	163.159-200.204	0.092-0.151	0.046-0.506	0.008-0.014	52.91-65.519	0.019-0.057	0.004-0.005	0.862-1.535	0.002-0.01	0.759-1.106
Rainy s.	KT-9EPA	Mean	10	183.377	0.127	0.212	0.012	59.231	0.038	0.005	1.171	0.007	0.884
Rainy s.	KT-9EPA	SD	1.1	18.754	0.031	0.256	0.003	6.305	0.019	0.001	0.34	0.004	0.193
Rainy s.	KT-10EPA	Range	7.1-11	55.444-66.412	0.024-0.066	0.367-0.490	0.052-0.101	112.142-509.052	0.095-0.156	0.028-0.099	0.58-1.41	0-0.006	0.066-0.162
Rainy s.	KT-10EPA	Mean	8.7	62.215	0.038	0.438	0.082	370.696	0.134	0.062	0.987	0.004	0.118
Rainy s.	KT-10EPA	SD	2.0	5.920	0.024	0.064	0.027	224.098	0.034	0.036	0.415	0.003	0.048
Rainy s.	KT-11EPA	Range	7.4-10.7	576.046-672.2	0.47-0.586	21.581-37.78	0.234-0.336	71.269-77.441	0.734-1.432	0.161-0.303	3.856-5.788	0.011-0.063	1.895-2.081
Rainy s.	KT-11EPA	Mean	9.1	631.495	0.531	29.416	0.288	74.932	1	0.246	4.874	0.032	1.986
Rainy s.	KT-11EPA	SD	1.6	49.744	0.058	8.112	0.051	3.244	0.377	0.075	0.97	0.027	0.093
Rainy s.	KT-12EPA	Range	8.5-11	113.831-137.234	0.025-0.17	0.098-0.843	0.034-0.046	134.169-177.814	0.052-0.135	0.01-0.019	0.947-6.059	0.002-0.008	0.278-1.021
Rainy s.	KT-12EPA	Mean	9.9	128.023	0.077	0.456	0.04	148.997	0.085	0.015	3.15	0.005	0.737
Rainy s.	KT-12EPA	SD	1.3	12.471	0.081	0.373	0.006	24.96	0.044	0.005	2.628	0.003	0.401
Rainy s.	KT-13EPA	Range	6.8-8.8	43.998-68.175	0.038-0.325	0.13-0.892	0.14-0.166	157.876-185.018	0.572-0.666	0.128-0.141	1.221-2.813	0.003-0.019	1.239-1.297
Rainy s.	KT-13EPA	Mean	7.8	58.013	0.188	0.587	0.155	170.556	0.629	0.133	1.984	0.009	1.259
Rainy s.	KT-13EPA	SD	1	12.54	0.144	0.403	0.013	13.659	0.050	0.007	0.798	0.009	0.033
Rainy s.	KT-14EPA	Range	8.5-10	42.644-95.628	0.04-0.084	0.132-0.482	0.039-0.056	255.44-307.843	0.101-0.124	0.016-0.041	1.536-3.21	0.002-0.011	0.089-0.14
Rainy s.	KT-14EPA	Mean	9.1	77.424	0.056	0.281	0.048	287.531	0.113	0.024	2.244	0.006	0.118
Rainy s.	KT-14EPA	SD	0.8	30.132	0.025	0.181	0.009	28.117	0.012	0.014	0.866	0.005	0.026
Rainy s.	KT-15EPA	Range	7.4-10.4	167.134-194.989	0.037-0.071	0.794-1.031	0.063-0.082	81.688-101.428	0.117-0.3	0.041-0.05	16.553-24.769	0.003-0.014	0.088-0.134
Rainy s.	KT-15EPA	Mean	8.9	183.582	0.052	0.908	0.071	93.589	0.203	0.046	19.752	0.01	0.113
Rainy s.	KT-15EPA	SD	1.5	14.596	0.017	0.119	0.01	10.478	0.092	0.005	4.399	0.006	0.023
Rainy s.	KT-16EPA	Range	8.2-10.6	107.217-113.831	0.035-0.053	0.422-0.666	0.041-0.051	101.428-177.814	0.063-0.074	0.032-0.035	5.233-11.992	0.004-0.008	0.278-0.355
Rainy s.	KT-16EPA	Mean	9.4	110.691	0.044	0.505	0.046	171.839	0.069	0.034	7.761	0.006	0.316
Rainy s.	KT-16EPA	SD	1.2	3.32	0.009	0.139	0.005	6.57	0.006	0.002	3.687	0.002	0.039
Rainy s.	KT-17EPA	Range	8.2-9.8	115.557-162.76	0.043-0.191	0.299-0.68	0.014-0.108	91.909-171.428	0.076-0.122	0.011-0.028	2.69-8.9	0.001-0.014	0.216-0.362
Rainy s.	KT-17EPA	Mean	9.2	131.356	0.101	0.531	0.049	117.863	0.104	0.022	6.342	0.006	0.3
Rainy s.	KT-17EPA	SD	0.9	27.197	0.079	0.204	0.052	46.396	0.024	0.01	3.246	0.007	0.075
Rainy s.	KT-18EPA	Range	8.5-11	370.293-447.029	1.516-2.143	3.414-16.451	0.37-0.51	86.937-96.145	0.132-0.287	0.092-0.217	4.274-4.845	0.005-0.02	0.976-1.475
Rainy s.	KT-18EPA	Mean	9.9	408.075	1.815	11.825	0.433	91.503	0.206	0.139	4.467	0.013	1.146
Rainy s.	KT-18EPA	SD	1.3	38.381	0.315	7.296	0.071	4.604	0.078	0.068	0.328	0.008	0.285

Table 1. Contd.

Rainy s.	KN-1EPA	Range	6.8-7.6	216.183-312.915	0.123-0.264	0.16-0.283	0.032-0.039	82.82-130.943	0.063-0.097	0.022-0.029	1.204-2.006	0.005-0.009	0.095-4.473
Rainy s.	KN-1EPA	Mean	7.2	264.549	0.193	0.221	0.036	106.881	0.08	0.026	1.605	0.007	2.284
Rainy s.	KN-1EPA	SD	0.6	68,4	0.1	0.087	0.005	34.028	0.024	0.005	0.567	0.003	3.096
Rainy s.	KN-2EPF	Range	8.1-8.4	85.238-86.997	0.18-0.476	0.564-1.225	0.022-0.037	14.099-47.277	0.175-0.82	0.006-0.031	3.991-4.088	0.01-0.02	0.282-0.368
Rainy s.	KN-2EPF	Mean	8.2	86.117	0.328	0.894	0.029	30.688	0.498	0.018	4.04	0.015	0.325
Rainy s.	KN-2EPF	SD	0.2	1.243	0.209	0.467	0.011	23.461	0.456	0.018	0.069	0.007	0.06
Rainy s.	KN-3EPA	Range	7.2-7.9	18.079-19.349	0.019-0.02	0.058-0.112	0.02-0.044	88.09-98.038	0.045-0.086	0.016-0.065	11.97-15.19	0.002-0.002	0.064-0.102
Rainy s.	KN-3EPA	Mean	7.5	18.714	0.02	0.085	0.032	93.064	0.065	0.04	13.58	0.002	0.083
Rainy s.	KN-3EPA	SD	0.5	0.898	0.001	0.039	0.017	7.034	0.029	0.034	2.277	0	0.027
Rainy s.	KN-4EPF	Range	5.5-5.8	4.604-5.004	0.023-5.004	0.056-0.127	0.022-0.023	65.417-69.077	0.037-0.098	0.017-0.017	1.459-2.839	0.025-0.043	0.079-0.13
Rainy s.	KN-4EPF	Mean	5.6	4.804	0.028	0.091	0.023	67.247	0.067	0.017	2.149	0.034	0.105
Rainy s.	KN-4EPF	SD	0.2	0.282	0.007	0.05	0.001	2.588	0.043	0	0.976	0.013	0.036
Rainy s.	KN-5EPF	Range	8-8	123.325-125.518	0.181-0.366	0.099-0.852	0.058-0.162	106.27-167.746	0.058-1.769	0.038-0.052	1.194-1.731	0.001-0.009	0.302-0.456
Rainy s.	KN-5EPF	Mean	8	124.422	0.273	0.475	0.11	137.008	0.913	0.045	1.463	0.005	0.379
Rainy s.	KN-5EPF	SD	0	1.551	0.131	0.532	0.074	43.470	1.21	0.01	0.38	0.005	0.109
Rainy s.	KN-6EPA	Range	5.9-6.2	83.244-91.345	0.04-0.053	374.753-384.405	0.087-0.123	44.364-73.073	1.496-2.538	0.038-0.039	5.955-14.481	0.01-0.02	7.634-8.839
Rainy s.	KN-6EPA	Mean	6	87.294	0.047	379.579	0.105	58.719	2.017	0.038	10.218	0.015	8.237
Rainy s.	KN-6EPA	SD	0.2	5.728	0.009	6.825	0.025	20.301	0.736	0.001	6.029	0.007	0.852
Sampling period	**Sampling site**	**Data type**	**pH value**	**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)**	
Dry s.	KT-1EPA	Range	6.4-7	0.327-0.608	0.211-0.475	11.895-14.735	31.823-166.126	0.669-1.717	0.645-1.158	7.793-11.123	15.425-16.875	0.157-0.18	
Dry s.	KT-1EPA	Mean	6.7	0.468	0.343	13.315	98.975	1.193	0.902	9.458	16.15	0.169	
Dry s.	KT-1EPA	SD	0.4	0.199	0.187	2.008	94.967	0.741	0.363	2.355	1.025	0.016	
Dry s.	KT-2EPA	Range	6.3-6.8	0.163-0.653	0.162-0.622	7.32-51.465	21.317-314.077	1.129-2.341	0.745-1.459	3.932-11.975	12.539-23.394	0.096-0.227	
Dry s.	KT-2EPA	Mean	6.5	0.408	0.392	29.393	167.697	1.735	1.102	7.954	17.967	0.162	
Dry s.	KT-2EPA	SD	0.4	0.346	0.325	31.215	207.013	0.857	0.505	5.687	7.676	0.093	
Dry s.	KT-3EPA	Range	6.3-6.8	0.252-0.653	0.146-0.446	39.564-51.42	212.648-300.658	0.741-1.583	0.877-1.012	4.288-7.808	8.114-11.155	0.372-0.625	
Dry s.	KT-3EPA	Mean	6.5	0.444	0.296	45.492	256.653	1.162	0.945	6.048	9.635	0.499	
Dry s.	KT-3EPA	SD	0.4	0.272	0.212	8.383	62.232	0.595	0.095	2.489	2.15	0.179	
Dry s.	KT-4EPA	Range	6.7-6.8	0.713-0.994	0.125-0.566	25.324-82.246	5.735-221.27	0.487-1.679	1.076-4.655	6.137-9.294	9.233-26.481	0.838-2.257	
Dry s.	KT-4EPA	Mean	6.8	0.854	0.346	53.785	113.503	1.083	2.866	7.716	17.857	1.548	
Dry s.	KT-4EPA	SD	0.1	0.199	0.312	40.250	152.406	0.843	2.531	2.232	12.196	1.003	
Dry s.	KT-5EPA	Range	6.2-6.8	0.391-0.742	0.146-0.708	5.621-34.787	58.167-375.777	0.641-2.067	0.518-1.33	6.823-12.521	11.448-23.104	0.14-3.368	
Dry s.	KT-5EPA	Mean	6.5	0.567	0.427	20.204	216.972	1.354	0.924	9.672	17.276	1.754	
Dry s.	KT-5EPA	SD	0.4	0.248	0.397	20.623	224.584	1.008	0.574	4.029	8.242	2.283	
Dry s.	KT-6EPA	Range	4.7-6.3	0.99-1,869	0.128-0.92	169.96-332.686	153-133.927	14.81-63.506	12.42-16.048	20.804-261.66	51.048-420.851	9.4-11.33	
Dry s.	KT-6EPA	Mean	5.5	1.430	0.524	251.321	143.98	39.158	14.234	141.232	235.95	10.365	

Table 1. Contd.

Dry s.	KT-6EPA	SD	1.1	0.622	0.56	115.067	13.487	34.433	2.565	170.311	261.49	1.365
Dry s.	KT-7EPA	Range	5.1-5.9	0.117-1.396	0.713-1.202	64.865-103.248	308.1-481.3	5.886-12.308	5.403-10.78	10.981-17.783	39.947-56.881	1.396-6.006
Dry s.	KT-7EPA	Mean	5.5	0.757	0.958	84.057	394.70	9.097	8.092	14.382	48.414	3.701
Dry s.	KT-7EPA	SD	0.6	0.904	0.346	27.141	122.471	4.541	3.802	4.81	11.974	3.26
Dry s.	KT-8EPF	Range	6.8-7.8	1.331-1.883	0.365-0.718	13.947-43.658	236.504-461.938	0.533-2.123	1.414-2.891	13.893-18.013	36.194-99.313	6.28-7.16
Dry s.	KT-8EPF	Mean	7.3	1.607	0.542	28.803	349.221	1.328	2.153	15.953	67.754	6.72
Dry s.	KT-8EPF	SD	0.7	0.39	0.25	21.009	159.406	1.124	1.044	2.913	44.632	0.622
Dry s.	KT-9EPA	Range	6.8-7.5	0.381-9.735	1.55-5.19	95.389-296.597	568.93-351.957	0.972-7.955	0.345-2.414	5.637-25.01	8.797-29.693	3.176-10.895
Dry s.	KT-9EPA	Mean	7.2	5.058	3.37	195.993	460.444	4.464	1.38	15.324	19.245	7.036
Dry s.	KT-9EPA	SD	0.5	6.614	3.56	142.276	153.423	4.938	1.463	13.699	14.776	5.458
Dry s.	KT-10EPA	Range	6-6	0.2-0.59	0.146-1.026	1344.49-1575.42	1767.42-4826.95	6.284-31.718	2.883-5.342	4.406-22.386	46.045-80.928	2.182-2.907
Dry s.	KT-10EPA	Mean	6	0.395	0.586	1459.96	3297.18	19.001	4.113	13.396	63.487	2.545
Dry s.	KT-10EPA	SD	0	0.276	0.622	163.292	2163.42	17.985	1.739	12.714	24.666	0.513
Dry s.	KT-11EPA	Range	4.9-5.6	0.83-4.474	0.772-1.24	13.729-15.413	1581.64-1653.45	361.4-571.3	1.559-2.784	36.93-131.76	128.67-779.05	1.28-3.994
Dry s.	KT-11EPA	Mean	5.3	2.785	1.006	14.571	1617.55	466.35	2.172	8.435	45.386	2.061
Dry s.	KT-11EPA	SD	0.5	2.765	0.331	1.191	50.777	148.422	0.866	6.705	45.989	2.734
Dry s.	KT-12EPA	Range	6.7-6.9	0.109-2.316	0.157-1.559	31.228-68.176	19.674-695.011	0.596-2.947	1.667-2.006	4.543-14.078	10.129-25.345	0.178-2.053
Dry s.	KT-12EPA	Mean	6.8	1.213	0.858	49.702	357.343	1.772	1.837	9.311	17.737	1.116
Dry s.	KT-12EPA	SD	0.1	1.561	0.991	26.126	477.535	1.662	0.24	6.742	10.759	1.326
Dry s.	KT-13EPA	Range	5.1-6	0.36-1.996	0.254-1.754	87.7-146.55	83.391-79.862	2.27-9.055	0.832-2.978	6.197-19.314	20.016-32.325	1.2-2.866
Dry s.	KT-13EPA	Mean	5.6	1.178	1.004	117.125	81.627	5.663	1.905	12.756	26.171	2.033
Dry s.	KT-13EPA	SD	0.6	1.157	1.061	41.613	2.495	4.798	1.517	9.275	8.704	1.178
Dry s.	KT-14EPA	Range	5.6-5.9	0.112-1.141	0.138-1.155	55.919-104.047	308.03-384.854	6.448-6.977	4.791-11.114	9.011-12.086	42.891-46.976	9.27-23.075
Dry s.	KT-14EPA	Mean	5.8	0.627	0.647	79.983	346.442	6.713	7.953	10.549	44.934	16.173
Dry s.	KT-14EPA	SD	0.2	0.728	0.719	34.032	54.323	0.374	4.471	2.174	2.889	9.762
Dry s.	KT-15EPA	Range	5.8-5.9	0.189-1.063	0.169-1.193	199.272-403.337	40.543-41.161	4.282-8.867	16.182-16.622	23.803-28.005	54.39-60.123	0.606-2.008
Dry s.	KT-15EPA	Mean	5.9	0.626	0.681	301.305	40.852	6.575	16.402	25.904	57.257	1.307
Dry s.	KT-15EPA	SD	0.1	0.618	0.724	144.296	0.437	3.242	0.311	2.971	4.054	0.991
Dry s.	KT-16EPA	Range	6.5-6.7	0.814-2.558	0.325-1.691	13.988-42.702	66.359-628.403	3.731-11.157	0.774-2.051	57.261-101.888	34.091-53.097	0.527-1.378
Dry s.	KT-16EPA	Mean	6.6	1.686	1.008	28.345	347.381	7.444	1.413	79.575	43.594	0.953
Dry s.	KT-16EPA	SD	0.1	1.233	0.966	20.304	397.425	5.251	0.903	31.556	13.439	0.602
Dry s.	KT-17EPA	Range	6.3-6.7	0.524-4.232	0.23-2.42	165.479-1748.17	70.499-2073.51	18.503-30.058	1.582-3.703	18.111-52.681	41.222-51.492	0.338-0.913
Dry s.	KT-17EPA	Mean	6.5	2.378	1.325	956.83	1072	24.281	2.643	35.396	46.357	0.626
Dry s.	KT-17EPA	SD	0.3	2.622	1.549	1119.134	1416.34	8.171	1.5	24.445	7.262	0.407
Dry s.	KT-18EPA	Range	6.7-6.8	4.43-4.518	0.356-2.308	212.307-331.156	2515.73-1657.20	54.596-133.045	2.229-2.961	133.235-347.829	272.037-1003.53	0.802-1.375
Dry s.	KT-18EPA	Mean	6.8	4.474	1.332	271.732	2086.47	93.821	2.595	240.532	637.784	1.089
Dry s.	KT-18EPA	SD	0	0.062	1.38	84.039	607.072	55.472	0.518	151.741	517.244	0.405

Table 1. Contd.

Rainy s.	KT-1EPA	Range	8.1-10.4	0.142-1.446	0.059-0.674	5.01-78.672	69.407-433.541	0.647-2.019	0.306-1.097	1.674-12.692	4.196-48.956	0.164-0.913
Rainy s.	KT-1EPA	Mean	9.2	0.66	0.393	31.377	191.721	1.331	0.786	8.135	23.441	0.458
Rainy s.	KT-1EPA	SD	1.1	0.692	0.311	41.049	209.427	0.686	0.422	5.751	23.029	0.4
Rainy s.	KT-2EPA	Range	8.1-10.3	0.229-0.624	0.063-0.324	3.661-83.944	2.616-84.746	2.587-68.96	1.228-8.422	13.943-30.527	39.057-79.027	0.192-0.497
Rainy s.	KT-2EPA	Mean	9.2	0.367	0.231	53.454	57.31	24.83	4.006	22.901	52.792	0.305
Rainy s.	KT-2EPA	SD	1.1	0.223	0.146	43.483	47.366	38.218	3.866	8.372	22.728	0.167
Rainy s.	KT-3EPA	Range	8.4-10.7	0.223-0.401	0.255-0.564	63.987-99.164	49.234-130.588	2.081-10.127	1.817-7.704	14.18-45.424	24.38-51.353	0.173-11.735
Rainy s.	KT-3EPA	Mean	9.7	0.303	0.419	75.92	85.826	4.923	5.206	26.981	40.153	4.676
Rainy s.	KT-3EPA	SD	1.2	0.09	0.155	20.132	41.288	4.513	3.043	16.368	14.056	6.19
Rainy s.	KT-4EPA	Range	8.3-10.7	0.51-1.448	0.059-0.677	0.397-15.304	2.999-89.147	1.228-27.768	1.508-1.707	8.383-16.392	27.833-36.853	0.986-2.395
Rainy s.	KT-4EPA	Mean	9.6	1.024	0.331	8.834	43.038	10.776	1.615	12.588	32.879	1.494
Rainy s.	KT-4EPA	SD	1.2	0.475	0.315	7.646	43.394	14.753	0.1	4.02	4.605	0.782
Rainy s.	KT-5EPA	Range	8.6-11.2	0.471-0.578	0.052-0.593	0.158-49.648	1.745-261.241	1.118-2.713	0.278-1.726	1.077-13.791	2.788-28.943	0.126-9.566
Rainy s.	KT-5EPA	Mean	10.1	0.522	0.318	19.428	109.96	1.682	0.882	7.012	14.273	3.331
Rainy s.	KT-5EPA	SD	1.3	0.054	0.271	26.5	135.002	0.894	0.753	6.399	13.365	5.4
Rainy s.	KT-6EPA	Range	6.9-8.9	0.301-0.572	0.328-0.686	42.434-165.617	138.486-238.699	5.865-12.273	2.875-9.612	10.06-25.235	17.855-71.87	11.172-30.03
Rainy s.	KT-6EPA	Mean	7.8	0.403	0.557	95.570	191.905	9.205	6.588	18.379	38.034	21.262
Rainy s.	KT-6EPA	SD	1	0.147	0.199	63.309	50.434	3.213	3.421	7.693	29.483	9.498
Rainy s.	KT-7EPA	Range	7.3-9.8	0.88-5.167	0.2-2.705	70.54-275.835	1269.2-2310.18	1.02-7.509	0.796-4.302	7.057-13.33	72.33-220.631	1.6-10.47
Rainy s.	KT-7EPA	Mean	8.7	2.322	1.222	140.164	1731.353	5.037	2.711	9.709	126.744	7.49
Rainy s.	KT-7EPA	SD	1.3	2.464	1.315	117.508	530.207	3.51	1.775	3.247	81.651	5.101
Rainy s.	KT-8EPF	Range	9-11	0.547-1.996	0.29-2.09	95.54-313.386	945.08-2325.44	1.46-6.517	0.416-1.999	3.84-25.471	5.583-41.344	11.246-8.494
Rainy s.	KT-8EPF	Mean	10	1.352	0.973	179.589	1555.17	4.014	1.193	17.623	29.315	17.270
Rainy s.	KT-8EPF	SD	1	0.738	0.975	117.134	703.982	2.519	0.792	11.975	20.553	9.729
Rainy s.	KT-9EPA	Range	8.9-11	0.751-1.028	0.125-0.261	19.776-50.498	51.011-130.124	0.421-1.45	0.448-0.546	2.792-14.767	8.088-11.194	2.762-3.352
Rainy s.	KT-9EPA	Mean	10	0.867	0.181	30.656	77.720	0.836	0.508	7.99	9.513	3.012
Rainy s.	KT-9EPA	SD	1.1	0.144	0.071	17.215	45.386	0.542	0.053	6.142	1.569	0.305
Rainy s.	KT-10EPA	Range	7.1-11	0.055-0.15	0.2-0.51	881.85-2229.49	1823-6392.32	3.088-21.194	1.089-5.539	1.63-12.21	16.752-62.807	0.471-1.499
Rainy s.	KT-10EPA	Mean	8.7	0.106	0.319	1639.41	3192.23	14.453	4.144	6.501	39.265	1.017
Rainy s.	KT-10EPA	SD	2.0	0.048	0.167	689.254	2780.95	9.899	2.649	5.34	23.045	0.517
Rainy s.	KT-11EPA	Range	7.4-10.7	8.001-9.531	0.237-1.627	41.381-130.782	213.386-1183.66	739.085-1083.11	7.405-10.63	149.495-228.215	1317.05-2214.14	3.18-3.418
Rainy s.	KT-11EPA	Mean	9.1	8.828	0.823	82.479	643.793	919.264	9.502	193.323	1706.63	3.262
Rainy s.	KT-11EPA	SD	1.6	0.773	0.72	45.134	494.312	172.594	1.818	40.114	460.029	0.135
Rainy s.	KT-12EPA	Range	8.5-11	0.596-1.114	0.366-0.5	12.62-39.864	94.209-132.567	2.122-18.373	0.67-1.724	10.663-75.675	34.462-63.509	3.52-9.005
Rainy s.	KT-12EPA	Mean	9.9	0.833	0.416	23.229	118.572	8.517	1.117	35.169	46.177	6.352
Rainy s.	KT-12EPA	SD	1.3	0.262	0.073	14.587	21.177	8.661	0.545	35.336	15.317	2.747

Table 1. Contd.

Rainy s.	KT-13EPA	Range	6.8-8.8	0.227-0.848	0.276-0.557	134.245-187.679	45.652-199.329	7.393-23.896	2.581-3.843	15.121-20.722	40.741-85.395	3.774-7.83
Rainy s.	KT-13EPA	Mean	7.8	0.493	0.456	162.795	107.996	12.954	3.219	17.344	64.336	5.366
Rainy s.	KT-13EPA	SD	1	0.32	0.156	26.905	80.836	9.476	0.631	2.974	22.435	2.164
Rainy s.	KT-14EPA	Range	8.5-10	0.118-0.401	0.281-0.403	47.834-62.121	38.165-224.596	5.869-12.648	5.742-15.471	12.045-18.396	14.477-25.833	4.58-8.061
Rainy s.	KT-14EPA	Mean	9.1	0.303	0.329	54.635	142.935	8.498	9.28	15.024	21.819	6.388
Rainy s.	KT-14EPA	SD	0.8	0.161	0.065	7.168	95.34	3.636	5.38	3.194	6.368	1.744
Rainy s.	KT-15EPA	Range	7.4-10.4	0.427-0.965	0.306-0.653	83.944-262.521	84.568-217.147	5.287-12.155	7.416-8.525	42.233-81.255	140.293-289.295	1.92-8.06
Rainy s.	KT-15EPA	Mean	8.9	0.669	0.497	146.206	138.174	7.721	8.121	64.691	191.185	4.034
Rainy s.	KT-15EPA	SD	1.5	0.273	0.176	100.815	69.835	3.846	0.613	20.168	84.986	3.488
Rainy s.	KT-16EPA	Range	8.2-10.6	1.114-1.625	0.366-0.845	17.204-58.858	132.567-235.205	5.055-13.887	0.67-2.08	75.675-160.911	31.892-34.462	1.618-3.659
Rainy s.	KT-16EPA	Mean	9.4	1.31	0.587	34.391	185.837	10.422	1.301	106.965	33.567	2.322
Rainy s.	KT-16EPA	SD	1.2	0.276	0.242	21.76	51.43	4.713	0.717	46.917	1.451	1.158
Rainy s.	KT-17EPA	Range	8.2-9.8	0.405-2.683	0.029-1.123	100-136.81	130.553-509.457	81.377-138.279	1.592-2.56	58.501-135.78	45.4-80.47	0.356-0.73
Rainy s.	KT-17EPA	Mean	9.2	1.214	0.525	119.968	290.67	118.985	2.181	105.352	60.189	0.565
Rainy s.	KT-17EPA	SD	0.9	1.274	0.554	18.603	196.147	32.573	0.517	41.174	18.169	0.191
Rainy s.	KT-18EPA	Range	8.5-11	1.537-2.338	0.516-2.26	235.06-310.588	661.32-2983.76	854.38-1346.34	3.821-15.503	72.53-216.35	986.875-1066.76	1.322-1.7
Rainy s.	KT-18EPA	Mean	9.9	2.055	1.604	263.515	1647.43	1094.28	9.344	132.402	1037.91	1.469
Rainy s.	KT-18EPA	SD	1.3	0.449	0.949	41.062	1200.18	246.206	5.867	74.872	44.322	0.203
Rainy s.	KN-1EPA	Range	6.8-7.6	0.11-0.574	0.426-0.449	15.846-146.279	80.939-111.771	2.989-3.078	3.56-5.567	10.755-16.999	26.41-54.751	7.234-7.316
Rainy s.	KN-1EPA	Mean	7.2	0.342	0.437	81.062	96.355	3.033	4.563	13.877	40.581	7.275
Rainy s.	KN-1EPA	SD	0.6	0.328	0.017	92.23	21.802	0.063	1.419	4.415	20.04	0.058
Rainy s.	KN-2EPF	Range	8.1-8.4	0.997-1.364	0.48-0.83	113.841-245.776	48.417-185.365	1.319-18.205	2.122-4.408	25.601-30.29	69.285-103.978	0.133-2.016
Rainy s.	KN-2EPF	Mean	8.2	1.181	0.655	179.809	116.891	9.762	3.265	27.946	86.632	1.074
Rainy s.	KN-2EPF	SD	0.2	0.26	0.248	93.292	96.837	11.940	1.616	3.316	24.532	1.331
Rainy s.	KN-3EPA	Range	7.2-7.9	0.027-0.117	0.292-0.354	11.975-38.057	106.628-404.275	2.612-2.877	4.365-4.493	5.062-62.705	37.535-40.733	1.604-5.046
Rainy s.	KN-3EPA	Mean	7.5	0.072	0.323	25.016	255.451	2.745	4.429	33.884	39.134	3.325
Rainy s.	KN-3EPA	SD	0.5	0.064	0.044	18.443	210.469	0.187	0.091	40.76	2.261	2.434
Rainy s.	KN-4EPF	Range	5.5-5.8	0.043-0.071	0.337-0.81	9.779-10.06	104.686-134.525	3.409-3.435	5.615-5.694	6.383-14.427	46.45-47.388	0.402-5.662
Rainy s.	KN-4EPF	Mean	5.6	0.057	0.573	9.919	119.606	3.422	5.654	10.405	46.919	3.032
Rainy s.	KN-4EPF	SD	0.2	002	0.335	0.199	21.099	0.018	0.056	5.688	0.663	3.719
Rainy s.	KN-5EPF	Range	8-8	0.094-0.263	0.09-0.276	13.77-67.157	15.926-60.083	0.586-3.605	1.372-6.255	8.567-38.492	42.62-235.715	0.071-0.237
Rainy s.	KN-5EPF	Mean	8	0.178	0.183	40.463	38.004	2.095	3.813	23.529	139.167	0.154
Rainy s.	KN-5EPF	SD	0	0.119	0.132	37.75	31.224	2.135	3.453	21.161	136.54	0.118
Rainy s.	KN-6EPA	Range	5.9-6.2	0.107-0.6	0.417-0.952	1346.41-1390.05	236.321-419.968	432.319-446.724	94.949-108.518	9558.19-9753.56	48900.05-49053.03	0.21-0.725
Rainy s.	KN-6EPA	Mean	6	0.353	0.684	1368.23	328.145	439.522	101.733	9655.88	48976.54	0.468
Rainy s.	KN-6EPA	SD	0.2	0.348	0.379	30.852	129.858	10.186	9.594	138.147	108.173	0.364

Dry s.: Dry season; EPA: hand-dug well; EPF: drilled well; KN: Kenya municipality; KT: Katuba municipality; Rainy s.: rainy season; SD: standard deviation.

Table 2. Mean and standard deviation values of pH and elevated trace element concentrations (µg/L) in Katuba and Kenya groundwater higher than the WHO (2017), US EPA (2018) and/or EU (2020) acceptable limits for drinking water.

Parameter	WHO MCLs	US EPA MCLs	EU MCLs	Katuba/Dry season	KT-2EPA	KT-3EPA	KT-4EPA	KT-5EPA	KT-6EPA	KT-7EPA	KT-8EPF	KT-9EPA
pH value	6.5-8.5	6.5-8.5*	6.5-9.5**	N=4	6.5±0.4	6.5±0.4	6.8±0.1	6.5±0.4	5.5±1.1	5.5±0.6	7.3±0.7	7.2±0.5
As (µg/L)	10	10	10	N=4	-	-	-	-	10.365±1.365	-	-	-
Cd (µg/L)	3	5	5	N=4	-	-	-	-	-	-	-	-
Cu (µg/L)	2000	1300	2000	N=4	-	-	-	-	-	-	-	-
Fe (µg/L)	Na	300*	200**	N=4	-	256.653±62.236	-	216.972±224.584	-	394.7±122.471	349.221±159.406	460.444±153.423
Mn (µg/L)	Na	300*	50**	N=4	-	-	53.785±40.25	-	251.321±115.067	84.057±27.141	-	195.993±142.276
Ni (µg/L)	70	100*	20	N=4	-	-	-	-	-	-	-	-
Pb (µg/L)	10	15	5	N=4	-	-	-	-	5.629±4.433	-	-	5.664±5.049
Zn (µg/L)	Na	2000*	Na	N=4	-	-	-	-	-	-	-	-

Parameter	WHO MCLs	US EPA MCLs	EU MCLs	Katuba/Rainy season	KT-2EPA	KT-3EPA	KT-4EPA	KT-5EPA	KT-6EPA	KT-7EPA	KT-8EPF	KT-9EPA
pH value	6.5-8.5	6.5-8.5*	6.5-9.5**	N=6	9.2±1.1	9.7±1.2	6.8±0.1	6.5±0.4	7.8±1	8.7±1.3	10±1	7.2±0.5
As (µg/L)	10	10	10	N=6	-	-	-	-	21.262±9.498	-	17.27±9.729	-
Cd (µg/L)	3	5	5	N=6	-	-	-	-	-	-	-	-
Cu (µg/L)	2000	1300	2000	N=6	-	-	-	-	-	-	-	-
Fe (µg/L)	Na	300*	200**	N=6	-	256.653±62.236	-	216.972±224.584	-	1731.35±530.207	1555.17±703.982	460.444±153.423
Mn (µg/L)	Na	300*	50**	N=6	53.454±43.483	75.92±20.132	-	-	95.57±63.309	140.164±117.508	179.589±117.134	-
Ni (µg/L)	70	100*	20	N=6	-	-	-	-	-	-	-	-
Pb (µg/L)	10	15	5	N=6	-	-	-	-	5.629±4.433	5.938±7.172	-	5.664±5.049
Zn (µg/L)	Na	2000*	Na	N=6	-	-	-	-	-	-	-	-

Parameter	WHO	US EPA	EU	Kenya/Rainy season	KN-1EPA	KN-2EPA	KN-3EPA	KN-4EPA	KN-5EPA	KN-6EPA		
pH value	6.5-8.5	6.5-8.5*	6.5-9.5**	N=4	7.2±0.6	8.2±0.2	7.5±0.5	5.6±0.2	8±0	6±0.2	-	-
As (µg/L)	10	10	10	N=4	-	-	-	-	-	-	-	-
Cd (µg/L)	3	5	5	N=4	-	-	-	-	-	379.579±6.825	-	-
Cu (µg/L)	2000	1300	2000	N=4	-	-	-	-	-	9655.88±138.147	-	-
Fe (µg/L)	Na	300*	200**	N=4	-	-	255.451±210.469	-	-	328.145±129.858	-	-
Mn (µg/L)	Na	300*	50**	N=4	81.062±92.23	179.809±93.292	-	-	-	1368.23±30.852	-	-
Ni (µg/L)	70	100*	20	N=4	-	-	-	-	-	101.733±9.594	-	-
Pb (µg/L)	10	15	5	N=4	-	**13.58**±2.277	-	-	-	10.218±6.029	-	-
Zn (µg/L)	Na	2000*	Na	N=4	-	-	-	-	-	48976.54±108.173	-	-

Parameter	WHO MCLs	US EPA MCLs	EU MCLs	Katuba/Dry season	KT-10EPA	KT-11EPA	KT-12EPA	KT-13EPA	KT-14EPA	KT-15EPA	KT-16EPA	KT-17EPA	KT-18EPA
pH value	6.5-8.5	6.5-8.5*	6.5-9.5**	N=4	6.0±0	5.3±0.5	6.8±0.1	5.6±0.6	5.8±0.2	5.9±0.1	6.6±0.1	6.5±0.3	6.8±0
As (µg/L)	10	10	10	N=4	-	-	-	-	16.173±9.762	-	-	-	-
Cd (µg/L)	3	5	5	N=4	-	7.04±0.085	-	-	-	-	-	-	-
Cu (µg/L)	2000	1300	2000	N=4	-	-	-	-	-	-	-	-	-
Fe (µg/L)	Na	300*	200**	N=4	3297.18±2163.42	1617.55±50.777	357.343±477.535	-	346.442±54.323	-	347.381±397.425	1072±1416.34	2086±607.072
Mn (µg/L)	Na	300*	50**	N=4	1459.96±163.292	-	-	117.125±41.613	79.983±34.032	301.305± 144.296	-	956.83±1119.134	271.732±84.039
Ni (µg/L)	70	100*	20	N=4	-	-	-	-	-	-	-	-	-

Table 2. Contd.

Pb (µg/L)	10	15	5	N=4	-	-	-	-	-	5.66± 0.713	5.262± 2.178	-	11.635± 3.703
Zn (µg/L)	Na	2000*	Na	N=4	-	-	-	-	-	-	-	-	-
pH value	6.5-8.5	6.5-8.5*	6.5-9.5**	N=6	8.7±2.0	9.1±1.6	6.8±0.1	7.8±1	9.1±0.8	8.9±1.5	9.4±1.2	9.2±0.9	9.9±1.3
As (µg/L)	10	10	10	N=6	-	-	-	-	16.173±9.762	-	-	-	-
Cd (µg/L)	3	5	5	N=6	-	29.416±8.112	-	-	-	-	-	-	11.825±7.296
Cu (µg/L)	2000	1300	2000	N=6	-	-	-	-	-	-	-	-	-
Fe (µg/L)	Na	300*	200**	N=6	3192.23±2780.95	643.793±494.312	357.343±477.535	-	346.442±54.323	-	347.381±397.425	290.67±196.147	1647.43±1200.18
Mn (µg/L)	Na	300*	50**	N=6	1639.41±89.254	82.479±45.134	-	162.795±26.905	54.635±7.168	146.206±00.815	-	119.968± 18.603	263.515±41.062
Ni (µg/L)	70	100*	20	N=6	-	-	-	-	-	19.752± 4.399	-	-	-
Pb (µg/L)	10	15	5	N=6	-	-	-	-	-	5.66± 0.713	7.761±3.687	6.342± 3.246	11.635±3.703
Zn (µg/L)	Na	2000*	Na	N=6	-	-	-	-	-	-	-	-	-

Parameter	WHO	US EPA	EU	Kenya/Rainy season
pH value	6.5-8.5	6.5-8.5*	6.5-9.5**	N=4
As (µg/L)	10	10	10	N=4
Cd (µg/L)	3	5	5	N=4
Cu (µg/L)	2000	1300	2000	N=4
Fe (µg/L)	Na	300*	200**	N=4
Mn (µg/L)	Na	300*	50**	N=4
Ni (µg/L)	70	100*	20	N=4
Pb (µg/L)	10	15	5	N=4
Zn (µg/L)	Na	2000*	Na	N=4

*United States Environmental Protection Agency 2018 Drinking Water Health Advisories (2018); **: European Union Drinking Water Indicator Parameters (2020); EU (European Union) Revised Drinking Water Directive (2020); MCLs: acceptable maximum contaminant levels for drinking water; Na: no available data; USEPA: United States Environmental Protection Agency 2018 Drinking Water Standards and Health Advisories (2018); Splg: sampling; WHO: World Health Organization Guidelines for Drinking-Water Quality (2017).

highest mean concentrations of several potential toxic elements including As (21.262 µg/L), Ba (370.696), Cs (0.433 µg/L), Co (1,094.28 µg/L), Pb (19.752 µg/L), Mn (1,639.41 µg/L), Mo (1.815 µg/L), Sr (631.495 µg/L), Tl (0.246 µg/L), and V (8.828 µg/L) were recorded in groundwater samples collected from various hand-dug wells. During the same season in Kenya municipality, the highest mean concentrations of Cd (379.579 µg/L), Cu (9,655.88 µg/L), Ni (101.734 µg/L), U(8.237 µg/L), W (2.017 µg/L), and Zn (48,976.54 µg/L) were found in samples from one hand-dug well (KN-6EPA). In dry season, only Cr, Fe, and Ni had the highest concentrations (3.37, 3,297.19, and 16.408 µg/L, respectively) in samples collected from three different spade-sunk wells in Katuba municipality. Elevated mean trace element concentrations in Katuba and Kenya groundwater are higher than the acceptable limits set for drinking water by WHO (2017), US EPA (2018) and/or EU (2020) presented in Table 2. The elevated metal concentrations might be due to atmospheric and soil pollutants taken away by rainwater and drained into the poorly protected hand-dug wells. Besides, the spade-sunk wells were very shallow (2- to 10-m deep), not well covered and could be easily reached by rainout and dust than the better protected drilled wells which were 15- to 60-m deep. Also, the Katuba and Kenya municipalities are close to the Lubumbashi slag heap that contains several potentially toxic metals and might permanently contaminate the surrounding soils, surface water and groundwater with those metals through rainwater drainage into the surface water and the water table. The high metal contamination of those wells might also be due to metal polluted rivers that flow near both municipalities as an interaction between surface and groundwater

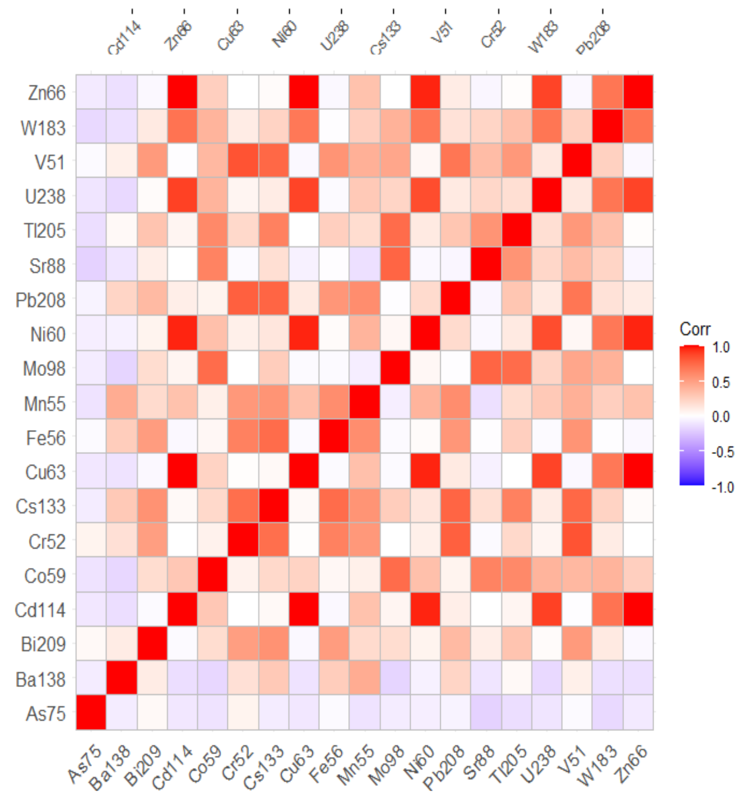

Figure 2. Evolution and correlation of nineteen trace elements recorded on the same vein in well waters in Katuba and Kenya municipalities of Lubumbashi city during the period of May 2016 March 2017.

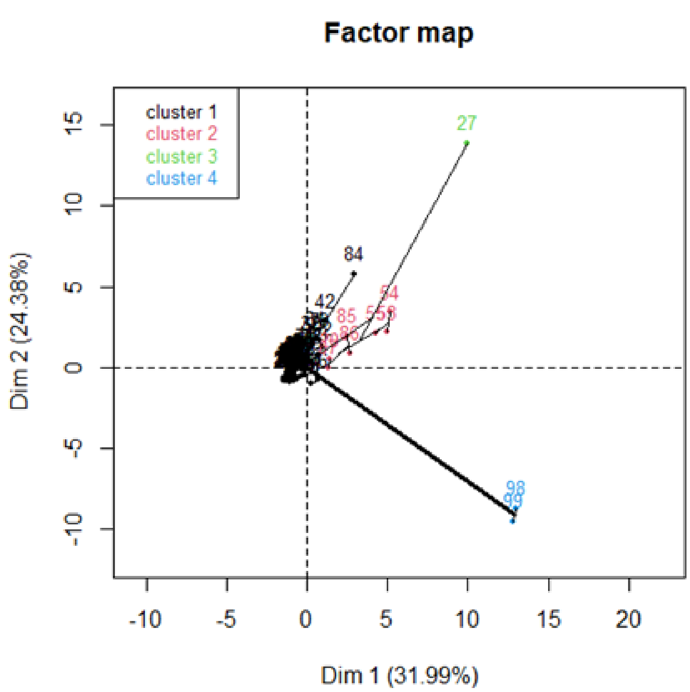

Figure 3. Graphical representation in classes of toxic trace elements in well waters in Katuba and Kenya municipalities of Lubumbashi city for the period of May 2016 to March 2017.

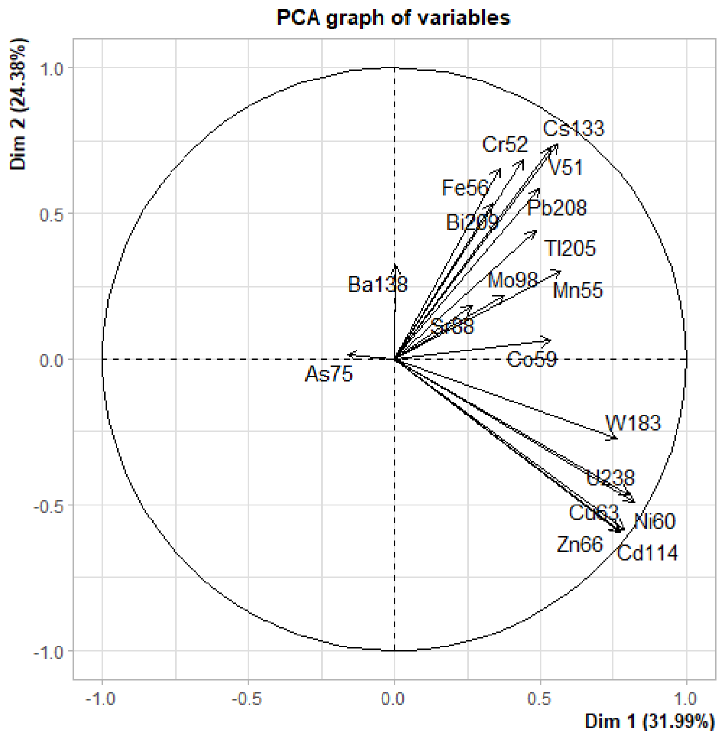

Figure 4. ACP (Principal Component Analysis) representation of potentially toxic trace elements in well waters in Katuba and Kenya municipalities of Lubumbashi city for the period of May 2016 to March 2017.

could not be excluded. Numerous researchers have pointed out trace metal contamination of Lubumbashi soils (Kashimbo, 2016; Muhaya et al., 2016), rivers (Muhaya et al., 2017a, b) and groundwater (Muhaya et al., 2021), and adverse human health effects of trace metals in Lubumbashi (Mukendi et al., 2018; Obadia et al., 2018; Cham et al., 2020; Malamba-Lez et al., 2021; Mudekereza et al., 2021; Ngoy et al., 2021) mainly due to anthropogenic activities including artisanal and industrial mining, ore processing, and waste disposal and mismanagement.

The acceptable drinking water maximum contaminant levels (MCLs) set by WHO (2017), USEPA (2018), and EU (2020) are shown in Table 3. As, Cd and Pb levels of groundwater, respectively exceeded the WHO, USEPA and EU drinking water MCLs in 12.22, 8.89 and 7.78% of the groundwater samples from Katuba municipality, and Cd, Pb, Ni and Cu exceeded the MCLs in 16.67, 25, 16.67 and 16.67% of the well water samples from Kenya municipality.

Also, Mn and Fe levels of groundwater above the EU (drinking water) indicator parameters of 50 and 200 µg/L were, respectively noted in 61.11 and 45% of the groundwater samples from Katuba municipality with the highest levels of 2,229.49 and 6,392.32 µg/L, respectively in 58.33 and 33.33% of the groundwater samples from Kenya municipality with the highest levels of 1,390.05 and 419.968 µg/L, respectively. Mn, Fe and Zn levels of groundwater exceeding the USEPA drinking water health advisories of 300, 300 and 2,000 µg/L (USEPA, 2018) were, respectively recorded in 11.11, 37.78 and 1.11% of the groundwater samples from Katuba municipality with the highest levels of 3,326.86, 13,392.65 and 2,214.14 µg/L, respectively in 16.67, 25 and 16.67% of the samples from Kenya municipality with the highest levels of 1,390.05, 419.968 and 49,053.03 µg/L.

The recorded concentrations of Ba, Cr, Tl and U in groundwater in Katuba and Kenya municipalities were far below the drinking water MCLs set for those elements by the WHO (2017), USEPA (2018) or EU (2020) as the highest concentrations of those metals in groundwater in both Katuba and Kenya municipalities were respectively 509.052 µg/L and 167.746 µg/L for Ba, 9.119 µg/L and 0.952 µg/L for Cr, 0.303 µg/L and 0.065 µg/L for Tl, and 2.081 µg/L and 8.839 µg/L for U (Table 1). The highest concentrations of Mo (5.857 µg/L) and Sr (672.2 µg/L) noted in groundwater in this study were below the USEPA (2018) drinking water health indicators of 40 µg/L and 4,000 µg/L, respectively. The Mo and Sr as well as the other trace metal levels of groundwater in both municipalities were probably associated with anthropogenic contamination but geogenic sources might

Table 3. WHO, USEPA, and EU drinking water optimum pH range values and acceptable maximum contaminant levels (µg/L).

WHO, USEPA & EU MCLs	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)	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	50	Na	Na	Na	70	2,000	Na	10
USEPA	6.5-8.5*	4,000*	40*	5	Na	2,000	Na	2	15	Na	30	Na	100	300*	300*	Na	100*	1,300	2,000*	10
EU	6.5-9.5**	Na	Na	5	Na	Na	Na	Na	5	Na	30	Na	25	50**	200**	Na	20	2,000	Na	10

*:United States Environmental Protection Agency 2018 Drinking Water Health Advisories (2018); **: European Union Drinking Water Indicator Parameters (2020); EU (European Union) Revised Drinking Water Directive (2020); MCLs: acceptable maximum contaminant levels for drinking water; Na: no available data; USEPA: United States Environmental Protection Agency 2018 Drinking Water Standards and Health Advisories (2018); WHO: World Health Organization Guidelines for Drinking-Water Quality (2017).

not be excluded. Harkness et al. (2017) reported that groundwater typically has low Mo (<2 µg/L) and that elevated levels are associated with anthropogenic contamination, although geogenic sources have been reported.

Sr concentrations in Katuba and Kenya groundwater wells were in the range of low concentrations (<2,000 µg/L) reported for untreated groundwater wells used for public supply in the United States (Water Resources, 2021). The report indicated that about 2.3% of drinking-water wells in the United States have concentrations of Sr at levels that present a potential human health risk, and that these wells provide water for an estimated 2.3 million people. According to the same source, concentrations in drinking-water wells that exceeded the health-based screening level of 4,000 µg/L largely occurred in carbonate-rock aquifers and in areas where upwelling brines mix with potable groundwater. Elevated Sr concentrations can adversely affect bone development and mineralization. Conventional water treatment processes, such as coagulation/filtration, are largely ineffective at removing Sr from drinking water. However, water-softening treatments such as lime-soda ash or cation-exchange water softners designed to reduce calcium concentrations also can decrease Sr concentrations (Water Resources, 2021). High Ba concentrations in groundwater are generally associated with very low SO_4 concentrations (<5 mg/L) resulting from sulfate reduction, suggesting a solubility control of Ba through barite ($BaSO_4$) precipitation (Bondu et al., 2020).

Heavy metals always evolve together. The presence of one indicates the presence of one or more others. Thus, thanks to the statistical analysis, we found the presence of metals which evolve together and which are predominantly found in the well water of Katuba and Kenya municipalities (Figure 2). The correlation is marked by the red color. The more bright-red is the color, the greater the correlation between the metals from 50 to 100%, the less vivid it is from 1 to 50% and the threshold is above or moderately above the WHO (2017) standards for drinking water: Cd and Cu, Cd and Ni, Cd and U, Cd and W, and Cd and Zn. Then, there is a weak correlation and the threshold is below 50% of the drinking water maximum concentration limits set by the WHO (2017) for the elements. It is white when the correlation is zero, that is to say 0%, and purple when the correlation is less than 0%.
The positively correlated variables are grouped together (Figure 3). Negatively correlated variables are positioned on opposite sides of the origin of the graph (opposite quadrants). The distance between the variables and the origin measures the quality of representation of the variables. Many of those trace elements, such as As, Cd, Cu, Fe, Mn, Ni, Pb and Zn in some wells had concentrations much higher than the WHO (2017), US EPA (2018) and EU (2020) permissible MCLs for drinking water. Variables that were far away from the origin are well represented by the principal component analysis (PCA) (Figure 4).

With PCA, we found that 31.9% of the trace elements were on the positive side of the origin of the graph and many of them tended to touch the edge of the quadrant. For these elements, the more the values of cos2 were used to estimate the quality of the representation, the closer a variable was to the correlation circle, and the better its representation on the PCA map (and it was more important for interpreting the principal components in consideration). The variables which were close to the center of the graph were less important for the first components.

The General Linear Model (GLM) allowed us to understand the affinities or correlations between trace elements and their environment, and between trace elements and the seasons. From this analysis, it was noted that all the trace elements were subject to seasonal influence in both Katuba and Kenya municipalities. Although the impact might be less significant when considering the 5% threshold of water pollution impact on human health, the concentrations of these trace elements could have adverse health effects following bioaccumulation and bio-amplification of some of the metals by the consumers of that water.

During the dry season, As, Pb, Cu, Cd, and Zn concentrations in water from many wells in both Katuba and Kenya municipalities were higher than the acceptable maximum concentration limits set for drinking water by WHO (2017), USEPA (2018) and EU (2020). During the rainy season, the concentrations of trace elements increased, probably due to the rainwater infiltration into the water table, the leaching of the topsoil with erosion as this leaching water ended up in poorly protected hand-dug wells and even in the better protected ones (the drilled wells).

The highest Bi, Cd, Co, Cu, Pb, Mn, Mo, Ni, Sr, U and Zn concentrations noted in groundwater in this study exceeded those of 0.049, 52.585, 54.026, 634.8, 38.162, 1,242.68, 0.498, 64.647, 290.98, 2.492 and 9,900.72 µg/L, respectively recorded in groundwater in the Lubumbashi, Kampemba and Kamalondo municipalities of Lubumbashi city (Muhaya et al., 2021). On the contrary, the highest levels of As (65.458 µg/L), Ba (740.24 µg/L), Cs (1.431 µg/L), Cr (10.014 µg/L), Fe (17,325.98 µg/L), Tl (0.409 µg/L), W (35.31 µg/L), and V (27.363 µg/L) reported for groundwater in Lubumbashi, Kampemba and Kamalondo municipalities (Muhaya et al., 2021) were above those respectively found in groundwater in this study. Pb levels of groundwater in the current study were much lower than those (110 - 490 µg/L, mean level: 270 µg/L) reported by Olusola et al. (2017) for twenty-one groundwater wells in Southwestern Nigeria.

The highest mean As and U levels of groundwater wells in Katuba and Kenya communes were lower than those estimated by Communications and Publishing (2021) in a new U.S. Geological Survey study. The study provided an updated, statewise estimate of high levels of naturally occurring As and U in private well water across the state of Connecticut and indicated that 3.9% of private wells across that state contained water with As at concentrations higher than the U.S. Environmental Protection Agency's acceptable maximum level (10 µg/L) for public drinking-water supplies. That research also projected that 4.7% of private wells in the state had U concentrations higher than the EPA's standard of 30 µg/L. Except the highest mean concentration of Ni (101.73 µg/L) noted in one hand-dug well, mean Ni concentrations recorded in groundwater wells in this study were far lower than those (55.95 - 88.09 µg/L) reported by Ghobadi and Jahangard (2017) for groundwater resources of Asadabad plain in Iran. However, mean Cr and Mn concentrations reported by these authors were much lower than those found in some groundwater wells in the current study. Concentrations of As, Cd, Cu, Fe, Mn, Ni, Pb and

Zn in some groundwater wells in this study were also higher than those reported by Tomasek et al. (2022) for groundwater wells, springs and tap water systems around Mount Meru, Arusha, Tanzania. However, the concentrations of U and Mo recorded in groundwater wells in this study were much lower than those (>30 and >70 µg/L, respectively) reported by these researchers.

Of the nineteen trace elements found in groundwater in this study, only Co, Cr (Cr III), Cu, Fe, Mn, Mo and Zn are essential for human body and they play an important biological role at low concentrations in the body (Boyers, 2018; U.S. Geological Survey, 2018). In the case of high levels or deficiency of these essential substances, adverse health effects may occur and induce some dysfunction of the body (Leyssens et al., 2017; U.S. Geological Survey, 2018; Guo et al., 2021). The other trace elements noted in this study have no known biological importance for human body and most of them are toxic to humans, even at low concentrations. Tl, Cd, As, Pb, U, Cr (Cr VI) and Ni are those which have the most deleterious impacts on human health, even at very low concentrations (U.S. Geological Survey, 2018). Numerous researchers have reported on adverse effects on human health due to exposure to some of these trace elements in drinking water. This is the case of exposure to As (Smith et al., 2018; U.S. Geological Survey, 2018; Ramadan and Haruna, 2019; Khandare et al., 2020; Malamba-Lez et al., 2021), Cd (Browar et al., 2018; U.S. Geological Survey, 2018; Ramadan and Haruna, 2019; Khandare et al., 2020; Malamba-Lez et al., 2021), Cr VI (U.S. Geological Survey, 2018; Ramadan and Haruna, 2019; Khandare et al., 2020; Malamba-Lez et al., 2021), Pb (Browar et al., 2018; Jain, 2018; U.S. Geological Survey 2018; Khandare et al., 2020; Malamba-Lez et al., 2021), Ni (U.S. Geological Survey, 2018; Malamba-Lez et al., 2021), Tl (Osorio-Rico et al., 2017; Jain, 2018; U.S. Geological Survey, 2018; Malamba-Lez et al., 2021; Nuvolone et al., 2021), U (Corlin et al., 2016; Li et al., 2021; Malamba-Lez et al., 2021) and V (Ngwa et al., 2017; Sengupta and Dutta, 2018).

Although no drinking water standards have been set for Bi, Cs, Sr, Tl, V, and W by WHO (2017) and EU (2020), these trace elements are known to be toxic to humans (Jain, 2018; Al-Khatib et al., 2019; Khandare et al., 2020; Roshandel et al., 2020; Mirzaee et al., 2021; Li et al., 2021; Malamba-Lez et al., 2021). The highest concentrations of those metals recorded in groundwater in Katuba and Kenya municipalities were, respectively 0.096 and 0.043 µg/L for Bi, 1.311 and 0.162 µg/L for Cs, 672.2 and 312.915 µg/L for Sr, 0.303 and 0.065 µg/L for Tl, 9.735 and 1.364 µg/L for V, and 1.432 and 2.538 µg/L for W (Table 1). The levels of these trace elements were still low but their adverse health effects to people who drink the contaminated water could not be excluded as these metals might bioaccumulate and biomagnify in some human organs, such as the liver and kidneys.

Mean groundwater pH values in Katuba municipality ranged from 5.3 to 7.3 in dry season with 38.9% of the water samples having mean pH values below the WHO (2017) drinking water pH optimum range values of 6.5 to 8.5, meaning that 38.9% of the water samples were acidic with mean pH values ranging from 5.3 to 6.0. In rainy season, mean groundwater pH values ranged from 7.7 to 10.1 with 88.9% of the water samples which were too alkaline (mean pH values ranging from 8.7 to 10.1) in Katuba municipality and from 5.6 to 8.2 with 11.1% of the groundwater samples which were acidic (mean pH values of 5.6 and 6.0) in Kenya municipality. Groundwater from many of the sampled wells in both municipalities being acidic or very alkaline, its physicochemical quality was not suitable for water intended to human consumption. Acidic water makes dissolved trace metals dissolved more available for bioaccumulation. The alkaline conditions (very high pH) of groundwater in many wells in Lubumbashi city might probably be due to the roach hosting the groundwater as the roach is made of dolomite (calcium and magnesium carbonate) which is very rich in calcium. During rainy season in Lubumbashi city (from November to March), the level of groundwater goes up and brings with it deep alkaline solutions which make the wellwater alkaline to very alkaline. It has been reported that if the soil or bedrock around groundwater sources includes carbonate, bicarbonate, or hydroxide compounds, those materials get dissolved and travel with the water, and these mineral deposits also increase the alkalinity of the water (Eldorado Marketing, 2021). According to this source, highly alkaline water can smell and taste unpleasant too, and high levels of pH in water can indicate that pollutants or unwanted chemicals are present; and those substances can be harmful to human health.

The trace metal contamination of groundwater wells in the Katuba and Kenya municipalities of 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 might 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. The studied hand-dug wells were not well protected and the tools used for withdrawing water from those wells were open and left in the air, thus facilitating contamination of the wells with dust and rainwater. Trace element contamination of the groundwater might also partially result from an interconnexion between surface water and groundwater. Indeed, water and sediments of the rivers that flow through Lubumbashi city (Muhaya et al., 2017a, b, c, d) and the city soil (Kashimbo, 2016; Muhaya et al., 2016) have been reported to be highly contaminated with various trace elements.

Groundwater in both Katuba and Kenya municipalities might be a source of chronic exposure to toxic metals and metalloids that the body does not require, and to high levels of some essential metals including Co, Cu, Fe, Mn and Zn.

Conclusions

Trace metal levels and pH of groundwater in Katuba and Kenya municipalities of Lubumbashi city were investigated in two hundred and four groundwater samples collected from twenty hand-dug wells and four drilled wells in May and October 2016 (dry season) and November 2016 to March 2017 (rainy season). Recorded mean pH values and levels of nineteen trace elements of the groundwater samples, including strontium, molybdenum, cadmium, cesium, barium, tungsten, thallium, lead, bismuth, uranium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc and arsenic, were compared to the drinking water maximum contaminant levels set by the World Health Organization, the United States Environmental Protection Agency and the European Union. Water of many wells in both municipalities was acidic or very alkaline and highly contaminated with arsenic, cadmium, lead, manganese, iron, nickel, zinc and other trace metals. This implies that the groundwater is unsuitable for human consumption and presents a high risk for the health of people who use it to meet their drinking water needs.

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

CONFLICT OF INTERESTS

The authors have no conflict of interests to be declared.

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