Journal of Environmental Science and Engineering A 14 (2025) 99-112
doi:10.17265/2162-5298/2025.02.002

Potentially Toxic Element Contamination of Groundwater, Surface Water and Tap Water in Kipushi Town and Lupoto Locality, Southeastern Democratic Republic of Congo

Bamba Bukengu Muhaya[1], Benjamin Busomoke Badarhi[2] and Emery Mutombo Kalonda[1]

1. Department of Chemistry, Faculty of Science and Technology, University of Lubumbashi, Lubumbashi 1825, Democratic Republic of Congo

2. Department of Zootechnics, Faculty of Veterinary Medicine, University of Lubumbashi, Lubumbashi 1825, Democratic Republic of Congo

Abstract: Groundwater, surface water and tap water contamination by PTEs (Potentially Toxic Elements) was assessed in Kipushi town and Lupoto locality of Kipushi administrative territory in the Upper-Katanga province, Democratic Republic of Congo. A total of fifty four water samples including thirty two samples from drilled water wells, ten samples from spade-sunk water wells, six samples from supplied tap water, four samples from a mine effluent and two samples from a river were collected from both localities in November and December 2017 and in January, February and March 2018. Then the samples were analyzed for their PTE contents by ICP-SF-MS (Inductively Coupled Plasma-Sector Field Mass Spectrometry). Twenty PTEs including aluminum, arsenic, barium, bismuth, cadmium, cesium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, strontium, thallium, tungsten, uranium, vanadium and zinc were detected at various concentrations in each one of the samples. Many samples had concentrations and mean concentrations of PTE, such as arsenic, aluminum, cadmium, iron, lead, manganese and zinc, higher than the respective acceptable limits set for drinking water by the EU (European Union), the USEPA (United States Environmental Protection Agency), and the WHO (World Health Organization) standards. Most PTEs being deleterious to human health even at very low concentrations, people who use the groundwater, surface water and tap water to meet their water needs in both localities are at risk.

Key words: Contamination, PTEs, groundwater, surface water, tap water, Kipushi, Lupoto, Upper-Katanga, Congo.

1. Introduction

Access to safe drinking water is not provided to everybody in the world. To meet their water needs for drinking, cooking, washing and watering their plants and domestic animals many people have to resort to groundwater, surface water and/or tap water. Unfortunately, those waters are often contaminated with various chemical contaminants including PTEs (Potentially Toxic Elements) in most parts of the world, especially in regions with abandoned and ongoing mining activities such as many regions of DR Congo (the Democratic Republic of Congo). Elevated PTE levels of groundwater may result from natural processes, such as geological weathering and aquifer characteristics, but many times anthropogenic activities, such as mining and ore processing activities and mismanagement of urban waste, also substantially pollute the groundwater. In the Upper-Katanga province, PTE contamination of groundwater and surface water has been well

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

documented [1-7]. Also, numerous researchers have reported on adverse human health effects of PTE in the region and elsewhere in the world [8-25]. No study on PTE contamination of water in Lupoto locality had been carried out previously and no recent PTE contamination of supplied tap water and groundwater in Kipushi town has been published after that reported by Muhaya et al. [1]. Thus, it was worth finding out whether the water consumed by inhabitants of both localities was PTE free.

The aim of this study was to assess PTE contamination of groundwater, tap water, river water and Kipushi mine effluent in Kipushi town and Lupoto locality to find out the chemical quality of those waters and to know whether they present any threat to the health of inhabitants of both localities.

2. Material and Methods

2.1 Study Area, Sampling Campaigns and Sample Pretreatment

Kipushi town is located at about 30 km from Lubumbashi, the capital city of the Upper-Katanga province between the latitude of 11°45′54″ South and the longitude of 27°14′42″ East at the altitude of about 1,350 m. The total population of Kipushi town was estimated to 174,000 inhabitants in 2003 [26]. Lupoto is a locality situated at about 25 km Northwest of Lubumbashi between the latitude of 11°36′2″ South and the longitude of 27°16′31″ East [27]. In Lupoto locality, water samples were collected from three spade-sunk water wells, two drilled water wells and one river in November 2017. In Kipushi town, water samples were collected from four drilled water wells, one spade-sunk water well, one tap water and from Kipushi mine effluent in December 2017, January, February and March 2018. At each sampling campaign, two water subsamples were collected from each sampling site. A total of fifty four samples were collected from seven and six sampling sites in Kipushi town and Lupoto locality (Fig. 1). The water samples were collected in 100 mL polyethylene plastic bottles and acidified with a few drops of concentrated hydrochloric acid.

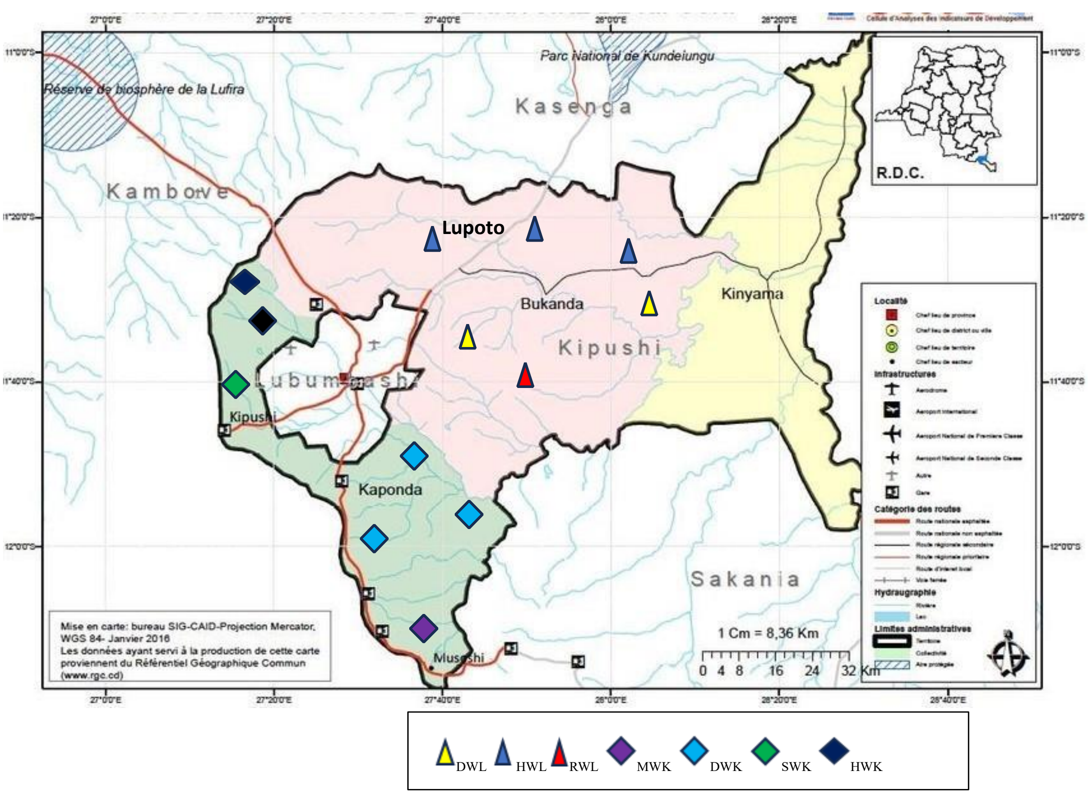

Fig. 1 Water sampling sites in both Kipushi town and Lupoto locality of Kipushi administrative territory in the Upper-Katanga province, Democratic Republic of Congo.

The plastic bottles were beforehand washed with liquid soap and rinsed with double distilled water. Before collecting the bottles were beforehand washed with liquid soap and rinsed with double distilled water. Before collecting the samples, the bottles were also rinsed three times with the water to be sampled. Acidified water samples were filtered on 0.45 µm disposable syringe filters (Chromafil, cellulose mixed ester). They were then stored at room temperature until their chemical analyses at the VUB (Brussels Free University) AMGC (Analytical and Environmental Chemistry and Geochemistry) laboratory.

2.2 Analytical Methods

Trace element analysis was carried out by ICP-SF-MS (Inductively Coupled Plasma-Sector Field Mass Spectrometry) (Thermo Scientific Element II). The instrument was equipped with an ESI (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 Sr, Mo, Cd, Cs, Pb, Bi and U; medium resolution was used for Al, V, Cr, Ni, Cu, Zn, Mn, Fe, Co; high resolution was used for As. Rhodium (1 ppb) was used as internal standard in all resolutions. Standard solutions were prepared from multielement standard solutions and single element standard solutions. Blanks, standards and QC (Quality Control) samples were reanalyzed throughout the procedures. The reference material SW-1 (SPS) was used as QC sample.

2.3 Statistical Analysis

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

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

3. Results and Discussion

The results of chemical analyses of the water samples indicate the presence of twenty PTEs detected at various concentrations in all the analyzed samples. The twenty PTEs include aluminum (Al), arsenic (As), barium (Ba), bismuth (Bi), cadmium (Cd), cesium (Cs), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), molybdenum (Mo), nickel (Ni), strontium (Sr), thallium (Tl), tungsten (W), uranium (U), vanadium (V) and zinc (Zn) (Table 1; Figs. 2-20). The PTE concentrations were compared with drinking water standards set by the EU [28], the USEPA [29] and the WHO [30] (Table 2).

Among the twenty PTEs found in water in this study, five of them including Bi, Cs, Co, W and V are the only ones for which the above international institutions have not set any maximum contaminant limit nor health advisory for drinking water. Concentrations of those PTEs in Kipushi and Lupoto waters respectively ranged from 0 to 0.019 µg/L and 0.003 to 0.017 µg/L with the highest mean concentrations of 0.01 µg/L in 7MWK

Table 1 Concentrations of PTEs in groundwater, surface water and tap water (µg/L) in Kipushi mining town and in Lupoto locality.

No. samples & value type	Sample code	Sr (µg/L)	Mo (µg/L)	Cd (µg/L)	Cs (µg/L)	Ba (µg/L)	W (µg/L)	Tl (µg/L)	Pb (µg/L)	Bi (µg/L)	U (µg/L)	Al (µg/L)	V (µg/L)	Cr (µg/L)	Mn (µg/L)	Fe (µg/L)	Co (µg/L)	Ni (µg/L)	Cu (µg/L)	Zn (µg/L)	As (µg/L)
Conc. range	1HWL	4.868-4.893	0.007-0.009	0.059-0.065	0.027-0.028	37.696-37.825	0.154-0.161	0.007-0.008	0.873-1.207	0.003-0.003	0.07-0.76	84.903-90.251	0.35-0.363	0.284-0.353	35.907-40.203	173.333-186.027	6.936-7.524	1.864-2.508	100.81-105.46	12.349-16.81	0.067-0.074
(N = 2) Mean conc.	1HWL	4.881	0.008	0.062	0.028	37.761	0.158	0.008	1.04	0.003	0.073	87.577	0.357	0.319	38.055	179.68	7.23	2.186	103.135	14.58	0.071
SD	1HWL	0.018	0.001	0.004	0.001	0.091	0.005	0.001	0.236	0.0	0.004	3.782	0.009	0.049	3.038	8.976	0.416	0.455	3.288	3.154	0.005
Conc. range	2HWL	10.451-13.551	0.008-0.013	0.061-0.096	0.033-0.038	80.866-81.819	0.102-0.175	0.01-0.011	1.279-1.689	0.003-0.007	0.047-0.052	67.269-68.389	0.348-0.369	0.481-0.766	71.266-89.659	163.926-190.494	26.262-31.613	7.597-8.468	163.447-180.855	25.975-48.128	0.131-0.151
(N = 2) Mean conc.	2HWL	12.001	0.011	0.079	0.036	81.343	0.139	0.011	1.484	0.005	0.05	67.829	0.359	0.624	80.463	177.21	28.938	8.033	172.151	37.052	0.141
SD	2HWL	2.192	0.004	0.025	0.004	0.674	0.052	0.001	0.29	0.003	0.004	0.792	0.015	0.202	13.006	18.786	3.784	0.616	12.309	15.665	0.014
Conc. range	3DWL	27.218-31.061	0.051-0.097	0.09-0.138	0.009-0.018	14.577-22.833	0.454-0.455	0.002-0.005	2.529-4.495	0.008-0.017	0.025-0.038	67.356-138.328	0.636-0.782	2.014-2.831	8.026-18.521	59.772-99.48	1.94-3.682	4.65-9.428	51.089-89.318	57.701-113.901	0.379-0.437
(N = 2) Mean conc.	3DWL	29.14	0.074	0.114	0.014	18.705	0.455	0.004	3.512	0.013	0.032	102.842	0.709	2.423	13.274	79.626	2.811	7.039	70.204	85.801	0.408
SD	3DWL	2.717	0.033	0.034	0.006	5.838	0.001	0.002	1.39	0.006	0.009	50.185	0.103	0.578	7.421	28.078	1.232	3.379	27.032	39.739	0.041
Conc. range	4DWL	20.822-21.288	0.043-0.066	0.03-0.073	0.009-0.01	10.633-11.122	0.226-304	0.001-0.002	1.587-2.945	0.003-0.007	0.027-0.038	29.891-34.783	0.369-0.376	2.032-3.164	9.343-9.812	310.255-349.389	1.467-2.288	7.248-7.408	32.394-55.153	19.093-31.095	0.18-0.183
(N = 2) Mean conc.	4DWL	21.055	0.055	0.052	0.01	10.878	0.265	0.002	2.266	0.005	0.033	32.337	0.373	2.598	9.578	329.822	1.878	7.328	43.774	25.094	0.182
SD	4DWL	0.33	0.016	0.03	0.001	0.346	0.055	0.001	0.96	0.003	0.008	3.459	0.005	0.8	0.332	27.672	0.581	0.113	16.093	8.487	0.002
Conc. range	5HWL	3.489-4.768	0.009-0.009	0.04-0.059	0.04-0.76	8.648-12.199	0.094-0.158	0.005-0.009	1.34-3.275	0.004-0.006	0.052-0.109	242.571-618.599	0.679-1.688	0.382-0.897	12.006-25.624	103.574-308.002	1.376-3.418	2.066-2.813	67.504-73.122	20.899-28.655	0.069-0.174
(N = 2) Mean conc.	5HWL	4.129	0.009	0.05	0,4	10.424	0.126	0.007	2.308	0.005	0.081	430.585	1.184	0.64	18.815	205.788	2.397	2.44	70.313	24.772	0.122
SD	5HWL	0.904	0.0	0.013	0.509	2.511	0.045	0003	1.368	0.001	0.04	265.892	0.713	0.364	9.629	144.552	1.444	0.528	3.973	5.491	0.074
Conc. range	6RWL	81.021-81.674	0.067-0.08	0.079-0.115	0.017-0.017	37.936-39.715	0.183-0.264	0.003-0.003	1.932-2.247	0.004-0.006	0.22-0.223	132.896-158.842	1.292-1.407	0.758-0.861	27.124-36.06	424.183-544.931	1.857-1.873	1.882-2.715	48.946-56.505	21.679-29.88	1.13-1.217
(N = 2) Mean conc.	6RWL	81.348	0.074	0.097	0.017	38.826	0.224	0.003	2.09	0.005	0.222	145.869	1.35	0.81	31.592	484.557	1.865	2.299	52.726	25.78	1.174
SD	6RWL	0.462	0.009	0.025	0	1.258	0.057	0	0.223	0.001	0.002	18.347	0.081	0.073	6.319	85.382	0.011	0.589	5.345	5.799	0.062
No. samples & value type	Sample code	Sr (µg/L)	Mo (µg/L)	Cd (µg/L)	Cs (µg/L)	Ba (µg/L)	W (µg/L)	Tl (µg/L)	Pb (µg/L)	Bi (µg/L)	U (µg/L)	Al (µg/L)	V (µg/L)	Cr (µg/L)	Mn (µg/L)	Fe (µg/L)	Co (µg/L)	Ni (µg/L)	Cu (µg/L)	Zn (µg/L)	As (µg/L)
Conc. range	1SWK	134.873-155.478	0.04-0.076	0.195-0.33	0.068-0.091	67.178-80.931	0.034-0.301	0.001-0.003	0.497-3.923	0.001-0.01	0.576-0.814	241.306-311.773	0.321-0.432	0.339-0.75	0.582-3.076	10.062-49.768	0.114-0.709	0.361-2.6	5.344-53.798	82.616-249.791	0.166-8.678
(N = 6) Mean conc.	1SWK	143.216	0.057	0.242	0.076	72.308	0.113	0.002	1.434	0.004	0.67	276.54	0.369	0.498	1.773	29.21	0.387	1.027	19.621	133.866	1.624
SD	1SWK	8.772	0.016	0.065	0.01	5.961	0.115	0.001	1.441	0.004	0.095	49.828	0.048	0.19	1.115	13.339	0.269	0.985	21.196	70.886	3.456
Conc. range	2DWK	33.019-42.154	0.009-0.18	0.15-0.584	0.8-0.984	24.018-33.527	0.015-1.105	0.012-0.017	0.525-9.979	0.001-0.012	0.068-0.204	208.38-425.063	0.141-0.45	0.393-1.899	1.662-11.076	6.977-153.048	0.189-3.783	6.164-10.349	3.065-55.24	33.681-150.027	0.248-0.646
(N = 8) Mean conc.	2DWK	35.754	0.043	0.29	0.896	28.191	0.269	0.014	2.154	0.003	0.125	316.722	0.209	0.71	3.344	47.411	0.72	7.582	16.244	61.433	0.377

Table 1 to be continued

SD	2DWK	2.856	0.057	0.151	0.064	3.167	0.46	0.002	3.189	0.004	0.042	153.218	0.1	0.515	3.16	45.283	1.244	1.28	22.483	39.484	0.139
Conc. range	3DWK	6.926-127.236	0.027-0.194	0.6-1.205	0.018-0.593	3.676-54.945	0.008-0.335	0.008-0.024	0.85-5.393	0.001-0.018	0.277-2.317	852.09-930.188	0.508-0.726	0.111-0.734	3.578-77.647	14.712-280.681	0.153-8.647	0.284-13.788	17.015-65.13	70.724-156.137	0.891-2.03
(*N* = 6) Mean conc.	3DWK	87.573	0.126	0.862	0.197	19.887	0.111	0.013	2.171	0.006	1.607	891.139	0.556	0.403	26.765	93.435	2.634	4.72	32.515	108.889	1.602
SD	3DWK	59.659	0.072	0.268	0.277	25.004	0.131	0.008	1.902	0.007	0.996	55.224	0.084	0.312	34.306	117.176	3.808	6.712	19.341	32.375	0.457
Conc. range	4DWK	62.221-79.488	0.021-0.076	0.021-0.149	0.132-0.244	6.952-9.459	0.007-0.149	0.003-0.006	0.26-3.625	0.001-0.01	1.452-2.431	294.977-614.781	0.505-1.271	0.067-0.658	0.638-4.932	7.815-125.18	0.113-2.726	0.427-1.381	2.052-26.307	249.067-607.926	0.444-0.577
(*N* = 6) Mean conc.	4DWK	69.268	0.053	0.06	0.164	7.999	0.056	0.004	1.47	0.004	1.941	454.879	0.728	0.257	1.959	44.016	0.695	0.73	8.427	429.326	0.489
SD	4DWK	7.844	0.022	0.051	0.047	0.984	0.061	0.001	1.434	0.004	0.335	226.136	0.326	0.232	1.749	46.208	1.023	0.381	9.443	152.905	0.049
Conc. range	5HWK	8.321-15.437	0.02-0.079	0.215-0.315	0.007-0.019	61.466-72.097	0.04-0.125	0.002-0.007	1.252-2.022	0.001-0.01	0.11-0.376	589.062-614.951	0.084-0.68	0.262-0.818	28.434-79.51	21.426-246.214	8.072-12.783	8.332-12.64	16.205-21.113	28.12-64.649	0.118-0.291
(*N* = 4) Mean conc.	5HWK	11.78	0.041	0.254	0.013	66.441	0.085	0.004	1.633	0.005	0.196	602.007	0.381	0.515	53.066	133.021	10.302	10.376	18.486	48.015	0.206
SD	5HWK	3.829	0.027	0.043	0.006	5.705	0.046	0.003	0.372	0.004	0.122	18.306	0.341	0.289	28.267	126.342	2.516	2.287	2.02	15.72	0.084
Conc. range	6HWK	8.217-19.838	0.005-0.255	0.074-0.265	0.005-0.066	12.695-105.507	0.007-0.164	0.001-0.017	0.283-4.525	0-0.007	0.036-0.228	419.131-464.401	0.015-0.658	0.203-0.778	2.699-76.373	31.387-3377.455	0.843-13.49	1.371-12.688	4.058-18.858	24.972-115.586	0.162-5.251
(*N* = 8) Mean conc.	6HWK	13.424	0.05	0.183	0.022	49.499	0.047	0.007	1.858	0.002	0.098	440.766	0.39	0.426	26.614	807.718	4.245	4.843	13.526	62.376	1.095
SD	6HWK	4.666	0.083	0.08	0.022	40.962	0.053	0.007	1.627	0.002	0.066	33.425	0.251	0.172	30.44	1,112.272	5.184	4.726	6.083	30.413	1.796
Conc. range	7MWK	494.183-607.049	3.121-7.849	23.917-66.378	0.888-0.93	56.771-59.396	0.105-0.718	0.006-0.06	23.488-221.117	0.004-0.019	3.372-6.311	320.272-416.583	0.697-3.933	0.498-2.078	30.338-99.249	889.961-8,335.139	10.697-17.121	3.345-5.649	139.756-996.934	3,169.971-8,732.116	9.476-43.62
(*N* = 4) Mean conc.	7MWK	553.456	6.361	44.772	0.909	58.259	0.449	0.043	122.288	0.01	4.715	368.428	1.962	1.219	64.83	4,262.883	13.94	4,573	561.549	5,908.233	22.883
SD	7MWK	61.311	2.21	24	0.018	1.152	0.278	0.025	114.049	0.006	1.534	68.102	1.568	0.807	39.483	3,907.836	3.526	1,186	485.937	3,148.506	16.504

DWL: drilled water well in Lupoto; HWL: hand-sunk water well in Lupoto; DWK: drilled water well in Kipushi; HWK: hand-sunk water well in Kipushi; MWK: Kipushi mine effluent/waste water; *N* samples: number of samples; RWL: Kipopo River water in Lupoto; SD: standard deviation; SWK: supplied tap water in Kipushi town.

Table 2 PTEs acceptable maximum contaminant levels and indicator parameters or health advisories set by the EU, USEPA, and WHO standards for drinking water.

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

*: Drinking Water Indicator Parameters set by the European Union; **: Drinking Water Health Advisories set by the United States Environmental Protection Agency; EU: European Union; Hth Adv: Health Advisories; Ind Par: Indicator Parameters; MCLs: Drinking water acceptable maximum contaminant levels; ND: non-available data; USEPA: United States Environment Protection Agency; WHO: World Health Organization.

and 0.013 µg/L in 3DWL for Bi, from 0.005 to 0.93 µg/L and 0.009 to 0.76 µg/L with the highest mean concentrations of 0.909 µg/L in 7MWK and 0.4 µg/L in 5HWL for Cs, from 0.113 to 17.121 µg/L and 1.376 to 31.613 µg/L with the highest mean concentrations of 13.94 µg/L in 7MWK and 28.938 in 2HWL µg/L for Co, from 0.007 to 1.105 µg/L and 0.094 to 0.455 µg/L with the highest mean concentrations of 0.449 µg/L in 7MWK and 0.455 µg/L in 3DWL for W, and from 0.015 to 3.933 µg/L and 0.348 to 1.688 µg/L with the highest mean concentrations of 1.962 µg/L in 7MWK and 1.35 µg/L in 6RWL for V (Table 1; Figs. 4, 8, 10, 13, 16, and 19). Despite their low concentrations, these PTEs might be detrimental to the health of people who use that contaminated water due to possible bioaccumulation and biomagnification of those metals by human organs. Even Co which is known to be among the essential trace elements for normal body function at very low concentrations, the toxicity of this metal in humans has been noted [31]. Guo et al. [19] have reported on the changes of essential trace elements in residents from e-waste site and the relationships between elements and hormones of the HPT (Hypothalamic-Pituitary-Thyroid) axis. Other researchers have reported on Bi toxicity [32-35], W toxicity [36, 37] and V neurotoxicity [9].

Symptoms of decreased appetite, nausea, diarrhea, and cardiac arrhythmia have been associated with consumption of Cs chloride [38-42].

For PTEs such as Al, As, Ba, Cd, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sr, Tl, U, and Zn, MCLs (Maximum Contaminant Levels) and health advisories/indicator parameters have been determined by various international standards for drinking water (Table 2). Some of these PTEs, such as Ba, Cr, Cu, Mo, Ni, Sr, Tl and U had much lower mean concentrations in water than their respective MCLs or health advisories/indicator parameters at all the sampling sites in both Kipushi town and Lupoto locality (Tables 1 and 2). The other PTEs, including Al, As, Cd, Fe, Mn, Pb and Zn had mean concentrations much higher than their respective MCLs or health advisories in water samples from some sampling sites in both localities (Tables 1 and 2).

In Kipushi town, the highest concentrations of As, Cd and Pb were respectively 8.678 µg/L, 0.33 µg/L and 3.923 µg/L in water samples from water supply tap, 2.05 µg/L, 1.205 µg/L and 9.979 µg/L in water samples from drilled water wells, 8.151 µg/L, 0.315 µg/L and 2.022 µg/L in water samples from spade-sunk water well, and 43.62 µg/L, 66.78 µg/L and 221.117 µg/L in water samples from Kipushi mine effluent (Table 1; Figs. 2, 4, 5, 12, 13, and 15, 16). The highest mean concentrations of these PTEs (As, Cd and Pb) were respectively 1.624 µg/L, 0.242 µg/L and 1.434 µg/L in water samples from water supply tap, 2.05 µg/L, 1.205 µg/L and 2.154 µg/L in water samples from drilled water wells, 8.151 µg/L, 0.315 µg/L and 2.022 µg/L in water samples from spade-sunk water well, and 22.883 µg/L, 44.772 µg/L and 122.288 µg/L in water samples from Kipushi mine effluent. The highest concentrations of Al, Fe, Mn and Zn were respectively 311.773 µg/L, 49.763 µg/L, 3.076 µg/L and 249.791 µg/L in water samples from the water supply tap, 930.188 µg/L, 3,377.455 µg/L, 77.647 µg/L and 607.926 µg/L in water samples from the drilled water wells, 614.951 µg/L, 246.214 µg/L, 79.51 µg/L and 64.649 µg/L in water samples from the spade-sunk water well, and 416.583 µg/L, 8,335.139 µg/L, 99.249 µg/L and 8,732.116 µg/L in water samples from the Kipushi mine effluent. And the highest mean concentrations of Al, Fe, Mn and Zn were respectively 276.54 µg/L, 29.21 µg/L, 1.773 µg/L and 133.866 µg/L in water samples from the water supply tap, 891.139 µg/L, 807.718 µg/L, 26.765 µg/L and 429.326 µg/L in water samples from the drilled water wells, 602.007 µg/L, 133.021 µg/L, 53.066 µg/L and 48.015 µg/L in water samples from the spade-sunk water well, and 368.428 µg/L, 4,262.883 µg/L, 64.83 µg/L and 5,908.233 µg/L in water samples from the Kipushi mine effluent (Table 1; Figs. 3, 5, 12, 14, 15, and 17). Kipushi mine effluent water had very high mean concentrations of Al, As, Cd, Fe, Mn, Pb, and Zn and was thus the most polluted water in Kipushi town (Table 1).

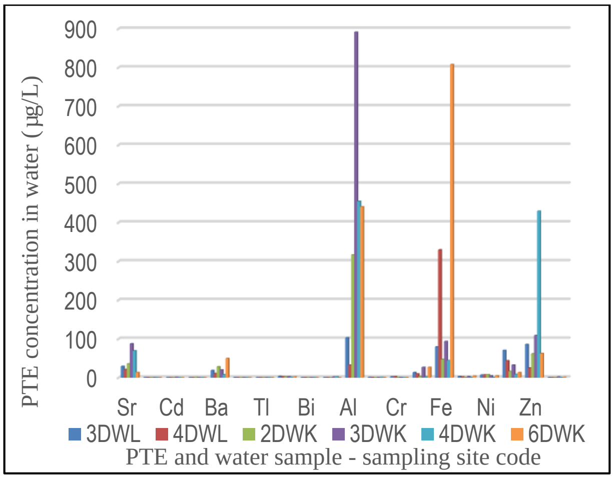

Fig. 2 Mean concentrations of all PTEs detected in water samples (µg/L) from drilled water wells in Kipushi town and Lupoto locality.

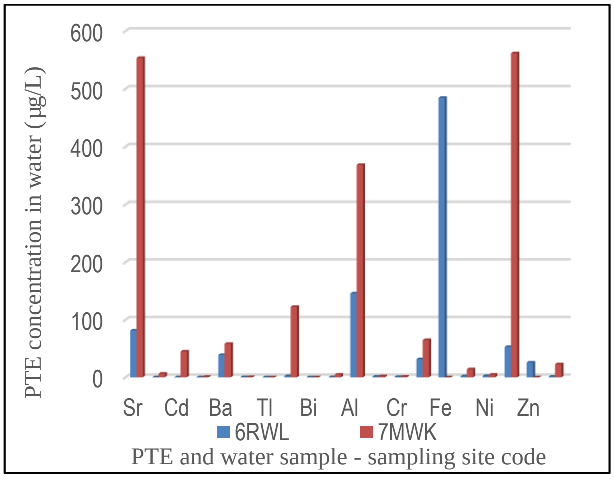

Fig. 5 Mean concentrations of all PTEs detected in water samples (µg/L) from Kipushi mine effluent in Kipushi town and Kipopo river in Lupoto locality.

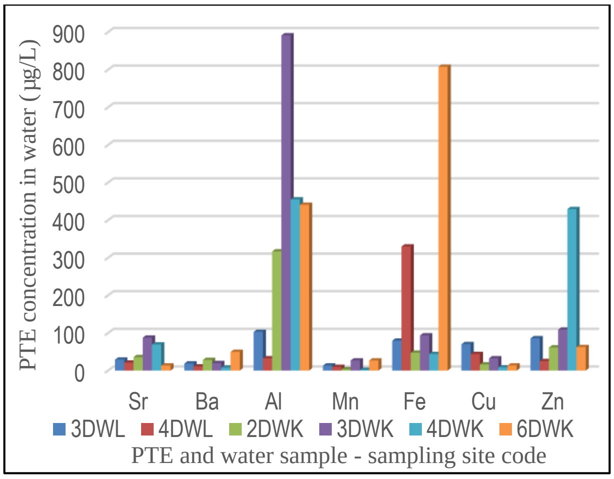

Fig. 3 High mean concentrations of various PTEs in water samples (µg/L) from drilled water wells in Kipushi town and Lupoto locality.

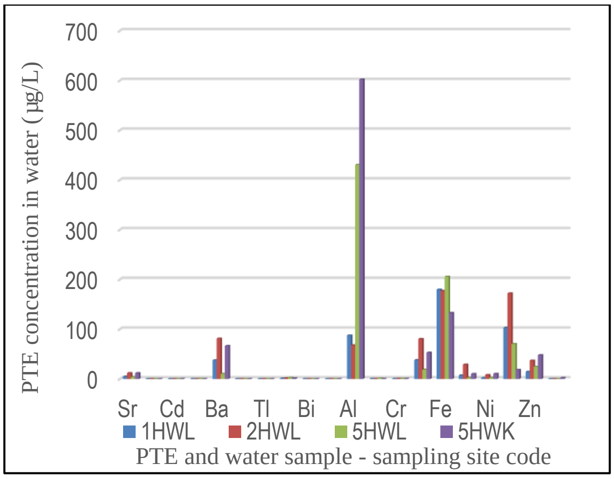

Fig. 6 Mean concentrations of all PTEs detected in water samples (µg/L) from spade-sunk water wells in Kipushi town and Lupoto locality.

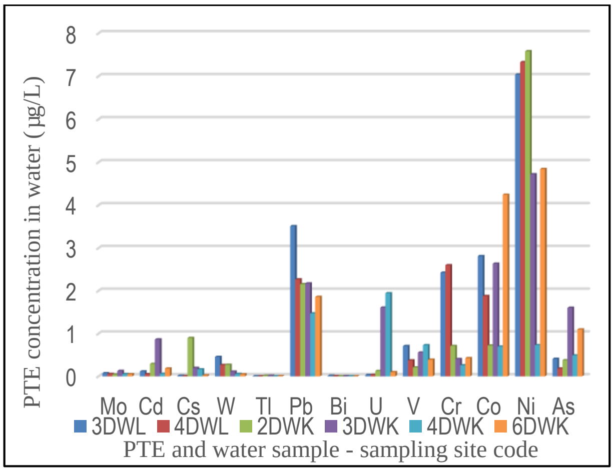

Fig. 4 Low mean concentrations of various PTEs in water samples (µg/L) from drilled water wells in Kipushi town and Lupoto locality.

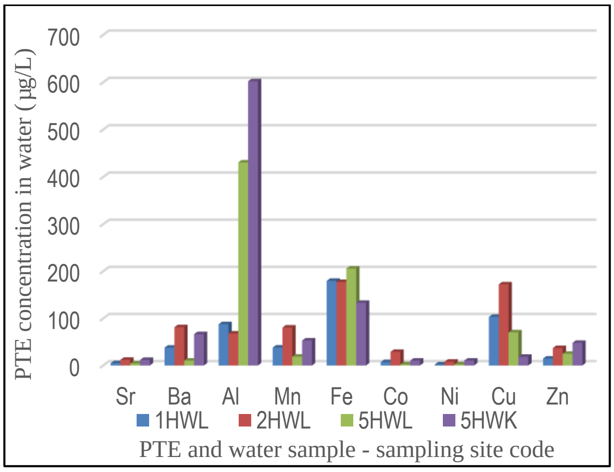

Fig. 7 High mean concentrations of various PTEs in water samples (µg/L) from spade-sunk water wells in Kipushi town and Lupoto locality.

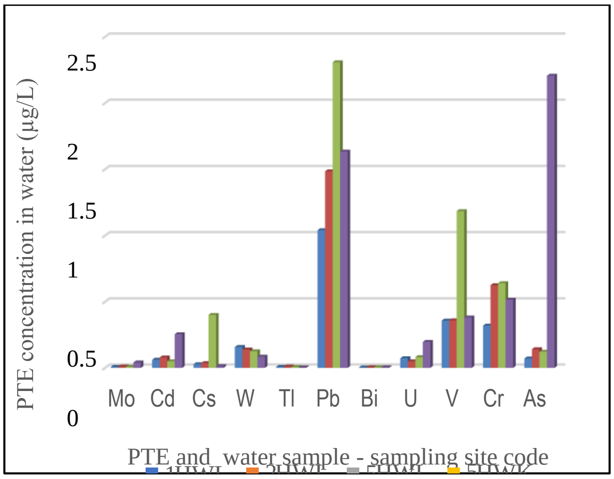

Fig. 8 Low mean concentrations of various PTEs in water samples (µg/L) from spade-sunk water wells in Kipushi town and Lupoto locality.

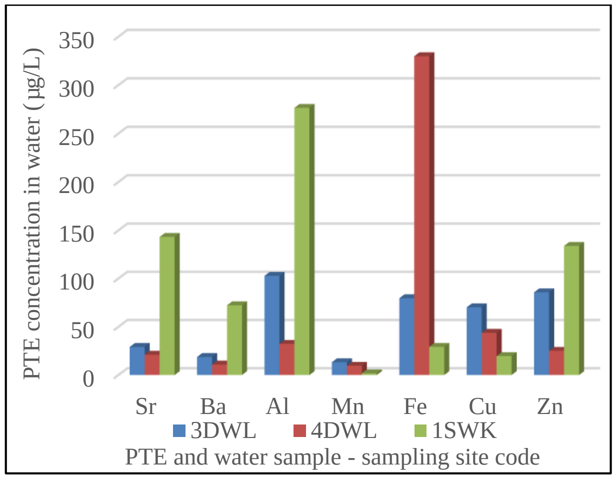

Fig. 11 High mean concentrations of various PTEs in water samples (µg/L) from water supply tap in Kipushi town and from drilled water wells in Lupoto locality.

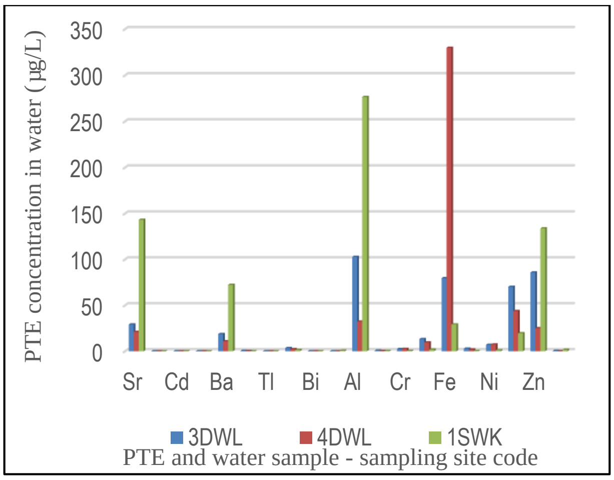

Fig. 9 Mean concentrations of all PTEs detected in water samples (µg/L) from water supply tap in Kipushi town and from drilled water wells in Lupoto locality.

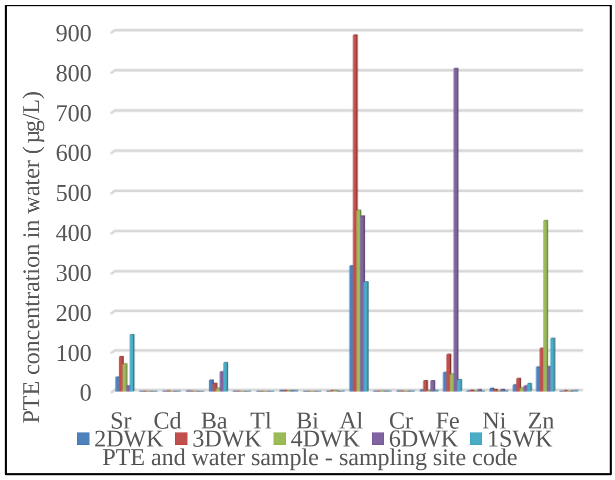

Fig. 12 Mean concentrations of all PTEs detected in water samples (µg/L) from water supply tap and drilled water wells in Kipushi town.

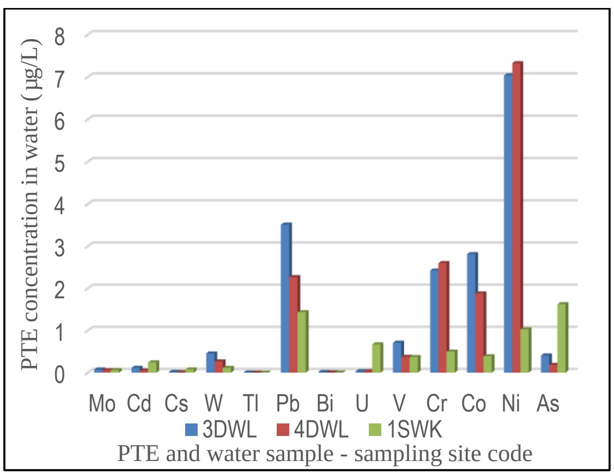

Fig. 10 Low mean concentrations of various PTEs in water samples (µg/L) from water supply tap in Kipushi town and from drilled water wells in Lupoto locality.

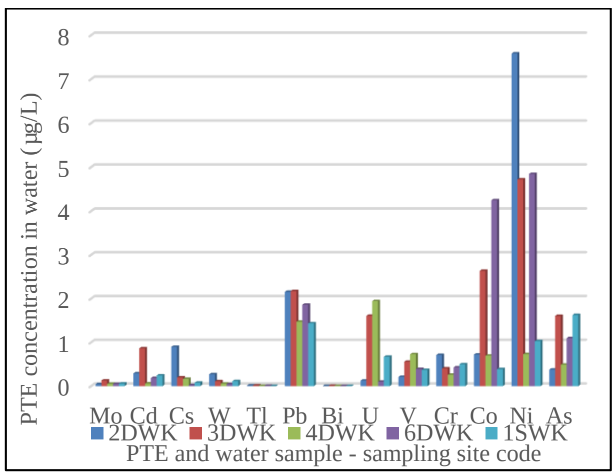

Fig. 13 Low mean concentrations of various PTEs in water samples (µg/L) from water supply tap and drilled water wells in Kipushi town.

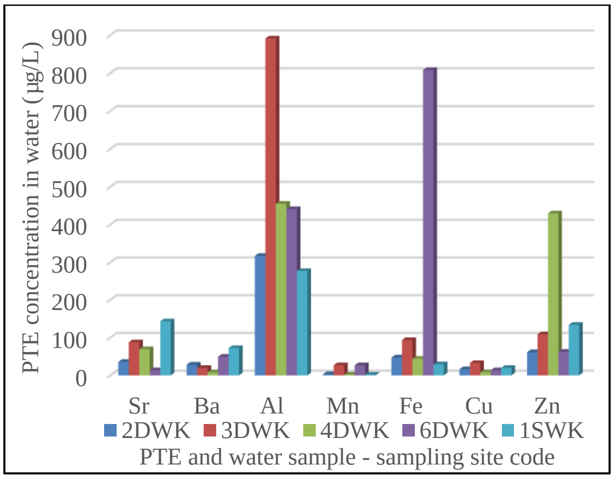

Fig. 14 High mean concentrations of various PTEs in water samples (µg/L) from water supply tap and drilled water wells in Kipushi town.

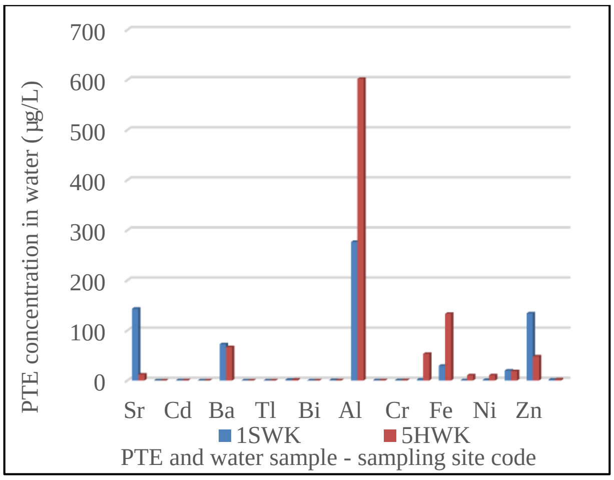

Fig. 15 Mean concentrations of all PTEs detected in water samples (µg/L) from water supply tap and spade-sunk water wells in Kipushi town.

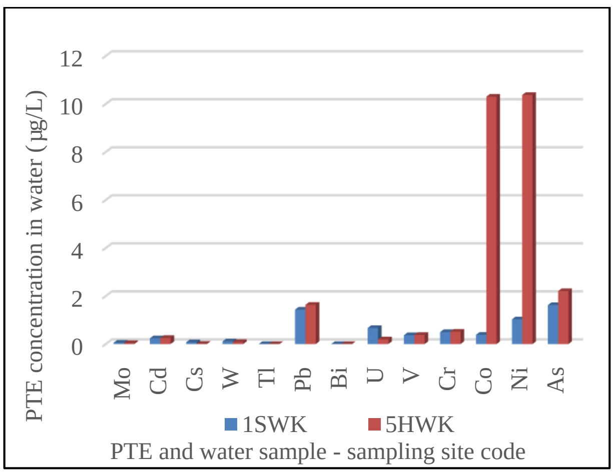

Fig. 16 Low mean concentrations of various PTEs in water samples (µg/L) from water supply tap and spade-sunk water wells in Kipushi town.

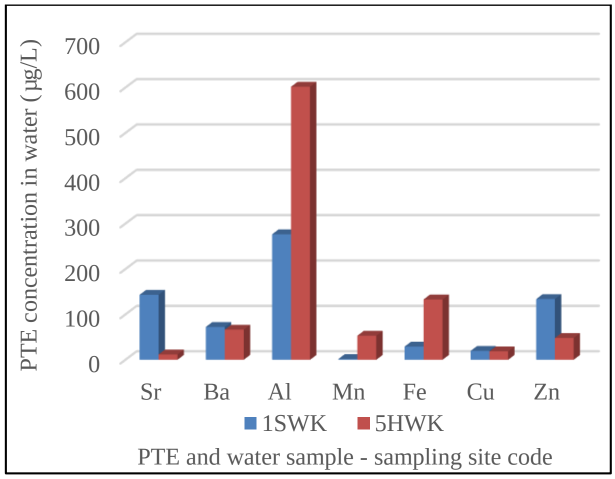

Fig. 17 High mean concentrations of various PTEs in water samples (µg/L) from water supply tap and spade-sunk water wells in Kipushi town.

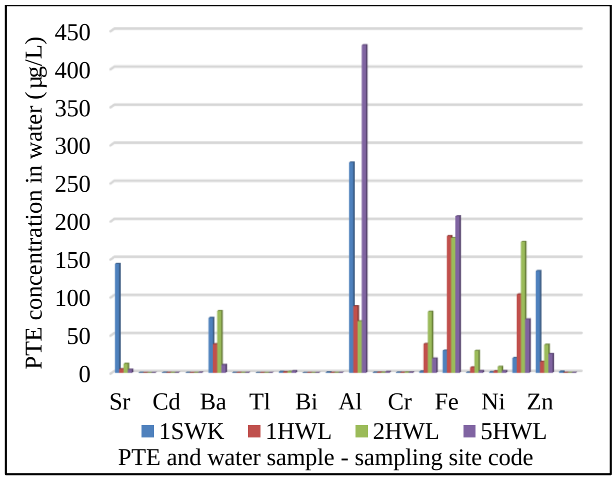

Fig. 18 Mean concentrations of all PTEs detected in water samples (µg/L) from water supply tap in Kipushi town and from spade-sunk water wells in Lupoto locality.

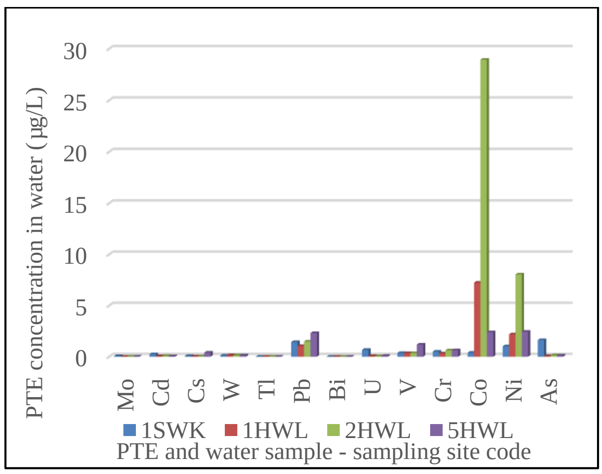

Fig. 19 Low mean concentrations of various PTEs in water samples (µg/L) from water supply tap in Kipushi town and from spade-sunk water wells in Lupoto locality.

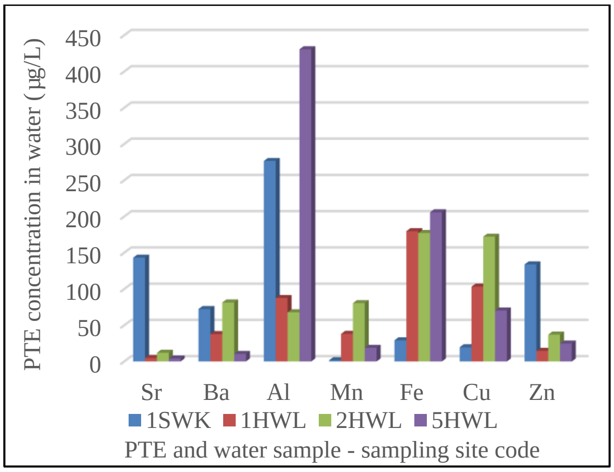

Fig. 20 High mean concentrations of various PTEs in water samples (μg/L) from water supply tap in Kipushi town and from spade-sunk water wells in Lupoto locality.

In Lupoto locality, the mean concentrations of As, Ba, Cd, Cr, Cu, Mo, Ni, Pb, Sr, Tl, U and Zn in all the water samples were respectively lower than their respective MCLs or health advisories (Tables 1 and 2; Figs. 2-11, 18-20). Mean concentrations of Fe in water samples from all the sampling sites were higher than the indicator parameter of 50 μg/L set by the EU (European Union) [28], with the highest concentrations and the highest mean concentrations of 349.389 μg/L and 329.822 μg/L in water samples collected from drilled water well 4DWL, 308.002 μg/L and 205.788 μg/L in water samples from spade-sunk water well 5HWL, and 544.931 μg/L and 484.557 μg/L in water samples from Kipopo river 6RWL. The concentrations of Al and Mn were higher than their respective EU indicator parameter and MCL of 200 μg/L and 50 μg/L, with the highest concentrations of 618.599 μg/L in spade-sunk water well 5HWL and 89.659 μg/L in spade-sunk water well 2HWL, and their highest mean concentrations were 430.585 μg/L and 80.463 μg/L, respectively (Tables 1 and 2). Many scientists among whom Guo et al. [43], and Wylie and Short [44] have noted that Mn is both a trace element and a heavy metal, and it is essential for brain development in appropriate doses; however, overexposure is toxic to health and development. They added that developing fetus and children are more susceptible than adults to Mn dysfunction in an inverted U-shaped relationship where both inadequate and excessive Mn status could induce developmental neurotoxicity. According to these scientists, humans acquire adequate amounts of Mn from nutritional sources, with toxicity tending to occur through contaminated air, water, and soil/foods or through occupational hazards, including metal processing.

Despite the low concentrations of As, Ba, Cd, Cr, Cu, Mo, Ni, Pb, Sr, Tl, U, Zn and some other PTEs in the water samples collected from water supply tap, drilled wells, spade-sunk water wells and Kipopo river (Table 1; Figs. 2, 4-6, 8-10, 12, 13, 15, 16, 18, 19), people in Kipushi town and Lupoto locality who use those waters to meet their drinking, cooking and bathing needs are at risk for their health. The highest mean concentrations of As and Pb in the waters used by the population of Kipushi town and Lupoto locality to meet their water needs were much lower than those respectively reported for similar water in Kinsevere (2.707 μg/L in 8EPF and 5.181 μg/L in 3EPF, respectively) [6]. The highest mean concentrations of both PTE in similar water in Katuba and Kenya municipalities of Lubumbashi city were 21.262 μg/L in 6EPA and 19.752 μg/L in 15EPA, respectively in Katuba municipality, and 7.275 μg/L in 1EPA and 13.58 μg/L in 3EPA, respectively in Kenya municipality [5]. In Lubumbashi and Kampemba municipalities of Lubumbashi city, the highest mean As and Pb concentrations in similar water (9.367 μg/L in 17EPF and 8.399 μg/L in 6EPA, respectively) in Lubumbashi municipality and (2.55 μg/L in 3EPA and 1.679 μg/L in 3EPA, respectively) in Kampemba municipality [4] were respectively higher than those noted in similar water in Kipushi town and Lupoto locality.

The highest mean concentration of Cd in water consumed by the population in Kipushi town was much elevated than that (0.63 μg/L in 4EPF) reported for similar water in Kinsevere but that of Cr was lower than the 0.835 μg/L in 10EPF noted for similar water in Kinsevere [6]. The highest mean concentration of Cd in water consumed by people in Kipushi town was lower than that (29.416 µg/L in 11EPA) noted in similar water in Katuba municipality but the Cr concentration found in similar water in Kipushi town was higher than that (0.684 µg/L in 6EPA) reported for similar water in Kenya municipality [5]. Also, the highest mean concentrations of Cd and Cr found in water consumed by people in Kipushi town were lower than those (9.367 µg/L in 17EPF) and (0.99 µg/L in 27EPA) noted in similar water in Lubumbashi municipality, and those (39.01 µg/L in 1EPF) and (1.142 µg/L in 1EPF) noted in similar water in Kampemba municipality, but the Cr concentration found in similar water in Kipushi town was higher than that (0.684 µg/L in 6EPA) reported for similar water in Kenya municipality [4]. The highest mean Cd concentration in water used by the population to meet their water needs in Kipushi town was lower than that (14.751 µg/L in 2EPF) noted in similar water in Kamalondo municipality but that of Cr in Kipushi town was higher than the highest mean Cr concentration (0.47 µg/L in 2EPF) reported for similar water in Kamalondo municipality [4]. For Ni and U, the respective highest mean concentrations in water consumed by people in Kipushi town (10.302 µg/L in 5HWK and 1.941 µg/L in 4DWK) were higher than those (5.493 µg/L in 3EPF and 1.084 µg/L in 2EPF) respectively reported for similar water in Kinsevere [6], those (7.784 µg/L in 15EPF and 1.554 µg/L in 3EPA) respectively reported for similar water in Lubumbashi municipality, and those (8.402 µg/L in 2EPF and 0.398 µg/L in 3EPA) respectively reported for similar water in Kampemba municipality [4]. However, the Ni highest mean concentration in Kipushi town water was lower than that (57.505 µg/L in 2EPF) noted in similar water in Kamalondo municipality but the highest mean concentration of U in Kipushi town water was higher than that (0.898 µg/L in 2EPF) in similar water in Kamalondo municipality [4]. The Ni highest mean concentration found in Kipushi town water was higher than that (9.502 µg/L in 11EPA) noted in similar water in Katuba municipality but the U highest mean concentrations in water consumed in Kipushi town and Lupoto locality water were much lower than that (9.672 µg/L in 5EPA) reported for similar water in Katuba municipality [5]. Also, the respective highest mean concentrations of Ni and U in water in Kipushi town and Lupoto locality were much lower than those (101.733 µg/L in 6EPA and 8.237 µg/L in 6EPA) respectively noted in similar water in Kenya municipality [5].

Some of the highest concentrations and mean concentrations of Al, As, Cd, Fe, Mn, Pb, and Zn found in waters in Kipushi town and Lupoto locality were more elevated than their respective MCLs and indicator parameters/health advisories set for drinking water by the EU [28], the USEPA [29] and the WHO [30]. PTE contamination of groundwater in both localities might be a result of natural and anthropogenic activities. Kurwadkar et al. [45] have reported that groundwater pollution is a result of natural and anthropogenic activities, and that while the elevated levels of various inorganic constituents could be attributed to natural processes, such as geological weathering and aquifer characteristics, many times, anthropogenic activities also substantially pollute the groundwater. According to the same researchers, extensive groundwater mining, the hydraulic connection between groundwater and other surface water bodies, and leaching underground buried infrastructure also contribute to groundwater quality. The PTE contamination of groundwater, surface water and tap water in Kipushi town and Lupoto locality might be due to interaction between rock and groundwater, to atmospheric deposition, and mainly to anthropogenic activities, such as mining and ore processing activities in both localities.

4. Conclusion

PTE contamination of water in Kipushi town and Lupoto locality of the Kipushi administrative territory in the Upper-Katanga province was assessed in order to find out the chemical quality of that water and to know whether the water could present any threat to the health of inhabitants of both localities. Fifty four water samples collected in both localities from tap water, six drilled water wells, four spade-sunk water wells, Kipopo river in Lupoto and Kipushi mine effluent/waste water were analyzed for their PTE contents by using ICP-SF-MS. Twenty PTEs including aluminum, arsenic, barium, bismuth, cadmium, cesium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, strontium, thallium, tungsten, uranium, vanadium and zinc were detected at various concentrations in each one of the water samples. Some of the water samples had mean concentrations of PTE, such as arsenic, aluminum, cadmium, iron, lead, manganese and zinc, higher than the respective PTE acceptable limits and indicator parameters/health advisories set for drinking water by international standards. Most PTEs being deleterious to human health even at very low concentrations, people who use the groundwater and surface water to meet their water needs in both localities are at risk.

Authors suggest that the provincial and national Governments strictly implement the Congolese Mining Rules to require that the owner of Kipushi mining and ore processing company treat the PTE polluted mine effluent in order to reduce PTE content of the waste water before releasing it into the nature. The national Government should also substantially finance REGIDESO, the Congolese water supply company to allow it to provide suitable drinking water to all inhabitants of Kipushi town and Lupoto locality.

Funding

We would like to acknowledge the funding received from UNESCO-SIDA project as well as Professor Martine Leermakers and Professor Willy Baeyens for their financial help to analyze the samples by the AMGC laboratory at VUB in Brussels, Belgium.

Acknowledgements

Ms. Clarisse Kunyonga and Ms. Sonya Mulongo, both Senior Assistant Lecturers at the University of Lubumbashi are respectively thanked, the former for her help during sampling campaigns and the latter for having stored the samples until they were taken to the AMGC laboratory at VUB for chemical analyses.

References

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

[2] Muhaya, B. B., Kayembe, M. W. K., Mulongo, S. C., Kunyonga, C. Z., and Mushobekwa, F. Z. 2017. "Trace Metal Contamination of Water in the Lubumbashi River Basin, Kafubu, Kimilolo and Kinkalabwamba Rivers in Lubumbashi City, Democratic Republic of Congo." *Journal of Environmental Science and Engineering B* 6 (6): 301-11. https://doi.org/10.17265/2162-5263/2017.06.002.

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

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

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

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

[7] Muhaya, B. B., and Badarhi, B. B. 2025. "Concentrations of Potentially Toxic Elements in Groundwater and Surface Water in Ruashi and Annexe Municipalities of Lubumbashi City, Southeastern Republic of Congo." *Journal of Environmental Science and Engineering A* 14 (1): 1-13. https://doi.org/10.17265/2162-5298/2025.01.001.

[8] Mudekereza, M. A., Gray, K., Tamubango, K. H., and Numbi, L. 2016. "Eléments traces dans le serum des enfants malnutris et bien nourris vivants à Lubumbashi et

Kawama dans un contexte d'un environnement de pollution minière." *Pan African Medical Journal* 24 (1): 11. https://doi.org/10.11604/pamj.2016.24.11.9236. (in French)

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

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

[11] Browar, A. W., Koufos, E. B., Wei, Y., Leavitt, L. L., Prozialeck, W., and Edwards, J. R. 2018. "Cadmium Exposure Disrupts Periodontal Bone in Experimental Animals: Implications for Periodontal Disease in Humans." *Toxics* 6 (2): 32-41. https://doi.org/10.3390/toxics6020032.

[12] Jain, R. B. 2018. "Trends over 1999-2014 in the Concentrations of Ba, Cs, Co, Mo, Pb, Sb, Tl, and W in Urine of US Children Aged 6-11 Years." *Toxicological and Environmental Chemistry* 100 (1): 115-33. https://doi.org/10.1080/02772248.2017.1402181.

[13] Mukendi, M. R. A., Banza, L. N. C., Mukeng, C. A. K., Ngwe, T. M. J., Mwembo, N.-A.-N. A., and Kalenga, M. K. P. 2018. "Exposition de l'homme aux éléments traces métalliques et altération du sperme : étude menée dans les zones minières au Haut-Katanga en République Démocratique du Congo." *The Pan African Medical Journal* 30: 35. https://doi.org/10.11604/pamj.2018.30.35. 13694. (in French)

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

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

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

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

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

[19] Guo, C., Qian, Y., Yan, L., Li, Z., Liu, H., Li, X., Wang, Z., Zhu, X., Wang, J., and Wei, Y. 2021. "The Changes of Essential Trace Elements in Residents from E-Waste Site and the Relationships between Elements and Hormones of the Hypothalamic-Pituitary-Thyroid (HPT) Axis." *Ecotoxicology and Environmental Safety* 222: 112513. https://doi.org/10.1016/j.ecoenv.2021.112513.

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

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

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

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

[24] Nuvolone, D., Petri, D., Aprea, M. C., Bertelloni, S., Voller, F., and Aragoni, I. 2021. "Thallium Contamination of Drinking Water: Health Implications in a Residential

Cohort Study in Tuscany (Italy)." *International Journal of Environmental Research and Public Health* 18 (8): 4058. https://doi.org/10.3390/ijerph18084058.

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

[26] https://fr.wikipedia.org/wiki/Kipushi, accessed on February 8, 2024.

[27] https://www.mindat.org/loc-159574.html, accessed on February 8, 2024.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[43] Guo, X., Xu, J., Tian, Y., Ouyang, F., Yu, X., Liu, J., Yan, C., and Zhang, J. 2024. "Interaction of Prenatal Maternal Selenium and Manganese Levels on Child Neurodevelopmental Trajectories—The Shanghai Birth Cohort." *Science of the Total Environment* 915: 170095. https://doi.org/10.1016/j.scitotenv.2024.170095.

[44] Wylie, A. C., and Short, S. J. 2023. "Environmental Toxicants and the Developing Brain." *Biological Psychiatry* 93 (10): 921-33. https://doi.org/10.1016/j.biopsych.2023.01.007.

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