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ASSESSMENT OF TRACE ELEMENT LEVELS IN WATER FROM RUNGWE GEOTHERMAL AREA, SW-TANZANIA

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ABSTRACT

Trace element concentrations in water sources are not only useful in indicating environmental pollution but also in the characterization of the water quality and applications. The presence of high concentrations of trace elements such as arsenic in water sources is a serious global health problem. The long-term use of water with high arsenic content may result in various life threatening diseases such as skin cancer. The purpose of this study is to assess the trace element concentration levels in water and also to evaluate the water quality from Rungwe geothermal area in SW-Tanzania. The study area is located within the area around the Rungwe, Ngozi and Kyejo volcanoes; this area has shown the existence of a geothermal resource. The assessment of trace element concentration levels in 13 water samples from Rungwe geothermal area indicated elevated levels of arsenic ranging from 70 to 130 µg/L. The As levels also indicated a potential health problem as it exceeds the WHO (2011) drinking water guideline value of 10 µg/L in 9 of the 13 water samples evaluated. The Ba concentrations also exceeded the WHO (2011) values in 8 samples and the Be concentration was above the US EPA (2006) drinking water value, while Mo concentrations exceeded the maximum value for the FAO (1994) irrigation water value of 10µg/L in 6 water samples. These higher levels were found in the hot and thermal springs rather than in the cold springs. The presence of trace elements in these water samples may be accounted for by leaching of Rungwe volcanic rocks by thermal water. None of these elements were found in high enough concentrations to allow commercial extraction.

1. INTRODUCTION

Tanzania is one of the East African countries that is transected by the East Africa Rift system, one of the world's known locations having potential geothermal energy resources. The geothermal studies of surface manifestations in Tanzania by McNitt (1982) indicated the existence of geothermal energy potential of more than 650 MW. The identified areas with surface manifestations of geothermal resources in Tanzania include the volcanic areas in the northern and southern parts of the country and the coastal areas. However, more detailed research is required to prove this potential. The Rungwe geothermal area in the southwest part of Tanzania is considered to be a good prospect for the development of geothermal energy. Geochemical exploration studies of the surface manifestations from Rungwe geothermal area were carried out and the major components of the water were studied by Mnjokava (2007). The Rungwe geothermal area is within the Rungwe Volcanic Province, and in the northern part of the Malawi rift. The weathering of Rungwe volcanic rocks is described as the source of the major, minor and trace element concentrations for Lake Malawi (Branchu et al., 2010).

Trace elements are important because of their association with environmental, plant, animal and human health issues. Some trace elements may be beneficial to the health of humans, plants and animals in low concentrations, but may be toxic if present in higher concentrations. Elements like As, Cd, Cr, Hg, Pb, Se, B, Mo, and U could be a threat to the environment and to human health. The toxicity level of these elements in water may require detailed understanding prior to any water utilization. Natural waters like the cold and hot springs of Rungwe geothermal area may contain these elements although, generally, emphasis is given to contaminated waters. This study aims to assess the concentration levels of trace elements in waters from springs and Lake Ngozi in the Rungwe geothermal area and compare their concentrations with the international water quality guidelines for drinking water, livestock and irrigation water. Possible uses of the water from the Rungwe geothermal area will also be addressed.

2. GEOSCIENTIFIC BACKGROUND OF RUNGWE AREA

Rungwe geothermal area is in the southern part of Mbeya region, in SW-Tanzania. It is comprised of Rungwe Mountain which is surrounded by the catchment forest reserve, covered primarily with miombo woodlands. This forest is home to a variety of species of both flora and fauna, including the newly discovered monkey species on the volcano, the highland mangabey, which was named Rungwecebus Kipunji after the locale (Jones et al., 2005). The Rungwe Volcanic Province is surrounded by a number of rivers like Songwe and Kiwira in the north which flow to the southwest, and Mbaka to the southeast, which flows into Lake Malawi (Nyasa). Rungwe district is known to have good climatic conditions that favour the production of a variety of agricultural products such as bananas, rice, beans, coffee and potatoes. Below is a short summary of the geology of Tanzania and Rungwe Volcanic Province and a description of the hydrothermal activity of Rungwe.

2.1 Geology of Tanzania

The geology of Tanzania can be simply summarized as follows (Figure 1). The Archean rocks dominate in the central to the northern parts of Tanzania, forming the Tanzanian Archean craton. These take the forms of sedimentary and volcanic rocks within a setting of migamatites and mobilized granites. The Archean craton is surrounded by Paleoproterozoic Ubendian and Usagaran mobile belts to the southwest and southeast, respectively. These mobile belts are composed of high grade, strongly folded metamorphic rocks and intrusive granites. According to Theunissen et al. (1992), the Usagaran belt was largely overprinted by the Pan-African Mozambique belt during the Neoproterozoic along the eastern margin of the Tanzanian craton. Also, resulting from the different rifting episodes, the Archean and Proterozoic rocks are covered partially by Permian Karoo to Quaternary sediments including Cenozoic volcanics (Delvaux 1991). The youngest sediments and volcanics are related to the active Cenozoic East African Rift System (EARS), which is divided into the western and eastern branches. The East African Rift System developed mostly parallel to the Ubendian and Usagaran mobile belts and the two branches form a triple junction between the Rukwa, Malawi (Nyasa) and Usangu rift basins in the Rungwe volcanic complex (Delvaux and Hanon, 1993) in the Mbeya area in the southwest part of Tanzania.

2.2 Geology of Rungwe area

The Rungwe Volcanic Province in southwest Tanzania is part of the East African system (EARS), composed of three major central volcanoes: Ngozi, Rungwe and Kyejo (Figure 2). The major rock types found are mainly of basaltic and trachytic composition of Miocene to Quaternary age which in-fill the northern section of the Malawi rift, described by Harkin (1960) and more recently by Ebinger et al. (1989; 1993). The volcanic rocks cover an area of over 3000 km^2 but dispersed pumice and ash extend over a much wider area. Mafic lavas such as nephelinites are found at Kyejo and basanites and alkali basalts are found mainly around Ngozi and Rungwe volcanoes. An older and younger extrusive sequence was recognized in the Rungwe volcanic rocks, occupying about half the total area (Harkin, 1960). The younger volcanics are principally lavas while the older series comprises mainly tuffs. Both series include basalt, trachyte, phonolitic trachyte and phonolite, but the tephrite is confined to the younger series. Extensive pumice deposits that are spread all over the Rungwe Volcanic Province region (Harkin, 1960) were later attributed to Holocene eruptions of Ngozi and Rungwe by Ivanov et al. (1998).

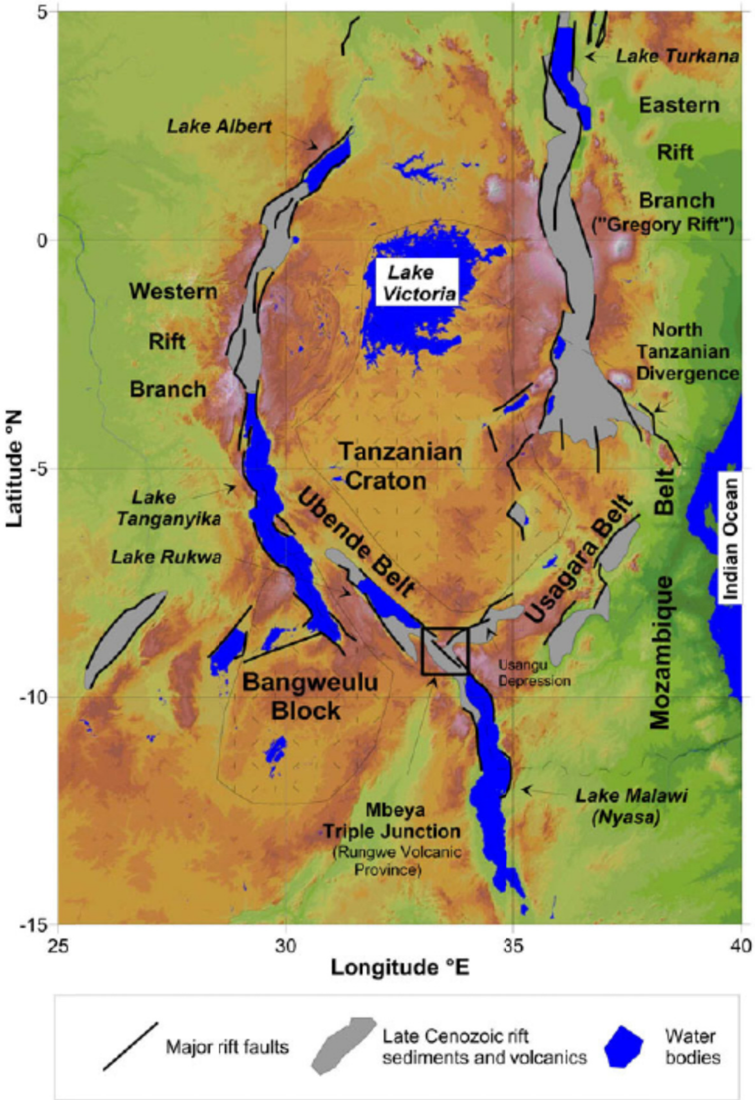

FIGURE 1: A simplified geological map of Tanzania, showing the East Africa Rift System (EARS), the triple junction and the study area (black box) at Rungwe Volcanic Province, SW-Tanzania (Delvaux et al., 2010)

Rungwe volcanism is thought to have initiated about 9 Ma ago (Fontijn et al., 2010). The tectonic and volcanic activity related to the Rungwe Volcanic Province was previously documented by Harkin (1960) and Ebinger et al. (1989). According to Fontijn et al. (2010), the volcano-tectonic architecture of the Rungwe Volcanic Province reveals strong control of tectonic activity on the regional location of at least two of the three major central volcanoes (Ngozi, Rungwe and Kyejo) as well as local distribution of eruptive vents on each of these three volcanoes. Several studies of the thermal springs in the area have been conducted by a number of authors including Harkin (1960), Hochstein et al. (2000), Hochstein (2005), and Branchu et al. (2005). These studies resulted in further investigations of the geothermal area in southwest Tanzania.

2.3 Hydrothermal activity in Rungwe

Hydrothermal activity associated with gas emissions and travertine deposits is widespread in the Rungwe Volcanic Province and coincides with the major active faults which favoured the rise of heat and volatiles (Harkin, 1960; Ebinger et al., 1993; Hochstein et al., 2000). Numerous small and large thermal springs surrounded by travertine deposits are found in the southern part of the area close to the

Kyejo basaltic lava flows, near Mbaka and also close to the Songwe River in the northwest part of the Rungwe area. According to studies by Harkin (1960), Ebinger et al. (1993), and Delvaux et al. (2010), the geothermal activity in the northernmost sub-basin of the Malawi rift, (Karonga basin) is tied to volcanism and a deep tectonic rift tapping heat and volatiles carried by rising deep water. The fluid geochemistry and the hydrothermal systems of the Rungwe Volcanic Province were studied earlier by Delalande et al. (2011), Hochstein et al. (2000), and Mnjokava (2007). According to Kraml et al. (2010), two different geothermal systems have been recognized in the Rungwe Volcanic Province, a northern and a southern system. The hydrothermal activity in the South Poroto-Rungwe volcanic province, which belongs to the southern system, is divided into two categories (Delalande et al., 2011). The first category is characterized by freshwater, cold and gas-rich (mainly CO_2) springs of temperatures of about 15 to 26°C**.** These springs (Shimwaga-S6, Mulagara-S7 and Isebe -S8) (Table 1) are from the northern volcanic highland area around Ngozi which also includes Rungwe and Tukuyu and Kyejo volcanoes (Figure 2). The second category is defined as the hot highly saline gaseous springs (Kilambo-S10, Mampulo-S11, Kandete-S12 and Kasimulo-S13) with temperatures ranging from 31.5 and 62.8°C, located in the southernmost part of Rungwe volcanic area, in the Kyela plain on the active Mbaka fault.

3. CHEMICAL CHARACTERISTICS OF WATER

The sampling and analysis of the water samples were done in June and November, 2006 by the Government of Tanzania in collaboration with the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany (Mnjokava, 2007). The full elemental analysis was done in the BGR laboratory, Germany, based on German standards. The geochemical sampling covered the area northwest of Mbeya town, including Ngozi, Kyejo, Tukuyu, to the northern part of Lake Malawi (Nyasa) (Figure 2). The analyses were conducted by applying the following methods (Mnjokava, 2007):

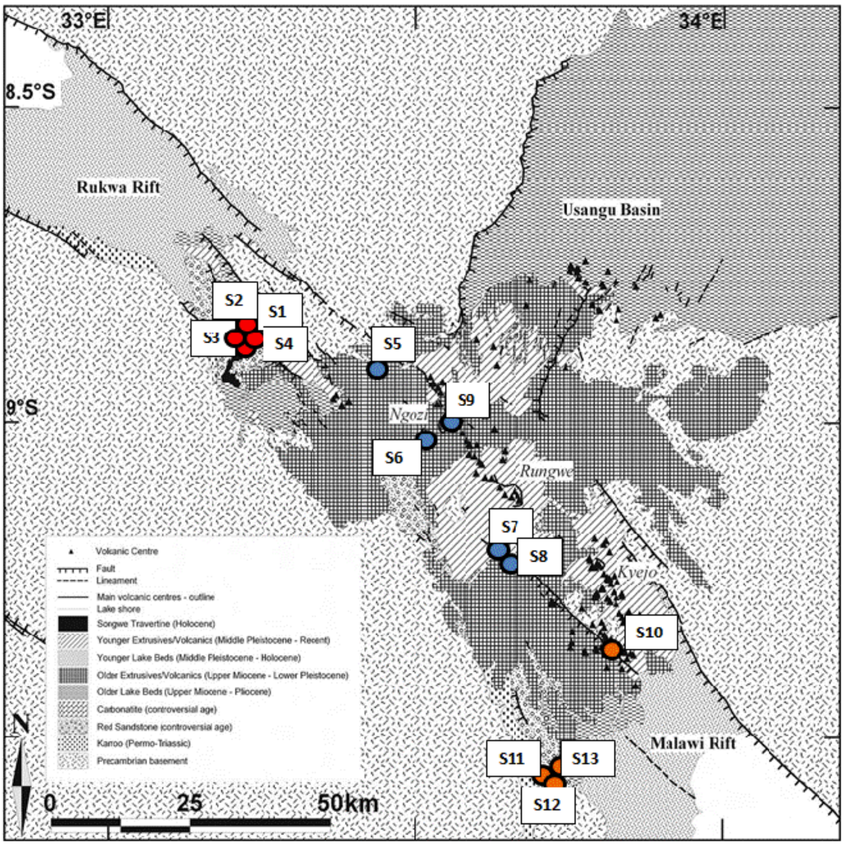

FIGURE 2: Rungwe Volcanic Province geological map, showing sampling points in Rungwe geothermal area (Fontijn et al., 2010)

The major components Na, K, Ca, Mg, B, Li, Al, Si, Mn and Fe were analyzed from Fa-samples (filtered acidified) by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), based on the German standard DINEN ISO 11885 (1998). Trace elements were analysed with Inductively Coupled Plasma Mass Spectrometry (ICP-MS) in three groups: (1) Ag, Ba, Be, Cd, Cs, Hf, Hg, In, Mo, Pb, Sb, Sn,Ta; (2) Te,Th,Tl; (3) U,W. Rare Earth Elements (REE) were analysed with low mass resolution ($m/\Delta m$ = 350). Al, Bi, Co, Cr, Cu, Ga, Li, Nb, Ni, Rb, Sc, Sr, Ti,V, Zn and Zr were analysed with medium resolution (m/Δm=3800) while As and Se were analysed with high mass resolution m/Δm=7500). Rh was used as an internal standard for all three groups. The Fu samples (filtered untreated) were used for the determination of the anions F^-, Cl^-, Br^-, NO_3^-, SO_4^{2-} using an Ion Chromatograph (ICP), based on the German standard DIN EN ISO 10304-1(1995).

3.1 Classification of water

The geochemistry and the geothermometer studies of Rungwe geothermal water were conducted earlier by Mnjokava (2007) and the dominant major and trace components ware identified. Mnjokava (2007) used the ternary diagrams Cl-SO_4-HCO_3 (Figure 3), Cl/100-B/4-Li and the Na-K-√Mg (Figure 3) diagram in classifying the geothermal water. Two major groups of water were identified from the Cl-SO_4-HCO_3 diagram: water from Lake Ngozi was found to be Cl-rich water; water from the springs was termed HCO_3 rich water. The Na-K-√Mg diagram showed that Shimwaga, Mulagara, Isebe, and Swaya are immature waters plotting close to the √Mg corner. The Main Spring B is also immature water, plotting further away from the √Mg corner. These immature waters could indicate a high proportion of cold groundwater, and have not attained equilibrium. Ilatile1, River Spring and Ilatile 4 are partially equilibrated and immature waters. The plot on the Cl/100-B/4-Li diagram showed that all the samples plotted in the Cl corner, indicating water from old geothermal systems. In this report, the water samples were grouped according to locations which coincide with temperature, with one exception. Starting from the northwest to the southeast (about 110 km distance), the groups are hot springs, cold water and thermal springs. The hot springs are located in the northwest part of the area and range in temperature from 70-82°C, except Swaya which has a temperature of 44°C. The thermal springs are located in the southeast of Rungwe Volcanic Province, close to Malawi rift, and have a range in temperature of 53-62°C. The cold waters are located in between those two groups near Ngozi, Rungwe and towards Kyejo volcanoes with temperatures of 20-26°C. A short description of the sampling locations, together with a field analysis, is shown in Table 1 and locations of the water samples are shown in Figure 2.

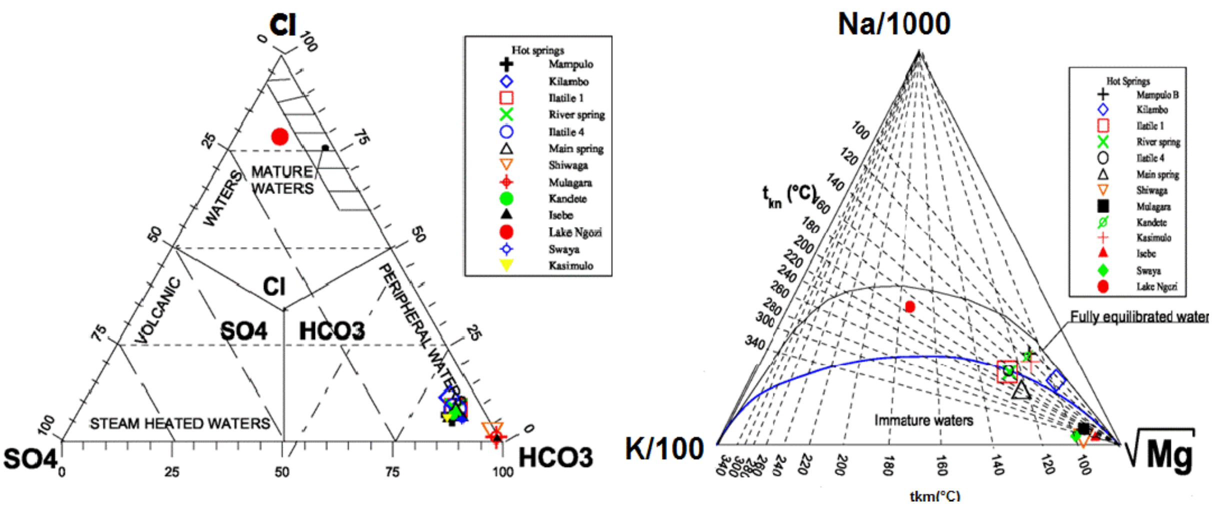

FIGURE 3: Classification of water from Rungwe using Cl-SO_4-HCO_3 diagram (left); The Na-K-Mg triangular diagram (right) for water from Rungwe geothermal area (Mnjokava, 2007)

3.2 Major components in water from the Rungwe geothermal area

The analytical results of the major components of water samples from Rungwe geothermal area are presented in Tables 2 and 3. Starting from the northwest with the hot springs, Main Spring B, Ilatile 1 and 4 and River Spring all have similar concentrations of the major elements (Table 2; Figure 2); the

TABLE 1: Description of water samples from Rungwe geothermal area with physical parameters (data from (1) Mnjokava, 2007; (2): Hochstein, 2000)

Sample ID	Sample code	Elevation[(1)] (m)	Temp.[(1)] (°C)	pH[(1)]	Conductivity[(1)] (µS/cm)	Location description
Main Spring B	S1	1140	74	7.9	3830	Differentiated rocks such as trachyte rocks with sedimentary rocks like travertine, near Songwe river.
Ilatile 1	S2	1127	72	8.3	3700	Hot spring near, Songwe travertine which is dominated by Mg-rich calcite.
Ilatile 4	S3	1087	80.2	8.5	3800	Hot spring, near Songwe travertine.
River Spring	S4	1087	74.1	8.3	3700	Hot spring, near Songwe travertine.
Swaya	S5	1810	44	7.5	360	Located between Songwe and Ngozi volcano, agricultural activities on soil of pumice origin.
Shimwaga uphill	S6	1713	26.5	7.1	140	Cold spring, CO_2 rich in the high altitude area close to Ngozi volcano.
Mulagara	S7	1470	26.5	7.1	960	Cold spring, close to Ngozi volcano, high altitude area.
Isebe	S8	1508	24.7	7.2	520	Cold spring, close to Ngozi volcano, high altitude area.
Lake Ngozi	S9	2190	20.9	7.4	4820	High elevated caldera lake with walls of phonolitic trachyte and tuffs; also alkali basalts; within vicinity of forest reserve.
Kilambo	S10	632	56.5	8.3	6000	Located in the vicinity of Mbaka fault zone and uplifted Precambrian gneiss [(2)]
Mampulo B	S11	531	61	8.4	7000	Occur in flat lying lacustrine sediments of Neogene age near lake Malawi. Discharge in a swampy areas covered by travertine deposits and carbonate crust[(2)]
Kandete	S12	537	56.6	8.1	5450	Volcanic and sedimentary rocks such as conglomerates and sandstone, also some agricultural activities in the area
Kasimulo	S13	512	54.7	8.0	4330	Flat lying lacustrine sediments between Songwe & Kiwira riv. near Lake Malawi; located in a swamp close to old gneissic rocks and less extensive travertine deposits; agricultural activities in the area.

distance between these springs is around 3 km. The most pronounced is the high concentration of the carbon oxides, sodium and potassium (Table 2); this could be due to dissolution of alkali–basaltic rocks due to CO_2 rich fluids, according to Kraml et al. (2010); all those springs belong to the northern Ngozi-Songwe geothermal system. The cold springs of Shimwaga uphill, Mulagara, and Isebe, which are located within a similar environment near Ngozi and Rungwe volcanoes, belong to the southern

(Ngozi–Kyejo) geothermal system. The Swaya spring, which is grouped with these northwest hot springs, is located about 32 km away from Ilatile 4 and has completely different major element concentrations. The distance between these springs is the most: 25 km (Figure 2). The concentration of the major elements is similar within this group, with a much lower sodium and potassium concentration than in the hot springs. The carbon oxide concentrations measure from ~100 up to 690 mg/l. Lake Ngozi, the caldera water, has completely different major element concentrations, as seen in Table 2. This can be explained by a dilution of an equilibrated hydrothermal solution with meteoric water.

TABLE 2: The concentration of the major components in water from Rungwe geothermal area (empty spaces indicate that data are not available)

Sample ID	Code	Temp °C	SiO_2 mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	Li mg/l	Al mg/l	Fe mg/l	Cl mg/l	HCO_3 mg/l	CO_3 mg/l	SO_4 mg/l	PO_4 mg/l	Br mg/l	F mg/l
Hot springs																	
Main Spr. B	S1	74	74	2202	1502	21	16.2	0.725	<0.005	0.024	175	1880		146	<0.03	0.7	
Ilatile 1	S2	72	68	2251	1529	10	7.9	0.758	0.007	0.011	181	1760	54	139	0.05	0.79	
Ilatile 4	S3	80,2	70	2290	1554	17	8.0	0.762	0.371	0.177	184	1760	66	143	0.03	0.81	
River spring	S4	74,1	79	2296	1559	16	8.5	0.751	0.056	0.03	180	1730	78	138	0.02	0.79	
Cold water																	
Swaya	S5	44	90	109	80	13	4,8	0.022	0.019	0.027	12.5	193		14	0.08	0.06	0.43
Shiwaga uphill	S6	26,5	75	34	26	7	1.2	0.006	0.181	0.281	2.2	86.8		1.05	<0.03	<0.03	0.39
Mulagara	S7	26,5	112	451	311	43	15.1	0.024	0.005	0.461	8.3	687		6.42	0.74	0.03	0.29
Isebe	S8	24,7	115	184	130	27	16.3	0.015	0.014	0.077	2.9	379		3.47	0.63	0.01	0.38
Lake Ngozi	S9	20,9	70	2938	1994	4	0.9	0.653	0.108	0.007	1416	181		200	0.33	4.6	
Thermal springs																	
Kilambo	S10	56,5	129	3343	2247	22	30.8	0.671	0.028	0.119	343	2410	30	186	0.1	<0.01	
Mampulo B	S11	61	126	3722	2502	13	14.0	0.414	0.02	0.285	224	2610	120	258	0.58	<0.01	
Kandete	S12	56,6	126	3606	2426	16	13.9	0.418	<0.005	0.254	224	2760		252	0,58	1.02	
Kasimulo	S13	54,7	105	3518	2368	26	15.8	0.386	<0.005	0.206	204	2800		317	0,68	0.94	

The group of thermal springs located to the southeast have similar major element concentrations to the hot springs in the northwest area (Table 2). According to Kraml et al. (2010), these springs belong to another geothermal system called the Kyejo-Mbaka system. The springs found in Rungwe geothermal area are rich in carbonates; the source of carbon dioxide in this water may be related to a deep-seated intrusion or the mantle. The location of most of these springs is near faults; for example, the thermal springs in the southern part are close to the Mbaka fault, indicating the possible access to deep levels for the formation of the carbon dioxide waters.

3.3 Trace element concentrations in water from Rungwe geothermal area

The water samples from Rungwe geothermal area in the Rungwe Volcanic Province show a variable range of trace element concentrations, as presented in Table 3. The general trend is that the highest measured concentrations are in the hot springs in the northwest, followed by the thermal spring water in the southeast; the lowest measured concentrations are in the cold water in the centre of the Rungwe volcanic system. The exception to this involves the elements B, U and Mn which are highest in the cold water samples. Lake Ngozi, of course, intersects all the hot springs.

Descriptions of selected trace elements in the water

Strontium (Sr) has the highest concentration of the trace elements (Figure 3). It measures four orders of magnitude in the hot spring and in the thermal spring but is still high in the cold water by three orders of magnitude (150-340 µg/l). The higher concentrations of Sr in hot water compared to the cold water, according to (Pisarskii et al., 1998) may be due to the existence of a magma chamber linked to the Poroto Rungwe massif. Strontium correlates highly with K and Li (see correlation matrix

TABLE 3: Concentration of trace elements in water from the Rungwe geothermal area

Sample ID	Code	Temp °C	Sr µg/l	Rb µg/l	Ba µg/l	B µg/l	As µg/l	Cs µg/l	Ge µg/l	Mo µg/l	Be µg/l	Mn µg/l	W µg/l	Tl µg/l	Sb µg/l	Zn µg/l	U µg/l	V µg/l	Ni µg/l	Cu µg/l	Co µg/l	Cr µg/l	Cd µg/l
Hot springs																							
Main Spr. B	S1	74	8660	382	149	20	113	36	22	13.1	5.448	<0.5	0.5	1.49	0.40	0.2	1.18	0.09	0.85	0.15	0.03	0.05	0.028
Ilatile 1	S2	72	6840	369	172	20	143	57	22	19.1	10.3	<1.00	6.9	1.45	2	<0.4	0.81	0.06	0.19	0.15	<0.02	0.03	0.052
Ilatile 4	S3	80.2	6890	381	170	28	149	59	24	19.3	9.035	4	6.6	1.50	1	1	0.84	1.09	0.4	1.05	0.15	0.38	0.041
River Spring	S4	74.1	8070	357	172	90	141	55	23	18.1	10.4	2	5.6	1.35	1	<0.4	0.83	0.37	0.28	0.27	0.06	0.07	0.038
Cold water																							
Swaya	S5	44	130	60	27	1080	1	0.5	0.4	1.7	0.137	10	0.3	0.03	0.03	0.6	0.71	4.27	0.24	0.27	0.03	2.11	0.009
Shiwaga uphill	S6	26.5	150	44	4	10	<0.3	0.2	<0.30	0.4	0.821	1358	0.0	0.12	0.01	8.1	0.07	0.04	0.53	0.06	0.38	0.08	0.048
Mulagara	S7	26.5	340	81	5	430	0.5	0.1	<0.30	3.3	0.486	79	0.0	0.03	0.01	2.2	5.01	1.70	0.35	0.2	0.04	0.09	0.036
Isebe	S8	24.7	170	50	7	380	0.5	0.1	<0.30	3.2	0.1048	54	0.0	0.02	0.01	2.2	2.48	1.52	0.11	0.07	0.02	0.12	0.05
Lake Ngozi	S9	20.9	200	787	6	150	74	50	14	28.3	2.273	10	60.9	0.61	2	0.5	0.12	0.58	0.2	0.15	0.01	0.17	0.04
Thermal springs																							
Kilambo	S10	56.5	3320	188	124	20	206	13	18	13.1	0.667	3	0.2	0.60	0.54	0.6	1.34	0.08	1.17	0.21	0.18	0.08	0.027
Mampulo B	S11	61	2880	163	92	130	132	12	14	15.5	0.521	14	1.5	0.30	0.08	<0.4	0.61	0.51	0.11	0.27	0.04	0.09	0.035
Kandete	S12	56.6	2560	157	89	40	101	9	16	9.8	0.651	11	1.3	0.34	0.05	<0.4	0.33	0.14	0.21	0.42	<0.02	0.06	0.019
Kasimulo	S13	54.7	2370	142	90	210	70	6	9	8.1	0.184	36	0.2	1.14	0.02	0.6	0.98	0.83	1.2	0.62	0.48	0.06	0.022

TABLE 3: Continued

Sample ID	Code	Temp °C	Pb µg/l	Ga µg/l	Y µg/l	Ti µg/l	Zr µg/l	Nb µg/l	Te µg/l	Sc µg/l	Sn µg/l	Hf µg/l	Ta µg/l	Bi µg/l	Th µg/l	Se µg/l	Ag µg/l	In µg/l	Lu µg/l
Hot springs																			
Main Spr. B	S1	74	<0.05	0.127	0.127	<0.01	0.033	0.008	0.012	0.131	0.05	0.006	<0.001	0.001	0.035	<5	0.004	<0.002	<0.0005
Ilatile 1	S2	72	<0.100	0.236	0.092	<0.02	0.027	0.009	0.031	<0.016	<0.04	0.003	0.004	0.003	0.0015	<10	<0.004	<0.004	<0.0010
Ilatile 4	S3	80.2	0.243	0.22	0.357	17	3.055	0.858	0.021	0.171	0.05	0.062	0.048	0.004	0.2068	<10	<0.004	<0.004	0.0052
River spring	S4	74.1	<0.100	0.224	0.146	1.96	0.745	0.147	0.021	0.058	<0.04	0.018	0.011	<0.002	0.0318	<10	<0.004	<0.004	<0.0010
Cold water																			
Swaya	S5	44	0.06	0.045	0.052	1.32	0.166	0.119	0.007	0.069	0.1	0.003	0.002	0.005	0.013	<5	<0.002	<0.002	0.0008
Shiwaga uphill	S6	26.5	0.07	0.02	0.64	0.77	0.56	0.109	0.035	0.115	0.04	0.009	0.002	0.003	0.019	<5	<0.002	<0.002	0.0142
Mulagara	S7	26.5	0.09	0.08	0.126	0.2	0.615	0.444	0.019	0.254	0.04	0.002	<0.001	0.002	0.006	<5	<0.002	<0.002	0.0034
Isebe	S8	24.7	<0.05	0.017	0.113	0.23	0.166	0.193	0.007	0.118	0.06	<0.001	<0.001	0.007	0.08	<5	0	<0.002	0.0023
Lake Ngozi	S9	20.9	0.45	0.051	0.073	0.49	0.179	0.15	0.022	0.097	0.08	0.007	0.002	0.038	0.097	10	0	<0.002	0.0009
Thermal springs																			
Kilambo	S10	56.5	<0.100	0.068	0.074	1.07	0.107	0.061	0.027	0.071	<0.04	0.003	0.002	<0.002	0.0105	<10	<0.004	<0.004	<0.0010
Mampulo B	S11	61	<0.100	0.14	0.06	0.66	0.157	0.018	0.03	0.172	<0.04	<0.002	<0.002	<0.002	0.0055	<10	<0.004	<0.004	<0.0010
Kandete	S12	56.6	<0.100	0.059	0.05	<0.02	0.098	<0.002	0.006	0.235	0.07	<0.002	<0.002	0.007	0.009	<10	0.004	<0.004	<0.0010
Kasimulo	S13	54.7	<0.100	0.136	0.156	<0.02	0.12	0.014	0.037	0.16	0.09	0.003	<0.002	0.034	0.067	<10	<0.004	<0.004	0.0018

in Appendix I). This could indicate that Sr originates from potassium feldspar and/or clay minerals of the Rungwe area.

Rubidium (Rb), barium (Ba) and arsenic (As) (Table 3) are generally measured in three orders of magnitude in the hot springs and the thermal springs (Table 3), but are lower in the cold water which measures one to three orders of magnitude. The highest concentrations of Rb were found in hot springs, Figure 4a, and concentrations were also high in the thermal springs, but lower in cold springs (Table 3) with the major exception of very high concentrations of Rb in the cold water of Lake Ngozi. Rb is strongly correlated with Li, Cl, Cs, and Mo.

Arsenic (As) contents of the hot springs and thermal springs are high compared to the cold waters (Table 3). The cold water of Lake Ngozi also measures higher As concentrations than that in the cold springs. As correlates highly with Sr and Li; this may indicate the magmatic origin of these elements. The elevated levels of arsenic and rubidium in this water may also be related to the magmatic activity of Rungwe Volcanic Province (Pisarskii et al., 1998).

Cesium (Cs), germanium (Ge), molybdenum (Mo), beryllium (Be), manganese (Mn), tungsten (W), thallium (Tl) and antimony (Sb) measure in two to one orders of magnitude or even lower (Figure 4). Cs, Ge and Mo were generally higher in the hot and thermal springs and lower in concentration in cold water. An anomalous concentration of Mn was observed in the cold spring of Shimwaga uphill, which is also characterized by high CO_2 gas bubbling. The rest of the trace elements in the water samples measure commonly below 1µg/L (Table 3).

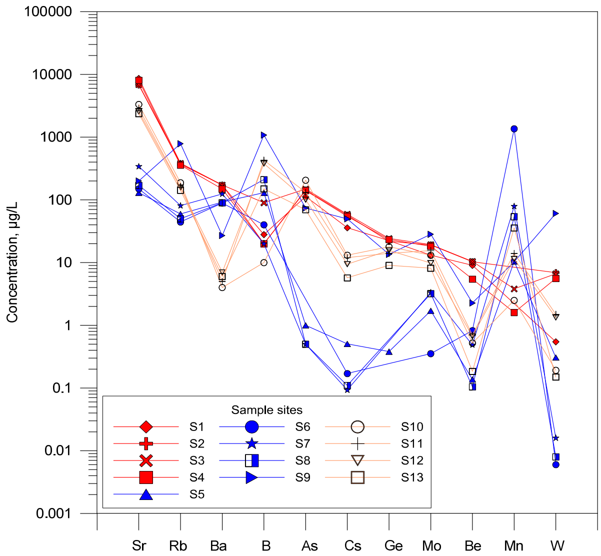

FIGURE 4a: The trace elements Sr, Rb, Ba, B, As, Cs, Ge, Mo, Be; Mn, and W concentrations in water from Rungwe geothermal area

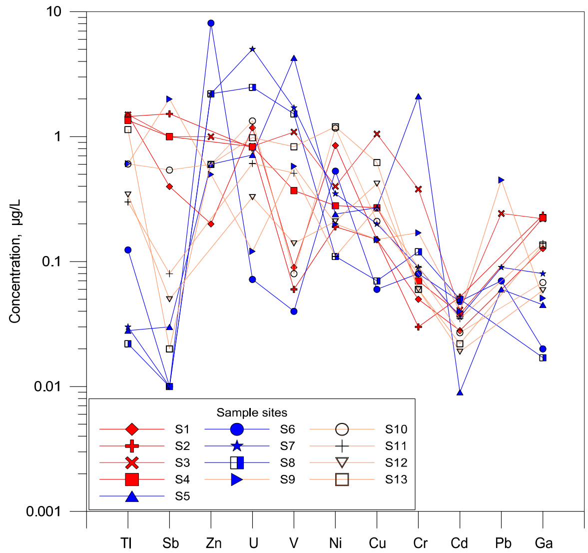

FIGURE 4b: The trace elements Tl, Sb, Zn, U, V, Ni, Cu; Cr, Cd, Pb and Ga concentrations in water from Rungwe geothermal area

3.4 Rare earth concentrations in water

The REE element concentrations are presented in Table 4. Some ranges of concentration of rare earth elements were observed in the water from Rungwe geothermal area, shown in Figure 5. The fluid geochemical studies of these elements indicated a positive Eu anomaly for the hot springs, which may be caused by plagioclase alteration during hot fluid/ rock interaction (Kraml et al., 2010). No significant Eu anomaly was found for the cold springs or Lake Ngozi water.

The rare earth element concentrations in hot springs indicated the following trends: the highest concentrations of La, Ce, Pr, Nd, Gd, Sm, Tb, Dy and Er were measured in Ilatile 4 (S3) while most of the elements concentrations in Main Spring B and Ilatile 1 measure close to or below the detection limits.

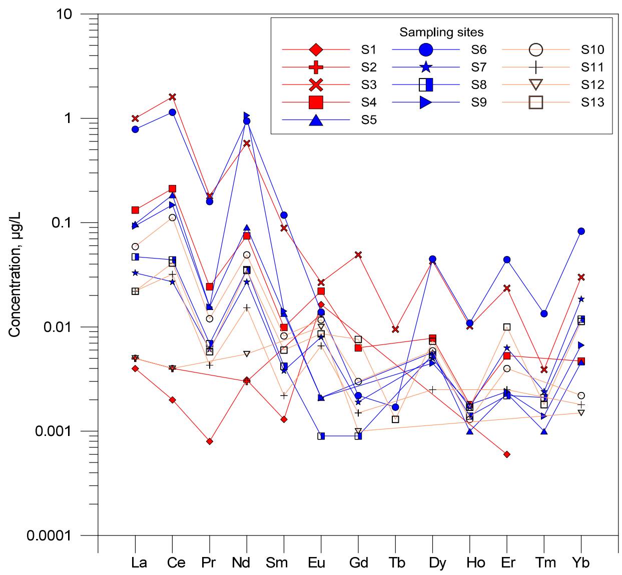

FIGURE 5: REE elements of analysed water samples from Rungwe geothermal area

Of the thermal springs in the southern part of area, the higher concentrations of La, Ce, Pr, and Nd, Sm and Eu were measured in Kilambo (S10) compared to Kasimulo (S11) where the latter one measured

TABLE 4: Rare earth element (REE) concentrations in water from Rungwe geothermal area

Sample ID	Code	Temp °C	La µg/l	Ce µg/l	Pr µg/l	Nd µg/l	Sm µg/l	Eu µg/l	Gd µg/l	Tb µg/l	Dy µg/l	Ho µg/l	Er µg/l	Tm µg/l	Yb µg/l
Hot springs															
Main Spr. B	S1	74	0.004	0.002	0.0008	0.0031	0.0013	0.0164	<0.0005	<0.0005	<0.0005	<0.0005	0.0006	<0.0005	<0.0005
Ilatile 1	S2	72	0.005	0.004	<0.0010	0.003	<0.0020	0.0133	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010
Ilatile 4	S3	80.2	0.998	1.606	0.1807	0.5773	0.0887	0.0267	0.0493	0.0095	0.0428	0.0102	0.0236	0.0039	0.03
River spring	S4	74.1	0.132	0.212	0.0243	0.0749	0.0099	0.0221	0.0063	<0.0010	0.0078	0.0018	0.0053	<0.0010	0.0047
Cold water															
Swaya	S5	44	0.097	0.184	0.0156	0.0902	0.0134	0.0021	<0.0005	<0.0005	0.0057	0.001	0.0023	0.001	0.0046
Shiwaga uphill	S6	26.5	0.785	1.143	0.1593	0.9424	0.1182	0.0139	0.0022	0.0017	0.0448	0.0109	0.0442	0.0134	0.0828
Mulagara	S7	26.5	0.033	0.027	0.0061	0.027	0.0038	0.008	0.0019	<0.0010	0.005	0.0017	0.0063	0.0024	0.0185
Isebe	S8	24.7	0.047	0.044	0.0069	0.0354	0.0042	0.0009	0.0009	<0.0005	0.0054	0.0014	0.0022	0.0021	0.0119
Lake Ngozi	S9	20.9	0.093	0.148	0.0155	1.07	0.0142	0.0021	<0.0005	<0.0005	0.0045	0.0018	0.0024	0.0014	0.0067
Thermal springs															
Kilambo	S10	56.5	0.059	0.112	0.012	0.0492	0.0082	0.0117	0.003	<0.0010	0.0059	0.0013	0.004	<0.0010	0.0022
Mampulo B	S11	61	0.022	0.032	0.0043	0.0153	0.0022	0.0066	0.0015	<0.0010	0.0025	<0.0010	0.0025	<0.0010	0.0018
Kandete	S12	56.6	0.005	0.004	<0.0010	0.0055	<0.0020	0.01	0.001	<0.0005	<0.0010	<0.0010	<0.0010	<0.0010	0.0015
Kasimulo	S13	54.7	0.022	0.041	0.0058	0.0348	0.006	0.0086	0.0076	0.0013	0.0073	0.0017	0.01	0.0018	0.0113

higher in concentrations of Nd, Gd, Er, Tm and Yb. For the group of cold waters, Shimwaga spring (S6) has the highest concentrations of all the measured REE in all water samples. Lake Ngozi water was also high in Nd concentrations. There is no clear difference in the concentrations of these elements between these groups of springs. Generally, the REE concentrations in most samples measured less than 1µg/l while many element measure around and below the detection limit of the analytical method applied. Generally, the REE in deep groundwater may be derived from the weatherable phase of a clay mineral rich in feldspars. Therefore, higher concentrations of Eu in hot springs may be due to plagioclase alterations during hot fluid/rock interaction. The higher Eu concentrations can be used as an indication of mixing of hot fluid with cold surface waters.

3.5 Water quality assessment

The trace element levels in water from the Rungwe geothermal area were studied. Their concentration levels were compared to the international water quality guideline values for drinking water, such as the World Health Organization (WHO) and United States Environmental Protection Agency (US EPA), and the irrigation water and livestock drinking water quality criteria of the Food and Agriculture Organization of the United Nations (FAO) (Appendix II). These guidelines show the quality of water suitable for different applications.

The spatial variations of some trace elements of environmental significance in these waters, like Cd, Cu, Cr, As, Ba, Be and B concentrations, relative to the given guideline values for water quality, are shown in Figure 6. The WHO (2011) guideline values summarized in Table 1 of Appendix II are set only for naturally occurring chemicals in the water and not for the anthropogenic pollution of water. In most cases, the trace elements were below the standards with a few exceptions: beryllium (Be) exceeds the US EPA safety limits whereas barium (Ba), and arsenic (As) exceed the WHO (2011) safety limits in the water from mostly hot and thermal springs in the Rungwe geothermal area, as shown in Figure 6.

The water quality of hot, thermal and cold springs and Ngozi caldera lake was evaluated for use as livestock drinking water. The trace element concentrations in these waters were compared to the FAO (FAO, 1994) guideline values for irrigation water. Most of the trace element concentrations, like for boron (B) and arsenic (As), in the water samples evaluated were within acceptable limits, as indicated in Figure 7.

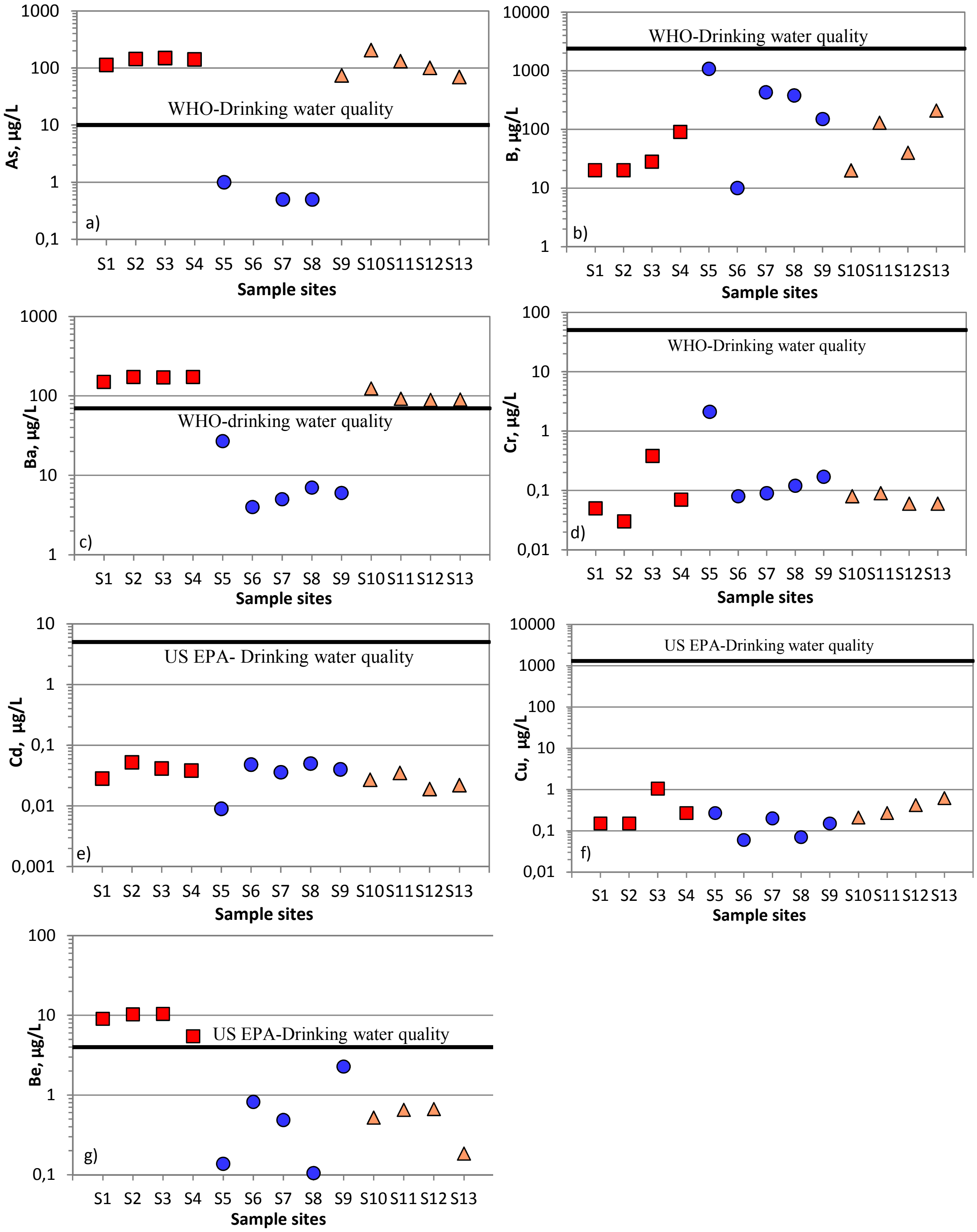

FIGURE 6: Concentrations of trace elements in water from Rungwe geothermal area relative to WHO (2011) and US EPA (2006) drinking water quality guidelines; a) arsenic (As), b) boron (B), c) barium (Ba), d) chromium (Cr), e) cadmium (Cd), f) copper (Cu), and g) beryllium (Be)

The water quality was also assessed for irrigation purposes. Most of the analysed trace elements in the water were within the FAO (FAO, 1994) standard limits for irrigation water, with the exception of Molybdenum (Mo) and arsenic (As) which exceeded the guideline values in some locations, as shown in Figure 8.

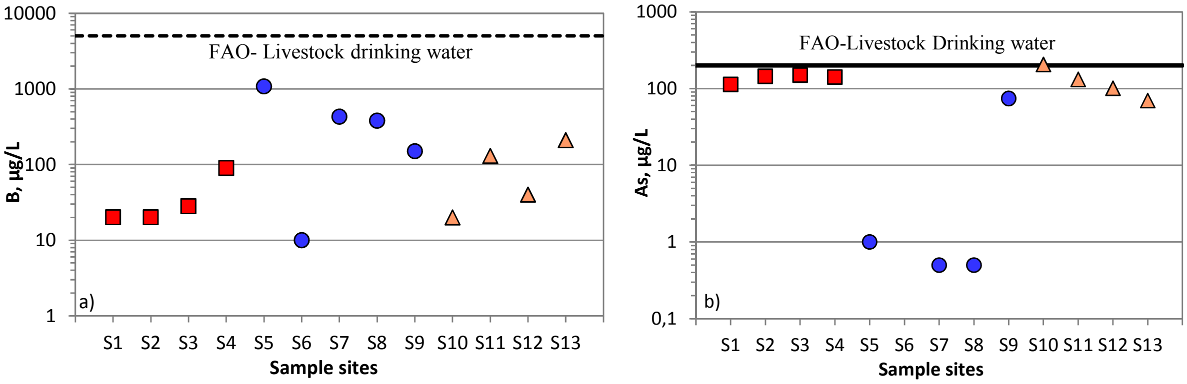

FIGURE 7: Concentrations of trace elements in water from Rungwe geothermal area relative to the FAO (1994) livestock drinking water quality guidelines; a) Boron (B), b) Arsenic (As)

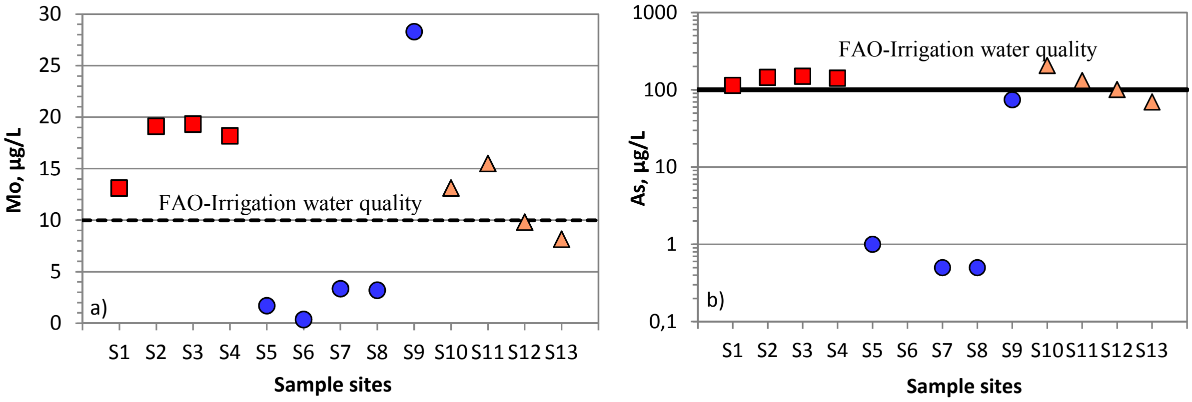

FIGURE 8: Concentrations of trace elements in water from Rungwe geothermal area relative to the FAO (1994) irrigation water quality guidelines; a) Molybdenum (Mo), b) Arsenic (As)

4. DISCUSSION

Geothermal water is known to contain some trace elements which are of great environmental concern. Generally, the trace elements in water from Rungwe geothermal area in SW-Tanzania measured at very low concentrations. However, the elevated levels of some trace elements, like As, Be, Ba and Mo, were observed in some of the water samples studied. In this study, the water samples were grouped based on their location and temperature ranges; there exists a wide variation in the trace element concentrations between the water sample groups, as described below.

4.1 Hot springs

There are four hot springs in this study which are Main Spring B (S1), Ilatile 1 (S2), Ilatile 4 (S3) and River Spring (S4), found in the northwest territory of the Rungwe geothermal area. These four hot springs have a temperature range of 72 to 80°C and have similar concentrations of trace elements. The trace element concentrations indicated high As, Ba, Be, and Mo in all the hot spring samples. The As concentrations ranged between 112-149 µg/L which exceeds the WHO (WHO, 2011) guidelines (Figure 6; Appendix II) of drinking water tolerance limits of 10 µg/l by a factor of 11-14 times. This concentration is too high and of high environmental significance. Mo concentrations were also found in excess of the FAO standard limits for irrigation water quality (FAO, 1994); Ba was above WHO (2011) standards, and Be concentrations exceeded US EPA (2006) drinking water quality values in this water.

4.2 Cold water samples

The cold water samples came from 4 spring waters, of considerable distance from each other, and with temperatures close to 25°C, with the exception of Swaya spring (S5) which is about 32 km away from the hot springs in the northwest part. The water from this spring has higher concentrations of V, while the As, Mo, Ge, Rb, Sr and Cs levels were much lower in this spring water. Ngozi Caldera Lake is one of the cold water sources in this group; it is a caldera lake of the Ngozi volcano. The water from Lake Ngozi was found to have a different chemistry in both major components and trace element concentrations, even though of the same temperature range. The highest trace element levels encountered in Lake Ngozi water were Rb, Sb, Mo, Pb and W; these were higher in Lake Ngozi water than in any other water samples from the Rungwe geothermal area. Other elements found in high concentrations include As, Cs, Be, Tl and Ge; the lowest concentration was for Mn. Previous studies (Mnjokava, 2007) classified Lake Ngozi water as a Cl-rich water; this may be the result of high vaporisation, with no outflow.

4.3 Thermal water samples

Thermal springs in Rungwe geothermal area have temperatures in the range of 54-61°C. Most of the trace elements from this group were found in similar concentration levels. The Sr, Rb, Ba As, Cs and Ge concentration levels measured higher in the thermal springs than in the cold waters. Kilambo (S10) and Kasimulo (S13) springs gave relatively higher Ni concentrations.

4.4 Trace element occurrences in water and their toxicity

Trace elements can come from both natural and anthropogenic sources. Natural sources include the weathering of rocks, volcanic activity, thermal springs, river and lake sediments and forest fires. The anthropogenic sources include metal mining and smelting, fossil fuel, biomass, waste disposal and agricultural activities. Some trace elements normally exist as a vapour in the atmosphere due to their high volatility, like Hg and Tl. The gaseous metals in the atmosphere can be derived from sources like volcanic activity (Br, Se, As, and Sb), released from biological activity (Hg, As, Se), burning of fossil fuels (Cd), and the smelting of metal ores (Zn, Pb, Cd). Geothermal activity can also be a source for trace elements such as As, B and Sb in the natural state or from geothermal power production. Studies of the chemistry of surface and groundwater indicate that generally groundwater contains more dissolved solids than surface water; this reflects a longer contact time with the geomedia and isolation from dilution by fresh precipitation (Landmuir, 1997).

Below is a short description of As, Be, Mo, Ge, Ba, B, Cu and Cd which are found in various proportions in Rungwe geothermal water.

Arsenic (As**)** in natural waters occurs through discharge from hot and cold springs in active volcanic terrains and solubilisation resulting from the reduction of ferric iron arsenate to arsenite. It usually occurs in conjunction with sulphur and metals. Arsenic is termed a typical component of active geothermal systems and commonly occurs with other environmental contaminants such as B, Hg, Sb, Se, Tl, Li, F and H_2S (Webster and Nordstrom, 2003). Arsenic occurs primarily with silica (SiO_2) and Mo in water with slightly high pH. Arsenic is reported in hot springs from different parts of the world: found in concentrations ranging from 0.16-10 mg/kg in Yellowstone National Park, USA (Webster and Nordstrom, 2003); 0.71-6.5 mg/kg in Waiotapu, New Zealand (Webster, 1990); and 0.001-0.048 mg/kg in Iceland (Arnórsson and Linvall, 2001). Arsenic is an element of environmental concern worldwide because of its known toxicity. It is classified as a human carcinogen. The acute toxicity of arsenic depends on its various forms and valences (organic, inorganic and gaseous forms). Chronic As exposure may result in skin cancer, internal organ cancers (bladder, kidney, liver or lung), hypertensive heart disease and increased risk of mortality due to diabetes.

Beryllium (Be) compounds may be potentially harmful or toxic; however, the probability of beryllium occurring at significantly toxic levels in ambient natural waters is minimal. Most beryllium is expected to be present either in the adsorbed state in suspended matter or in sediment rather than in a dissolved form in most natural waters. Beryllium has been shown to be a carcinogen in rats and rabbits in high concentrations. Long-term and high levels of beryllium exposure may develop sensitization and a risk of developing chronic beryllium disease.

Molybdenum (Mo) is an element that is present in very small amounts in the body. It is involved in many important biological processes, possibly including development of the nervous system, waste processing in the kidneys, and energy production in cells. Mo is present in all plant and animal tissues and considered an essential micronutrient for most life forms. Mo is considered essential for aquatic plant growth. The concentrations observed to cause adverse effects in sensitive species were 50 mg/l for growth and 108 mg/l for development.

Germanium (Ge) is also found in geothermal water as well as in some non-thermal groundwater, the ocean and river water (Burton et al., 1959). Germanium concentrations were reported between 2 and 30 ppb for Icelandic geothermal waters (Arnórsson, 1984), 0.4-43.8 ppb for geothermal waters in Japan (Uzumasa et al.,1959) and 2-20 ppb in Vichy, France (Criaud and Fouillac, 1986). Germanium exposure to human health can be a threat, for example, germanium chloride ($GeCl_4$) and germane, (GeH_4) are liquid and gas, respectively, that can be very irritating to the eyes, skin, lungs, and throat.

Barium (Ba) is found in lakes, rivers and streams in the form of barium carbonate ($BaCO_3$) or sulphate ($BaSO_4$). Exposure to water that is polluted with barium may have some health effects. The health effects of barium depend upon the water-solubility of the compounds. The uptake of very large amounts of barium that are water-soluble may cause paralysis and in some cases even death, while smaller amounts can result in problems such as stomach irritation, muscle weakness and breathing difficulties.

Boron (B) is an essential element for plant growth in relatively small amounts, as it plays an important role in strengthening the cell walls of all plants. However, if it is present in larger amounts than needed, it becomes toxic: For some crops, 0.2 mg/l of boron in water is essential; 1 to 2 mg/l may be toxic (FAO, 1994). Surface water rarely contains enough boron to be toxic but well water or spring water occasionally contains toxic amounts, especially near geothermal areas and earthquake faults.

Copper (Cu) generally occurs as various sulphides such as chalcopyrite ($CuFeS_2$) and chalcocite (Cu_2S). Copper is naturally discharged into air and water during volcanic eruptions and with windblown dust, and also through anthropogenic sources. It has long been recognized that copper corrodes in a sulphide-containing environment. Copper is termed toxic to a number of plants at 0.1 to 1.0 mg/l in nutrient solutions (FAO, 1994).

Cadmium (Cd) is normally associated with zinc ores; Spharelite (ZnS) cadmium can be an environmental hazard, for example, as it is termed toxic to beans at a concentration as low as 0.1 mg/l (FAO, 1994) and also to aquatic organisms such as fish. Cd occurs in well oxygenated and low dissolved organic matters, fresh water and sediments. Human exposures to environmental cadmium are primarily the result of fossil fuel combustion, phosphate fertilizers, natural sources, and municipal solid waste incineration. Cadmium exposure to humans can lead to cardiovascular disease.

4.5 Possible uses of water from Rungwe geothermal area

Geothermal water may contain various concentrations of dissolved constituents which make it useful or useless for different applications. The chemistry of the discharged fluids largely depends on the geochemistry and geology of the reservoir, as well as the operating conditions used for power generation and varies from one geothermal field to another. The geothermal areas are also considered to release these elements in their natural states. The Rungwe geothermal water also contains some trace element concentrations which may limit some applications. Most trace elements have the tendency of bioaccumulation in sediments, and aquatic flora and fauna; for this reason, their concentration levels are of high environmental concern.

4.6 Water for drinking purposes

A natural water source may contain some chemical constituents which may lower the quality of the drinking water and also lead to serious impacts on human health. Consideration is, therefore, required concerning the essentiality, non-essentiality and toxicity of these elements, which mainly depends on their concentrations in water, apart from other contributing factors. The proper assessment of these elements in water is critical, depending on proper sampling and analysis. The evaluation of the concentration of trace elements in water from Rungwe geothermal area against drinking water quality criteria is presented in Table 5.

TABLE 5: Assessment of water quality for drinking

Trace element	**Sample codes**												
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**
As	X	X	X	X	S	S	N/A	S	S	X	X	X	X
Be	X	X	X	X	S	S	S	S	S	S	S	S	S
Ba	X	X	X	X	S	S	S	S	S	X	X	X	X
B	S	S	S	S	S	S	S	S	S	S	S	S	S
Cd	S	S	S	S	S	S	S	S	S	S	S	S	S
Co	S	S	N/A	S	S	S	S	S	N/A	S	S	S	S
Cr	S	S	S	S	S	S	S	S	S	S	S	S	S
Cu	S	S	S	S	S	S	S	S	S	S	S	S	S
Pb	N/A	N/A	N/A	N/A	S	N/A	S	S	N/A	N/A	N/A	S	S
Sb	S	S	S	S	S	S	S	S	S	S	S	S	S
U	S	S	S	S	S	S	S	S	S	S	S	S	S

X: Above the drinking water values of WHO (2011) and US EPA (2006)
S: Below the drinking water values of WHO (2011) and US EPA (2006)
N/A: Below detection limits of the specific analytical method used

As shown in Table 5, the waters from Main Spring B (S1), Ilatile 1 (S2), Ilatile 4 (S3) River Spring (S4), Kilambo (S10), Mampulo (S11), Kandete (S12) and Kasimulo (S13) have too high concentrations of As and Ba, exceeding the safety limits in drinking water for WHO (2011) and the US EPA (2006) for which the maximum limit of arsenic in drinking water is 50 µg/l. The concentration of Be was also found to exceed limits in Main Spring B (S1), Ilatile 1 (S2), Ilatile 4 (S3) and River Spring (S4) waters in the Rungwe geothermal area. Water from locations with elevated levels of Ba, Be and As are not regarded suitable for drinking water purposes. Necessary steps are required prior to utilization of the water from this area, due to possible adverse health effects from elements such as arsenic (As), a known human carcinogen.

4.7 Livestock drinking water

Water known to contain some amounts of dissolved chemical constituents may have some health effects on animals drinking it. Water from Rungwe geothermal area was assessed for this kind of application. All the trace element concentrations in water from Rungwe geothermal area were evaluated for comparison to FAO guidelines (FAO, 1994), and were found to be within the safe limits; no potentially hazardous elements were observed. Therefore, the water from Rungwe geothermal area is regarded as suitable for use as livestock drinking water.

4.8 Water for irrigation purposes

The levels of trace elements found in the water may define the suitability of the water for irrigation purposes. Different trace elements found in the water, depending on their amounts, can be toxic to plants as they may affect soil fertility and the crop yields, even though they are essential to plants as micronutrients. The chemical compositions of the Rungwe water samples were assessed to determine their effect on water quality for irrigation purposes. Elevated concentration levels for Mo were observed, which may be hazardous to plants with regard to the internationally recommended limits in irrigation water given by FAO (1994; Figure 8; Appendix II).

The hot spring waters contain high levels of Mo, as shown in Figure 8. Water samples from the northwest hot springs (Main Spring B (S1), Ilatile 1 (S2), Ilatile 4(S3), and River Spring (S4)) were above the limit as was Lake Ngozi cold water (S9) and also water from Mampulo spring (S11) in the southeast part of the Rungwe geothermal area. Water from these locations needs further studies to understand the origin, mobility and distribution of Mo prior to utilization for irrigation purposes. The arsenic concentrations were slightly high in the following springs: Main Spring B (S1), Ilatile 1 (S2), Ilatile 4 (S3), River Spring (S4), Kilambo (S10) and Mampulo B (S11); these are hot and thermal springs. As and Mo are the only elements which can be termed to lower the irrigation water quality in this study.

5. CONCLUSIONS

This study has shown that most of the trace element concentration levels in Rungwe geothermal water are within the international guideline values for water quality criteria for human, livestock and plants with regard to health and water consumption. However, some water samples had some exceptions with As, Mo, Be and Ba exceeding the tolerance limits for water. Arsenic is the trace element of highest environmental interest in the Rungwe water. Its concentrations far exceeded the World Health Organization guideline (WHO, 2011) value of 10µg/l for drinking water. Evaluation of the toxicity of As to humans and other living organisms is of great importance prior to any application of water from the Rungwe geothermal area.

The development of any geothermal field for power generation tends to increase the rate and volume of geothermal fluid reaching the surface. The development of Rungwe geothermal area is no exception. Waste water, after power generation, often has higher contaminant concentrations of As, Mo, B and Sb than natural hot spring water; this is because the processes that remove or immobilize contaminants in natural geothermal water, such as precipitation of mineral-rich sinters, have been bypassed. Then the geothermal water becomes an environmental problem if proper disposal is not achieved.

Detailed studies regarding trace element levels in sediments, plants, surface- and ground waters is highly recommended. It is important to understand the sources of these trace elements, apart from linking them to the magmatic activity of the Rungwe Volcanic Province; it is also important to understand their mobility, speciation and distribution over the area. These kinds of background studies are of great importance in the development of the Rungwe geothermal area as well as for strategic planning for water exploitation and consumption.

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APPENDIX I: Correlation matrix for the chemical components of the water samples from Rungwe, SW-Tanzania

	Cl	SO4	HCO3	PO4	BO2	SiO2	K	Na	Mg	Ca	Al	Fe	Cu	Co	Li	Mn	As	Ba	Be	Cd	Ce	Cr	Cs	V	La	Mo	Rb	Sb	Sr
Cl	1,00																												
SO4	0,40	1,00																											
HCO3	-0,11	0,82	1,00																										
PO4	0,00	0,22	0,16	1,00																									
BO2	0,77	0,82	0,52	-0,07	1,00																								
SiO2	-0,23	0,24	0,42	0,68	-0,05	1,00																							
K	0,60	0,65	0,45	-0,24	0,84	-0,38	1,00																						
Na	0,45	0,97	0,83	0,12	0,90	0,23	0,72	1,00																					
Mg	-0,24	0,27	0,58	0,27	0,10	0,72	-0,04	0,34	1,00																				
Ca	-0,44	-0,19	0,11	0,54	-0,41	0,47	-0,29	-0,21	0,59	1,00																			
Al	0,11	-0,13	-0,20	-0,42	0,07	-0,49	0,08	-0,09	-0,41	-0,30	1,00																		
Fe	-0,34	-0,04	0,12	0,58	-0,31	0,49	-0,46	-0,08	0,16	0,49	0,06	1,00																	
Cu	-0,07	0,40	0,43	0,00	0,24	-0,07	0,27	0,35	0,00	0,08	0,61	0,16	1,00																
Co	-0,17	0,19	0,16	0,02	-0,09	-0,01	-0,24	0,04	0,04	0,03	0,24	0,29	0,28	1,00															
Li	0,43	0,59	0,54	-0,46	0,80	-0,34	0,90	0,72	0,12	-0,31	0,20	-0,48	0,32	-0,16	1,00														
Mn	-0,21	-0,41	-0,42	-0,23	-0,43	-0,23	-0,52	-0,47	-0,39	-0,29	0,32	0,32	-0,27	0,53	-0,45	1,00													
As	0,22	0,62	0,72	-0,37	0,73	0,03	0,67	0,77	0,42	-0,22	0,12	-0,28	0,31	-0,09	0,89	-0,42	1,00												
Ba	-0,13	0,45	0,69	-0,48	0,44	-0,22	0,64	0,55	0,25	-0,12	0,14	-0,34	0,43	-0,06	0,83	-0,39	0,84	1,00											
Be	0,01	0,04	0,15	-0,61	0,26	-0,67	0,59	0,15	-0,26	-0,24	0,36	-0,45	0,27	-0,23	0,72	-0,20	0,52	0,78	1,00										
Cd	0,07	-0,30	-0,31	-0,11	-0,04	-0,36	0,01	-0,23	-0,25	-0,12	0,33	-0,02	-0,22	-0,05	0,10	0,33	0,00	0,02	0,41	1,00									
Ce	-0,12	-0,25	-0,22	-0,45	-0,14	-0,45	-0,12	-0,24	-0,40	-0,27	0,96	0,15	0,54	0,37	0,04	0,51	0,00	0,09	0,28	0,30	1,00								
Cr	-0,15	-0,36	-0,39	-0,24	-0,37	-0,12	-0,33	-0,42	-0,30	-0,16	0,02	-0,26	0,08	-0,16	-0,36	-0,10	-0,35	-0,24	-0,18	-0,56	0,07	1,00							
Cs	0,43	0,24	0,13	-0,55	0,59	-0,68	0,81	0,37	-0,30	-0,40	0,41	-0,54	0,29	-0,29	0,86	-0,32	0,60	0,68	0,90	0,37	0,24	-0,21	1,00						
V	-0,23	-0,47	-0,48	0,10	-0,53	0,04	-0,47	-0,56	-0,21	0,20	-0,06	-0,05	0,08	-0,18	-0,56	-0,19	-0,56	-0,42	-0,30	-0,45	-0,02	0,90	-0,36	1,00					
La	-0,13	-0,27	-0,24	-0,44	-0,17	-0,45	-0,15	-0,26	-0,41	-0,27	0,95	0,18	0,50	0,39	0,00	0,55	-0,03	0,06	0,26	0,33	1,00	0,04	0,21	-0,04	1,00				
Mo	0,74	0,55	0,27	-0,26	0,88	-0,37	0,89	0,67	-0,14	-0,44	0,25	-0,45	0,22	-0,31	0,87	-0,45	0,68	0,51	0,58	0,24	0,01	-0,31	0,86	-0,44	-0,02	1,00			
Rb	0,84	0,35	-0,03	-0,32	0,76	-0,57	0,85	0,44	-0,33	-0,45	0,27	-0,53	0,08	-0,30	0,73	-0,31	0,42	0,29	0,51	0,23	0,03	-0,21	0,82	-0,33	0,01	0,91	1,00		
Sb	0,75	0,20	-0,12	-0,42	0,66	-0,61	0,71	0,31	-0,37	-0,49	0,29	-0,57	0,03	-0,30	0,70	-0,25	0,43	0,32	0,63	0,39	0,08	-0,17	0,86	-0,29	0,06	0,88	0,92	1,00	
Sr	-0,12	0,29	0,52	-0,54	0,35	-0,40	0,68	0,39	0,13	-0,09	0,15	-0,38	0,30	-0,15	0,81	-0,33	0,71	0,94	0,85	0,12	0,10	-0,28	0,74	-0,43	0,08	0,50	0,37	0,35	1,00

Values greater than 0.441 are significant at the 95% confidence level, based on n=13

APPENDIX II: International guidelines for water quality

TABLE 1: Guideline values for naturally occurring chemicals that are of health significance in drinking water (WHO, 2011)

Chemical	Value (µg/l)
Arsenic (As)	10
Barium (Ba)	70
Boron (B)	2400
Chromium (Cr)	50
Fluoride (F)	1500
Selenium (Se)	40
Uranium (U)	30

TABLE 2: National primary drinking water standards (US EPA, 2006)

Contaminant	Maximum level (µg/l)
Antimony (Sb)	6
Arsenic (As)	50
Barium (Ba)	2000
Beryllium (Be)	4
Cadmium(Cd)	5
Chromium (Cr) (total)	100
Copper (Cu)	1300
Lead (Pb)	15
Mercury (Hg) (inorganic)	2
Nitrate (as N)	10000
Nitrite (as N)	1000
Selenium (Se)	50
Thorium	2

TABLE 3: Recommended maximum concentrations of trace elements in irrigation water (FAO, 1994)

Element	Maximum concentration (µg/l)
Aluminium	5000
Arsenic (As)	100
Beryllium (Be)	100
Cadmium (Cd)	10
Cobalt (Co)	50
Chromium Cr)	100
Copper (Cu)	200
Fluoride (F)	1000
Iron (Fe)	5000
Lithium (Li)	2500
Manganese (Mn)	200
Molybdenum (Mo)	10
Ni (nickel)	200
Lead (Pb)	5000
Selenium (Se)	20
Vanadium (V)	100
Zinc (Zn)	2000

TABLE 4: Guidelines for levels of toxic substances in livestock drinking water (FAO, 1994)

Constituent (symbol)	Upper limit (µg/l)
Aluminium (Al)	5000
Arsenic (As)	200
Beryllium (Be)	100
Boron (B)	5000
Cadmium (Cd)	50
Chromium (Cr)	1000
Cobalt (Co)	1000
Copper (Cu)	500
Fluoride (F)	2.0
Lead (Pb)	100
Manganese (Mn)	50
Mercury (Hg)	10
Nitrate + Nitrite (NO_3-N + No_2-N)	100
Nitrite (NO_2-N)	10000
Selenium (Se)	50
Vanadium (V)	100
Zinc (Zn)	24000