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Groundwater vulnerability to geogenic contaminants: a case study, Tanzania

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Groundwater quality is in most cases influenced by geogenic contaminants, which include arsenic, fluoride, salinity, iron and hardness. The main factors behind the natural occurrence of these constituents in groundwater are geologic settings and types of rocks. In Tanzania, the main sources of fluoride in groundwater are the volcanic ashes caused by rifting of the East African Rift System (EARS). During a field survey in Tanzania, primary and secondary data were collected. Fluoride concentrations were measured by SPADNS Colorimetric method and arsenic by Wagtech Kit. Higher median fluorides were recorded in Shinyanga (2.9 mg/L), Arusha (1.2 mg/L), Singida (1.1 mg/L), and Mwanza Region (1.5 mg/L). All water samples indicated arsenic concentration below the WHO guideline value of 10 µg/L. Excessive salinity in terms of Total Dissolved Solids ranging from 60 to 11300 mg/L, were recorded in Singida, Dar es Salaam, and Kilimanjaro Regions.

Introduction

The United Republic of Tanzania in East Africa occupies a total land area of 945,089 square kilometres and lies between longitudes 29° and 41° east and latitudes 1° and 12° south. Since 1975, Tanzania was divided into 25 administrative regions and from 2003 to 2012 five more regions have been created. According to the 2012 population and housing census preliminary results, there are about 45 million people in Tanzania. In 2010, only 44% of rural and 79% of urban population in Tanzania had access to improved drinking water supply (WHO/UNICEF, 2012).

With regards to climatic conditions, almost one third of the geographic area in Tanzania is either arid or semiarid. The mean annual rainfalls in the arid and semiarid regions, mainly in central and northern parts of the country, range from 400 to 800 mm. Higher annual mean rainfalls, from 1000 to 1800 mm, are reported in the southern and western plains (MacDonald and Tyler-Whittle, 2002).

The main sources of drinking water in Tanzania are lakes (e.g. Lake Victoria, Lake Tanganyika, Lake Nyasa, and Lake Eyasi), rivers, springs and groundwater resources. Groundwater is the main water source in the central and northern parts of Tanzania, which include Dodoma, Singida, Mara, Manyara, Arusha, and southern parts of Kilimanjaro Region (AWEC).

Tanzania is among the tropical countries where groundwater resources are highly vulnerable to naturally occurring contaminants such as fluoride (Mjengera and Mkongo, 2003). It is reported that about 30% of drinking water sources in Tanzania are contaminated with fluoride levels above the World Health Organisation (WHO) limit value of 1.5 mg/L (Fawell et al., 2006). Some of the main factors which are associated with the natural occurrence of fluoride in groundwater are geologic factors, types of rocks (igneous, volcanic, sedimentary and metamorphic rocks) and fluorine bearing minerals such as fluorite, apatite, mica, rock phosphate, and hornblende (Ozsvath, 2009). In Tanzania, the most reported geologic factor is the volcanic series of the East African Rift System (Mollel and Swisher III, 2012). The bulk of previous research has focused on fluoride problems mainly in Arusha, Kilimanjaro and Singida Regions, with no information on the magnitude of the problem in other regions. The geostatistical model of Amini et al. (2008) predicts an elevated probability of fluoride levels above 1.5 mg/L in these regions and also in the west and northwest of the country. Ingestion of fluoride contaminated water can lead to dental fluorosis

(mottling of enamel) and even skeletal fluorosis, which severely affects joints and muscle. To avoid these diseases, the WHO sets a guideline value of 1.5 mg/L in drinking water (see Table 1). Another chemical, which occurs naturally in groundwater resources and poses significant threat to human health is arsenic. However, there is a lack of empirical data to determine the extent of arsenic contamination of groundwater resources in Tanzania.

Geology of Tanzania

Geologically, Tanzania is underlain by six major geogenic systems, which are Cenozoic, Palaeozoic, Mesozoic, Mozambique Belt, Palaeoproterozoic Ubendan-Usagaran Belt, and the Archaean Domains (P. Pinna et al., 2008). The Cenozoic systems, which are characterized by continental sedimentary and alkaline volcanic rocks, cover mainly the northern parts of Tanzania; namely, Arusha, Manyara and Kilimanjaro Regions. A small number of Cenozoic lakes are also reported in the western regions. The Palaeozoic and Mesozoic systems are mainly seen in the coastal areas and they are composed of cretaceous, marine and Jurassic sediments. The Mozambique Belt (Neoproterozoic high grade mafic and felsic granulite) underlies the eastern areas, the northeast of Uluguru Mountains and to the north it covers parts of the Pare and Usambara Mountains. The western regions are covered by sedimentary volcano formations while the central parts are underlined by the Archaean Domains (mainly granites, metamorphic rocks and gneisses).

Drinking water standards

In Tanzania, the national drinking water standards are set by the Tanzania Bureau of Standards (TBS). In formulating these standards, the TBS refers to other international standards such as those set by the WHO and the Kenyan Bureau of Standards (KBS). Table 1 contains some of the chemical and physical drinking (potable) water standards, which are intended for water systems serving the public in cities, municipalities, and village communities. The standards are also intended for drinking (potable) water supplied in the food industries, domestic and catering.

Table 1. Drinking (potable) water standards

Selected parameters	Units	Tanzanian Standards (TZS)	WHO Guidelines
Fluoride (F)	mg/L	4	1.5
Arsenic (As)	mg/L	0.05	0.01
Nitrate (NO_3^-)	mg/L as NO_3	75	50
Total Dissolved Solids (TDS)	mg/L	500 – 2000	Not mentioned
pH	-	6.5 – 9.2	Not mentioned
Calcium (Ca^{2+})	mg/L	75 – 300	Not mentioned
Magnesium (Mg^{2+})	mg/L	50 – 100	Not mentioned
Total hardness as $CaCO_3$	mg/L	500 – 600	Not mentioned
Sulphate (SO_4^{2-})	mg/L	200 – 600	Not mentioned

Source:(TBS, 2008) and (WHO, 2011)

Materials and methods

A field survey was conducted in Tanzania for primary and secondary data collection. Secondary data were collected from the Tanzanian Ministry of Water which included the Central Water Quality Department, the Drilling and Dam Construction Agency (DDCA), Singida and Shinyanga Water Quality Divisions as well as from Ngurdoto Defluoridation Research Station (NDRS). Other sources were the Japanese International Cooperation Agency (JICA), UNICEF and the Chemistry Department of University of Dar es Salaam. A water sampling campaign was conducted in Kigoma and Kagera Regions, covering six districts (four in

Kigoma and two in Kagera). Additional water samples were collected in Ifakara Town in Morogoro Region. In total, 178 water samples from boreholes, dug wells and springs were collected. Fluoride and arsenic were chemically analysed by using the SPADNS method (Hach Fluoride Pocket Colorimeter II and Spectrophotometer DR2800) and an arsenic field test kit (Wagtech/Palintest Visual Arsenic Detection Kit) respectively. Fluoride measurement devices were checked for their accuracy by regularly measuring a 1 mg/L fluoride standard solution (Hach A2108) and blanks. Total Dissolved Solids (TDS), electrical conductivity and temperature were measured directly in situ with a Conductivity/TDS Meter (Extech EC150). In addition to the field measurements, 59 representative samples were collected by using 20 mL disposable syringes to filter water (0.45 µm membrane) into 15 ml high density polyethylene sampling bottles. Thirty of these bottles were pre-acidified by addition of 1.5 ml nitric acid and 1.35 ml nanopure water. These samples were later analysed at the Swiss Federal Institute for Aquatic Science and Technology (Eawag). Inductively Coupled Plasma Spectrometry (ICP-MS, 7500 cx) was used for measurement of cations in acidified samples, which included As, Ca2+, Mg2+, Na+, Fe2+ and Mn2+. Anions (F–, Cl–, NO3–, SO43–, Br– etc.) were measured in non-acidified samples with Ion Chromatography (IC, DIONEX ICS-2100). Both primary and secondary data were mapped by using the Geographical Information System (ArcGIS 10.1) environmental software, when the geo-referenced coordinates were available.

Results and discussion

Table 2 below contains the statistical summary classification for concentrations of fluoride, TDS and Total Hardness as analysed from twelve out of thirty administrative regions of Tanzania. Higher median fluoride concentrations were recorded in Shinyanga (2.9 mg/L), Mwanza (1.5 mg/L), Arusha (1.2 mg/L), and in Singida Region (1.1 mg/L). Groundwater samples for Kigoma, Kagera and Dar es Salaam indicated the lowest fluoride concentrations in the range from 0 to 1.1 mg/L, which is below the WHO guideline value of 1.5 mg/L.

Table 2. Summary statistics for fluoride, TDS and total hardness as analysed from both primary and secondary data

Parameter	Region	Number of samples, N	Range	Median	90th percentile
Fluoride (mg/L)	Arusha & Manyara	700	0.1/66	1.2	5.6
	Kilimanjaro	44	0/16.3	0.8	2.7
	Singida	433	0/38.2	1.1	6.3
	Shinyanga	150	0/80	2.9	10.2
	Mwanza	35	0/4.8	1.5	3.3
	Dodoma	176	0/6	0.9	2.6
	Tabora	45	0/4.1	0.8	3.0
	Dar es Salaam	100	0/1.1	0.2	0.7
	Kigoma	119	0/1.1	0.1	0.4
	Kagera	23	0/0.7	0.2	0.6
	Morogoro	31	0.3/4.8	0.7	1.7
TDS (mg/L)	Arusha & Manyara	583	0/3440	150	680
	Kilimanjaro	37	53/2760	570	1260
	Singida	56	140/6000	710	1400
	Shinyanga	18	125/4460	385	1150
	Mwanza	45	10/3000	190	600
	Dodoma	146	300/7190	950	2550
	Tabora	12	38/4700	160	720
	Dar es Salaam	140	60/11300	690	2540
	Kigoma	124	5/500	30	140
	Kagera	23	15/516	110	420
	Morogoro	31	107/885	240	500
Total Hardness (mg/L)	Arusha & Manyara	707	6/2120	110	410
	Kilimanjaro	46	17/1750	260	720
	Singida	179	3/1530	120	390
	Shinyanga	10	34/58	40	55
	Mwanza	53	12/503	140	270
	Dodoma	137	59/2450	300	840
	Tabora	9	25/1900	100	680

A total of 1,856 data points analysed for fluoride were compiled, of which 37% exceeded the WHO guideline of 1.5 mg/L and 14% exceeded the TBS standard of 4 mg/L. For 1,240 of these analyses latitudes and longitudes were available or could be estimated from village names. These are mapped in Figure 2.

Figure 1 shows fluoride levels from different regions in different ranges, based on secondary data analysis. All of the primary data samples analysed from Dar es Salaam, Kigoma and Kagera Regions (not included in figure 1) indicated fluoride concentrations below 1.5 mg/L.

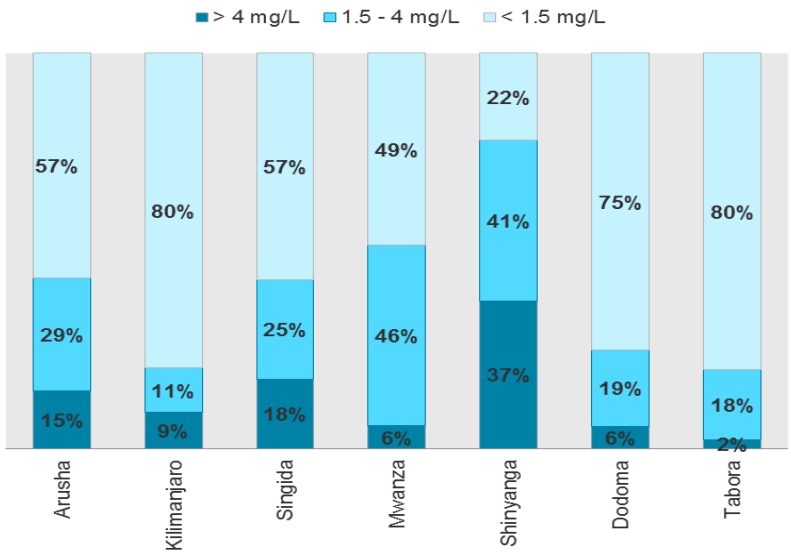

Figure 1. Fluoride levels in water samples by region

Figure 2, plotting both primary and secondary data, shows that most water sources with fluoride levels above 4 mg/L were recorded in Shinyanga, Singida and Arusha Regions. In Kigoma, Kagera (old name "Ziwa Magharibi") and in Dar es Salaam Regions, all points indicate fluoride levels ranging from 0 to 1.5 mg/L.

Elevated fluoride levels in Shinyanga Region may be influenced by fluorine rich granite minerals and kimberlitic volcanic rocks (Bugaisa, 1969). Moreover, data analysis indicated a strong positive correlation coefficient (0.91) between fluoride and total alkalinity in this region, which may reflect supersaturation of calcite, and resultant dissolution of fluorite minerals. According to Mollel and Swisher III (2012) and Ghiglieri et al. (2012), the volcanic series of the East African Rift Valley in Tanzania is reported to be the main factors which influence natural fluoride contamination of groundwater in Arusha and Manyara Regions.

All water samples analyzed for arsenic indicated concentrations below the WHO guideline value of 10 µg/L. Nearly all samples yielded concentrations below the detection limit of 0.02 µg/L. Arsenic is always elevated in mining areas. Kigoma and Kagera Regions, where primary arsenic data were analysed, are not mining areas. Likewise, most of the secondary data showing low arsenic levels were not collected from mining areas within Tanzania (e.g. Bulyanhulu, Geita, Musoma, and Nzega mining sites, which are located in Mwanza, Shinyanga and Mara Regions). Therefore it is possible that this data compilation has missed any mining-related arsenic contamination in Tanzania.

The Tanzanian standard for total dissolved solids (TDS) in drinking water is in the range from 500 to 2000 mg/L (see Table 1). Excessive TDS levels were recorded in four regions; namely, Dodoma (950 mg/L), Dar es Salaam (690 mg/L), Singida (710 mg/L) and Kilimanjaro (570 mg/L). In these regions, and in Shinyanga, 10% or more of the samples exceeded 1000 mg/L, above which levels notable impacts on taste can occur (WHO, 2011). Elevated TDS values in Dar es Salaam might be due to wastewater discharges from industries and poor septic systems, and/or sea water intrusion. In Singida and Kilimanjaro Regions, evaporative waters from irrigation during dry season, and use of artificial fertilizers and manure for agriculture might account for the mentioned high levels of TDS. The lowest TDS levels were recorded in

groundwater samples of Kigoma Region (90% < 140 mg/L). All in all, dissolution of natural materials is generally associated with high salinity in groundwater.

Relatively hard waters were recorded in three regions Dodoma, Kilimanjaro and Tabora, where more than 10% of samples exceeded 500 mg/L. In these regions, hardness was negatively correlated with fluoride levels, implying a possible solubility control of CaF_2. The opposite trend is observed in Shinyanga Region (see Table 1).

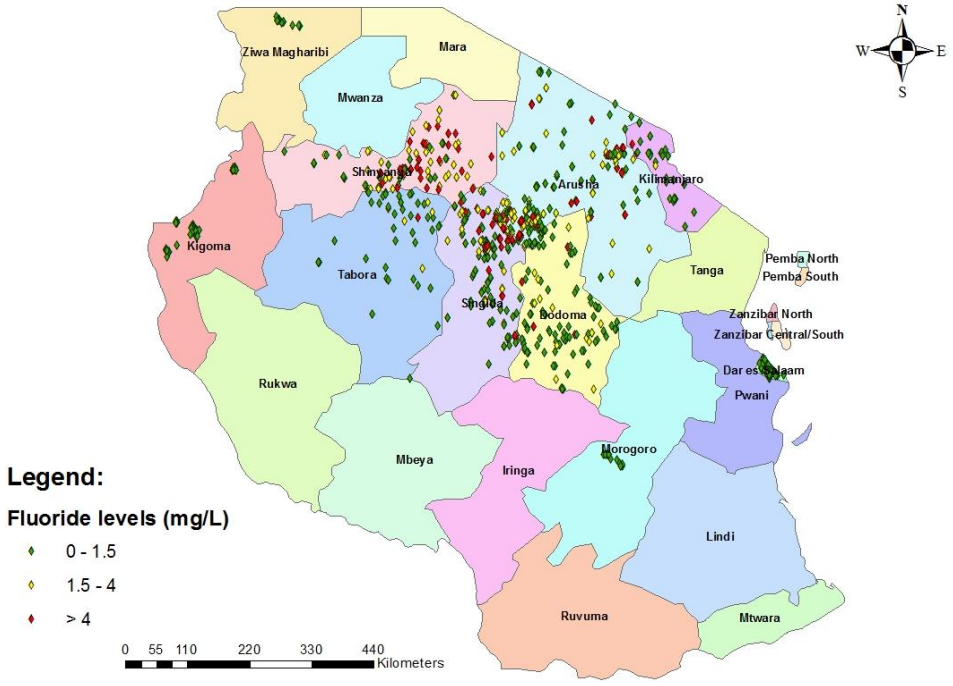

Figure 2. Fluoride distributions in groundwater of the selected regions in Tanzania from both primary and secondary data

Conclusion

The most fluoride vulnerable regions in Tanzania are Shinyanga, Arusha, Manyara, Singida, Kilimanjaro and Mwanza. Volcanic series, fluorine bearing minerals, low hardness and high alkalinity are the main factors which contribute to natural occurrence of fluoride in groundwater of Tanzania. Saline groundwater is a problem in Kilimanjaro, Sindida and Dar es Salaam Regions. No evidence was found of arsenic contamination of groundwater originating from natural causes. However, it is premature to come into conclusion as arsenic might have been contaminating groundwater due to anthropogenic factors such as mining activities. With reference to the fluoride prediction model by Amini et al. (2008), other areas whose groundwater resources are contaminated with fluoride above 1.5 mg/L include East Africa (Kenya, Burundi, Rwanda and Ethiopia), South and North Africa, Asia and South America.

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