Hydrogeochemistry of fluoride and salinization mechanism of groundwater in the Singida region, central Tanzania

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Abstract

This study focuses on the determination of factors that control high fluoride groundwater and salinization in basement aquifers of a semi-arid area in central Tanzania. Water samples were collected from productive dugouts, shallow wells and boreholes. The presence of ^{18}O, ^{2}H, and major cation and anion chemistry, including fluoride, was determined with the use of standard analytical techniques. A sodium-bicarbonate type of water dominates the study area. The ^{18}O - ^{2}H relationships suggest that the infiltration of water and groundwater has undergone evaporation while in some cases preferential flow mechanisms are suggested. Shallow wells and dugouts were found to have higher concentrations of both fluoride and chloride and this fact is partly attributed to the effect of evapotranspiration. The main mechanism for fluoride input into groundwater as well as salinization is attributed to the leaching of surface and near-surface soil salts, especially trona. No clear relationship was observed between the depth of wells/boreholes and fluoride concentration. Similarly, there is hardly any clear relationship between the fluoride concentration and the geomorphology of the study area. A more detailed investigation is needed to determine the relationship between sampling depth, fluoride concentration and salinization.

Introduction

High fluoride concentration in groundwater is one of the most important health-related geo-environmental problems that result in fluorosis. Fluorosis is rampant in both central and northern Tanzania, despite the fact that the two areas are covered by different geological formations. The central Tanzania area is occupied by fractured basement rocks in a semi-arid environment and has been studied less than northern Tanzania, which is dominated by volcanic rocks and a humid climate. Fluoride in groundwater occurs in the form of the anion F^-. Although traces of fluoride are present in many water sources, higher concentrations are often associated with volcanic rocks. In some African countries, concentrations exceed national and international standards for fluoride in drinking water supplies, which are typically within the range of 1-2 mg/ℓ. In countries in which the soil is rich in fluoride-bearing minerals, the national standards of fluoride in drinking water may be set relatively high. For example, in the United Republic of Tanzania, the fluoride concentration can be up to 8 mg/ℓ (Mambali, 1981).This value exceeds the WHO guideline for drinking water of 1.5 mg/ℓ (WHO, 1993). High fluoride concentrations have been reported in association with rift zones, volcanic rocks and granitic (Ca-poor) basement rocks (Bugaisa, 1971; Kilham and Hecky, 1973; Nanyaro *et al.*, 1984).

This study was conducted in the northern Iramba district, which is located in semi-arid central Tanzania at elevations that range from 1 062 to 1 744 m above mean sea level(**Figure 1**). The study area falls within the Tanzanian craton at the margins of the East African Rift System which is volcanically active and has rocks that contain high fluoride-bearing minerals. The hydrothermal activities of the rift faults favour the dissolution of these minerals. Minerals such as villiaumite and fluorite are often present in these rocks.

Groundwater in the study area occurs in the saprolite and in fractured basement aquifers that have static water-level that is generally measured at 10 m below ground surface. Groundwater for domestic water supply is exploited from shallow wells and boreholes. The concentration of fluoride in groundwater is attributed to factors that include evaporation, leaching of soil salts and dissolution of fluoride-bearing minerals. The saprolite is approximately 15 m thick and overlays the less weathered bedrock (saprock). Boreholes as deep as

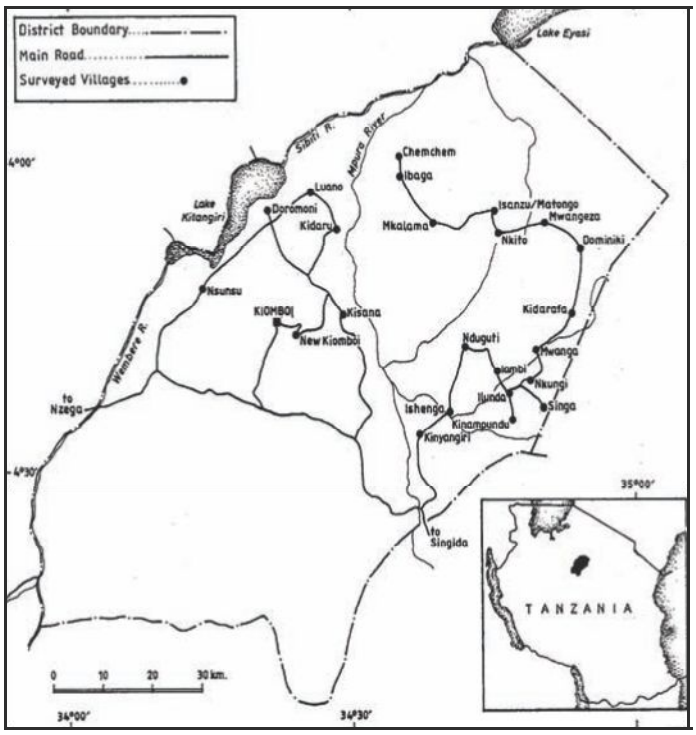


Figure 1: Location map of Iramba District showing study area (Kabuhu, 1996).

90 m, shallow wells of up to 10 m and dugouts of less than 1 m are constructed as groundwater supply points among various communities in the area.

Several studies have been conducted in volcanic rocks in Tanzania to investigate the occurrence of fluoride in groundwater, but hardly any studies have been undertaken on basement rocks. This study was conducted to find answers to the following basic questions:

1. What are the processes that control fluoride occurrence in groundwater in fractured basement aquifers?
2. How is the fluoride concentration related to the depth of wells and boreholes?
3. What is the relationship between the fluoride concentration and the geomorphology of the study area?
4. What are the nature and controls of the overall chemical character of groundwater in this area?
5. What are the mechanisms that are responsible for groundwater salinization in semi-arid areas and fractured basement aquifers?

Intensive groundwater sampling was carried out covering on both shallow and deep groundwater flow systems in the area. Dugouts that had been constructed in streambeds, shallow wells and boreholes located at various altitudes and within different rock types were sampled. Major and minor chemistry and stable isotopes were determined in various laboratories.

Materials and methods

Geological mapping

Preliminary geological mapping was conducted at the scale of 1: 50 000 (**Figure 2**). The mapping was conducted in various geomorphologic units at various altitudes. Basement rocks, including high-grade metamorphic rocks, along with granitic rocks and quaternary alluvial sediments, were observed. The area is characterized by mountains and valleys that are at altitudes that range from 1 480 m to 1 750 m above mean sea level.

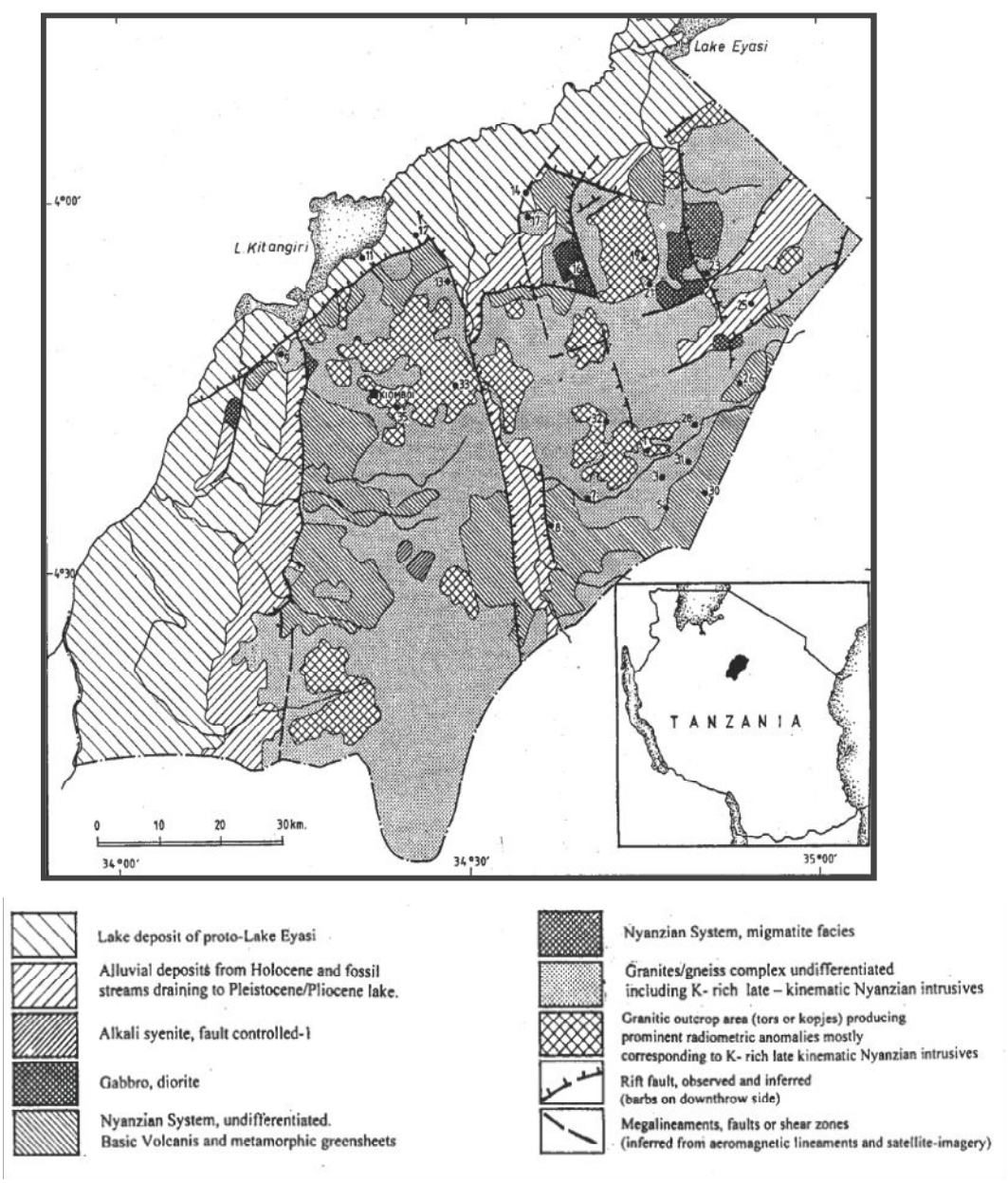


Figure 2: Geological map of the study area

Water sampling

Random water sampling was adopted for this study and standard methods were used for the determination of the chemical and physical characteristics of the water as described by the APHA (1985). Samples were collected from various sites at variable altitudes and water sources including boreholes, shallow wells and dugouts. Six sub- samples were collected at each sampling site, all of which were filtered with the use of 45 µm filter papers. Two of the sub-samples were collected in 30 mℓ polyethylene bottles and then acidified with 0.6 mℓ of 6 N HCl and with 0.3 mℓ of 6 N HNO_3. One sub-sample was collected in a 60 mℓ polyethylene bottle for stable isotope analyses. Glass bottles of 40 mℓ capacity were used for collecting the rest of the water samples for fluoride determination. Thereafter all samples were stored in a cool box during fieldwork and then in the refrigerator at the Department of Geology of the University of Dar Es Salaam before sending them to the British Geological Survey in the UK for laboratory analysis. **Table 1** shows village and location names of the sampling sites as well as their altitude, latitude and longitude.

Table 1: Location of the water samples

Sample Number	Water Source	Village	Location	Altitude (m amsl)	Latitude S (Degrees)	Longitude E
IR1	B	Iambi	Kikundya	1 503	4.351	34.752
IR2	W	Iambi	Kihau	1 481	4.351	34.769
IR3	B	Ilunda	Mtundua	1 526	4.349	34.800
IR4	W	Ilunda	Ilunda	1 527	4.368	34.797
IR5	B	Kinampundu	Mwembe	1 561	4.404	34.789
IR6	B	Kinampundu	Kisutu	1 550	4.415	34.794
IR7	W	Ishenga	Madukani	1 459	4.389	34.687
IR8	D	Kitangiri	Stream	1 485	4.457	34.616
IR9	B	Nsunsu	Soweto	1 100	4.223	34.233
IR10	W	Nsunsu	Ng'unga	1 105	4.199	34.222
IR11	D	Doromoni	River	1 062	4.090	34.330
IR12	D	Luono	River	1 066	4.064	34.397
IR13	W	Kidaru	Kidaru	1 065	4.051	34.579
IR14	W	Chemchem	Shuleni	1 116	4.108	34.491
IR15	D	Chemchem	Mission	1 121	4.050	34.582
IR16	W	Mkalama	Mkailu	1 253	4.106	34.644
IR17	B	Ibaga	Manamba	1 171	4.078	34.590
IR18	D	Ibaga	River	1 182	4.085	34.601
IR19	B	Matongo	Hindamili	1 569	4.083	34.744
IR20	W	Matongo	Mponoelo	1 554	4.089	34.747
IR21	B	Nkito	Miula	1 574	4.146	34.748
IR22	B	Nkito	Kinyantungu	1 594	4.148	34.768
IR23	W	Mwangeza	Dar es salaam	1 413	4.091	34.815
IR24	B	Mwangeza	Kisene	1 460	4.103	34.814
IR25	B	Dominiki	Mzanga	1 468	4.132	34.919
IR26	B	Kidarafa	Kidarafa A	1 672	4.211	34.935
IR27	B	Kidarafa	Hailosi A	1 709	4.211	34.910
IR28	B	Mwanga	Mpaligogo	1 580	4.269	34.889
IR29	W	Mwanga	Singida Street	1 542	4.288	34.866
IR30	B	Singa	Kagera	1 610	4.400	34.859
IR31	B	Nkungi	Nkungi	1 554	4.339	34.835
IR32	W	Nduguti	Uswahilini	1 569	4.302	34.700
IR33	W	Kisana	Kintamba	1 736	4.248	34.482
IR34	W	Kisana	Kisana	1 744	4.238	34.480
IR35	B	New Kiomboi	Magula	1 562	4.256	34.389
IR36	W	Lulumba	Water Department	1 596	4.267	34.393

B = Borehole; D = Dugout in the riverbed; W = Shallow well

Laboratory methods

Chemical analyses of water samples were conducted at the British Geological Survey in the UK. Major elements were determined by ICP-AES following the analytical techniques described by Banks *et al.* (1998b, c). Measurements for Cl were conducted with the use of automated colorimetry. Analyses for fluoride were conducted at the Department of Geology, University of Dar es Salaam, with the use of an Orion ion specific electrode, following the methodology described by Frant and Ross (1966). The fluoride electrode was calibrated

at 23°C. Standard fluoride concentrations of 0.1 mg/ℓ, 0.2 mg/ℓ, 0.5 mg/ℓ, 1 mg/ℓ, 5 mg/ℓ, 10 mg/ℓ, and 20 mg/ℓ were prepared for establishing the calibration curve. About 3 ml of each standard was mixed with 3 ml of Total Ionic Strength Adjustment Buffer (TISAB), and measured in millivolts (mV) of fluoride with the use of the Orion fluoride electrode to obtain the calibration curve. The (TISAB) was added to each sample to provide a constant ionic strength background, thereby minimizing variations between samples and standards (Hitchon, 1995). The voltage values of fluoride were taken at constant potential readings. For electrical conductivity (EC) measurements the EC meter was calibrated at room temperature with the use of 1413 µS/cm and 718 µS/cm solutions. The stable isotopes of ^{18}O and ^{2}H were determined with the use of a mass spectrometer at the British Geological Survey in the UK.

Results

Hydrogeology of the study area

The study area is characterized by Quaternary alluvium and lake deposits as well as Precambrian granites and greenstones (**Figure 2**). Granite rocks dominate the area and are known to contain elevated concentrations of fluoride-bearing minerals. However, the extent to which these minerals influence the levels of fluoride in groundwater in this area is not yet known. Groundwater is always encountered in weathered and fractured zones at depths of about 10 meters below ground surface. A saprolite of about 15 meters covers the basement although exposed basement formations in some areas are not uncommon. In riverbeds, which are mainly covered with sands, groundwater occurs at about half a meter below ground surface. Groundwater occurrence and flow seem to be fracture controlled. The static water level, at about 5 to 10 m below ground surface, is highly variable among adjacent boreholes, which indicates the existence of discrete fracture systems. Pumping-test data show that the facture systems have hydraulic conductivity values of about 10^{-4} m/sec and storativity values of about 10^{-3}. Deep groundwater occurs under confined conditions while shallow groundwater occurs mainly under water table conditions.

Most of the water samples were collected from Precambrian granite terrain with fluoride concentrations above 3 mg/ℓ. Fluoride concentrations below 1.5 mg/ℓ have also been found in the same terrain. The exceptions are some samples that were located in the Quaternary lake deposits, alluvium and in the greenstone rocks (**Figure 2**). Precambrian granites contain a high proportion of high-fluorine bearing minerals such as mica, amphiboles and occasionally fluorite. These minerals probably contribute to the observed elevated fluoride concentrations in groundwater.

Although elevated fluoride concentration is found to be predominant in the granite terrain, the relationship between fluoride concentration in groundwater and the geology seems rather obscure. It is therefore unclear whether the high fluoride concentrations are related to bedrock geology or to other factors that could lead to secondary enrichment.

Hydrochemistry

Fluoride concentrations

The results obtained are given in **Tables 2**, **3**, and **4** with the sources from which the samples were collected. It was found that 72 % of the water samples had fluoride concentrations that exceed the WHO guideline of 1.5 mg/ℓ for drinking water (WHO, 1993). The majority of the samples (52.7%) were collected from shallow groundwater sources of which 73.7% had a fluoride concentration that is above the WHO guideline, while 70.6% of the boreholes had a fluoride concentration that is above the guideline.

The highest concentration of fluoride appeared in a water sample that was collected from the riverbed of the Luono River (sample IR 12). It may be attributed to the leaching of surface or near-surface soil salts that had concentrated in the soil matrix as a result of evaporation. The lowest concentration appeared in a shallow well at the New Kiomboi Water Department. This area is also characterized by low salinity as indicated by the low electrical conductivity values. This finding may indicate the bypass flow of water through macropores, which result in a minimum of water-rock contact time during infiltration and percolation to the water table.

The presence of fluoride in groundwater is generally a natural phenomenon that is influenced by local and regional hydrogeological conditions (Agrawal *et al.*, 1997). Differences in fluoride concentrations in the shallow wells and dugouts are large, even at very short distances. This observation is similar to that made by Latha *et al.* (1999). Changes in fluoride concentration among adjacent boreholes and wells may indicate hydraulic and lithologic heterogeneity in aquifer formations.

Table 2: Fluoride and major ion concentrations in dugouts.

Sample Number	HCO_3 Mg/l	SEC µS/cm	Cl mg/ℓ	TON mg/ℓ	F mg/ℓ	SO_4 mg/ℓ	Ca mg/ℓ	K Mg/ℓ	Mg Mg/ℓ	Na Mg/ℓ	Ion Balance%	$\delta^{2}H$ (‰)	δ 18O (‰)
IR8	663	1 223	73.25	4.98	1.59	33.6	77.1	3.1	48.1	157	2.52	-9.9	-1.99
IR11	296	550	14.32	1.65	1.46	10.6	39.1	3.5	5.97	86.7	2.26	-15.5	-3.32
IR12	845	1 660	128.6	6.07	14.33	66.5	7.7	5.7	2.07	449	2.37	-20.1	-4.08
IR15	443	753	31.08	-0.22	2.01	21.5	42.6	2.6	15.2	123	1.33	-13.1	-2.44
IR18	172	369	35.06	-0.22	1.36	9.2	37.3	2.1	9.43	35.5	3.07	-16.3	-3.56

Table 3: Fluoride and major ion concentrations in shallow wells

Sample Number	HCO_3 mg/ℓ	SEC µs/cm	Cl mg/ℓ	TON mg/ℓ	F mg/ℓ	SO_4 mg/ℓ	Ca mg/ℓ	K Mg/ℓ	Mg mg/ℓ	Na mg/ℓ	Ion Balance%	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)
IR2	566	964	39.21	2.55	5.14	11.5	49.5	1.1	20.6	173	4.08	-15.2	-3.11
IR4	750	1470	69.34	6.58	5.26	48.1	18.1	4.4	18.6	318	2.07	-16.38	-3.57
IR7	312	663	35.79	11.43	3.1	8.3	67	3.5	14.1	70	3.58	-15.6	-3.38
IR13	307	766	63.58	2.09	2.97	44.4	33.8	1.4	10.9	139	4.61	-16.6	-3.04
IR14	269	491	24.62	-0.22	2.27	9.1	40.7	1.3	9.98	62.4	2.89	-23.6	-5.15
IR10	340	806	51.92	6.09	2.19	36.9	59.8	0.9	14.4	105	3.05	-6.9	-2.17
IR16	518	1 172	139.4	2.74	4.41	29.4	59.1	4.9	27.7	205	3.78	-10.2	-2.47
IR20	536	1 012	41.02	3.29	2.61	56.2	59.3	< 0.5	27.1	167	4.62	-18.3	-3.77
IR23	600	1 436	160	0.33	8.73	67.7	47.4	5.4	17.3	284	1.57	-21.4	-3.81
IR29	707	1 127	47.23	7.61	4.16	14.2	51.6	2.9	47.1	193	4.05	-16	-3.24
IR32	247.5	769	39.07	25.1	1.62	34.3	55.1	17.1	23.2	71.8	3.55	-17.5	-4.29
IR33	37	146	4.08	5.36	0.49	8	5.5	10.9	2.89	11.7	1.51	-13.1	-3.31
IR34	44	191	2.55	0.77	0.67	4	3.3	1.4	1.19	15.8	2.95	-10.5	-3
IR36	16	58.4	4	-0.22	0.21	2.4	4.3	1	0.23	5.7	5.31		

Table 4: Fluoride and major ion concentrations in boreholes

Sample Number	HCO_3 mg/ℓ	SEC µS/cm	Cl mg/ℓ	TON mg/ℓ	F mg/ℓ	SO_4 mg/ℓ	Ca mg/ℓ	K Mg/ℓ	Mg mg/ℓ	Na mg/ℓ	Ion Balance%	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)
IR3	490	853	8.26	4.11	4.64	21.9	52.1	10.1	32.2	98.4	4.11	-19.8	-4.06
IR1	489.7	1007	46.78	0.77	2.85	6.6	73.3	5	24.3	127	8.49	-18.3	-3.69
IR5	569	1027	48.84	16.97	2.33	9.6	77.7	14	53.2	94	2.36	-14.5	-2.73
IR6	449	808	56.66	1.65	1.57	13.9	83.6	3.4	26.2	77.7	2.27	-18.17	-3.78
IR9	291	389	2.23	-0.22	1.42	2.2	73.8	1.7	9	12.9	1.60	-13.8	-3.19
IR17	201	382	18.64	0.33	1.87	7.3	27.6	1	8.61	49.9	3.43	-13.6	-3.51
IR19	569	1013	82.48	0.49	2.86	34.1	70.1	4.9	25.8	175	3.71	-16.1	-4.02
IR21	576	947	69.11	7.15	2.04	44.4	99.6	1.1	38	121	2.14	-22.8	-4.93
IR22	602	662	36.05	5.93	1.46	5	76.3	9.1	19.2	47.6	-1.57	-23.2	-3.98
IR24	444	765	41.25	0.82	1.85	7.3	53.4	1.5	24.2	97.1	1.54	-15.5	-3.54
IR25	632	871	31.71	2.41	2.01	19.9	84	6.7	41.9	103	1.90	-22.7	-3.65
IR26	488	822	42.99	8.23	4.5	8.6	71.1	1.8	27.8	117	4.78	-18.1	-3.75
IR27	430.7	923	26.7	30.1	0.82	11.4	100	17.6	46.7	60.5	7.81	-15.4	-4.03
IR28	557	971	48.71	13.79	0.99	60.7	111	5.3	42.3	96.2	2.26		
IR30	589	1187	83.01	9.85	1.46	36.9	76.2	33	74.3	81	2.96	-19	-4.28
IR31	583	1055	43.44	23	1.79	39.7	104	14.7	56.9	78.2	1.53	-19	-4.44
IR35	445	766	23.98	0.99	2.44	37.3	68.6	0.9	29.2	82.3	3.35		

TON =Total Oxidized Nitrogen

Table 5: δ^2H (‰) and $\delta^{18}O$ (‰) content of local rainfall

$\delta^{18}O$(‰)	-6.09	-9.35	-5	-0.4	0.25	-2.27	-6.76	-3.06	-2.99	-5.18
δ^2H(‰)	-33.7	-58.4	-18.2	19.8	21	-2.1	-40.7	-15.9	-8.9	-33.6
$\delta^{18}O$(‰)	-4.42	-3.65	-4.27	-6.22	-7.71	-7.1	-7.98	-5.69	-7.71	-0.27
δ^2H(‰)	-22.5	-9.7	-17.8	-32.6	-46.4	-42.8	-50.2	-30.9	-44.9	13
$\delta^{18}O$(‰)	0.48	-1.48	-1.78	-1.83	-1.57	-1.71	-4.73	-5.83	-5.83	-9.07
δ^2H(‰)	17.1	-3.9	2.1	-1.4	-3.4	-2.5	-20.8	-37.9	-57.2	-74.4
$\delta^{18}O$(‰)	-10.4	-8.28	-8.97	-5.34	-4.26	-8.79	-0.85	-1	-1.05	-2.41
δ^2H(‰)	-57.2	-55.2	-61.1	-26.4	-19.3	-55.2	4.7	6.3	1.2	-7.3
$\delta^{18}O$(‰)	-7.65	-4.52	-5.44	-6.1	-5.43					
δ^2H(‰)	-45.4	-20.3	-27.7	-33.4	-34.5					

Major cation and anion chemistry

Na^+ concentrations are found to be higher than any of the other cations (Ca^{2+}, K^+, and Mg^{2+}) as shown in **Tables 2, 3 and 4** and are positively correlated with fluoride concentrations. Elevated Na^+ concentrations may be due to cation exchange where Ca^{2+} from groundwater is adsorbed on clayey materials in exchange of Na^+. Another possible reason for the higher Na^+ concentration could be dissolution of trona ($Na_2CO_3.NaHCO_3.2H_2O$), a white salt commonly found in the semi-arid East African Rift Valley with lots of fluoride. While conducting fieldwork, trona was found in almost all the dry riverbeds that have flow towards the study area during the wet season.

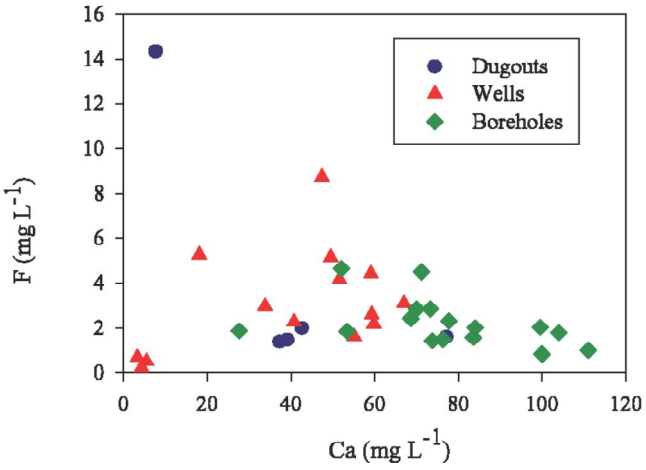
Large variations in chloride concentrations were observed in the groundwater, which may be attributed to evaporation of rainfall, leaching from the surface and/or soils salts and minor contributions from acidic rocks. High concentrations of chloride were observed in the wells that are within sediments that are predominantly composed of materials that derive from the volcanic area (faults of the Rift Valley). Fuge (1988) reports that chloride occurs in minerals such as sodalite ($Na_4\ Al_3\ Si_3\ O_{12}\ Cl$). According to Fuge (1977), fluorine and chlorine occupy the hydroxyl sites of hydroxy silicates, such as micas and amphiboles, and also apatite. Fluorine is richest in granite rocks, while chlorine is richest in the hydroxy minerals of basic rocks.

The occurrence of SO_4 can be associated with volcanic activities (Haile, 1999). Other sources of SO_4 include rainfall, gypsum dissolution, oxidation of pyrite and agricultural fertilizers.

Total oxidized nitrogen (TON) values in the study area are high (see **Table 4**) although agricultural fertilizers are not used in this area. The elevated values (of TON) suggest domestic pollution by the leaching of sewage from pit latrines into the groundwater flow system. Livestock farming could be another source of pollution as large numbers of grazing cattle were observed in the study area.

The majority of boreholes have a high calcium and low fluoride concentration, which suggests that Ca concentration in the bedrock of the aquifers plays an important role in limiting the amount of fluoride. Shallow wells contain low calcium with high fluoride concentrations, except for those shallow wells in Kintamba and Kisana that are located at the highest altitude of the area (**Figure 3**).

Figure 3: Relationship between Ca and F in the various water sources of the Northern Iramba District



The highest fluoride concentration observed in a dugout in the bed of the Luono River had the lowest concentration of Ca^{2+} and highest concentrations of both Na^{+} (**Figure 4**) and HCO_3^{-} (**Figure 5**). This finding may be attributed to the dissolution of trona ($Na_2CO_3.NaHCO_3.2H_2O$), an evaporite mineral that is commonly found in the East African Rift System and is always contaminated with fluoride. The latter may also indicate that evaporation processes took place and therefore concentrated salts on the surface and within the near-surface soils with subsequent leaching that leads to elevated concentrations in the groundwater system.

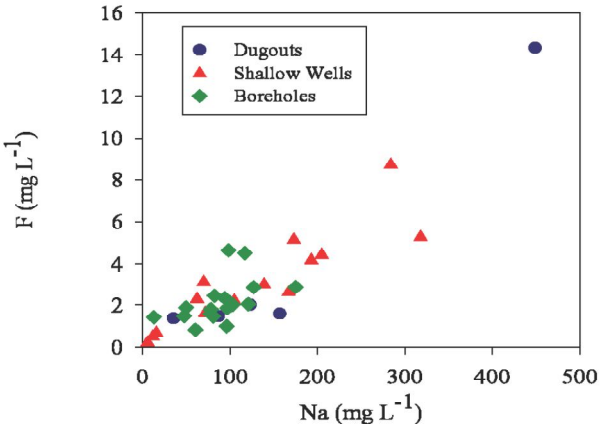


Figure 4: Relationship between Na+ and F- in different water sources in Northern Iramba District

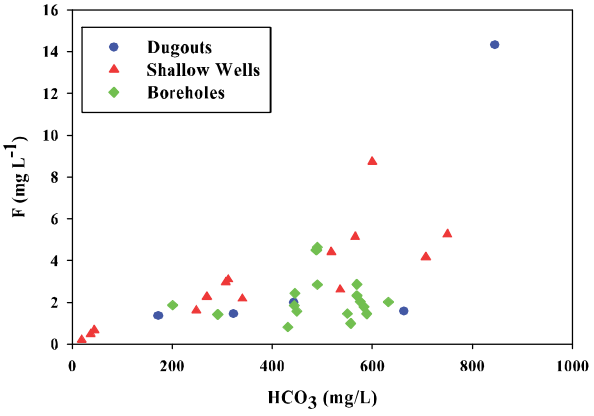


Figure 5: Relationship between F and HCO_3 in different water sources in Northern Iramba District

A relationship between salinity (EC values) and fluoride concentration (**Figure 6**) has a positive correlation, which indicates that fluoride mobilisation through the leaching process results in an increase in the salinity values of the groundwater due to the dissolution of easily leachable salts such as trona.

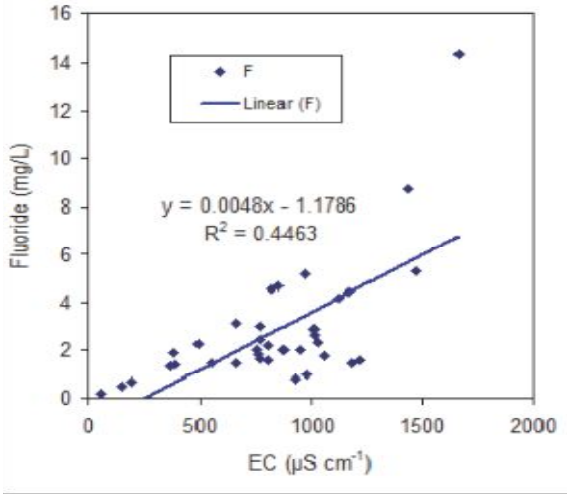


Figure 6: Relationship between salinity and F values in the various water sources in the Northern Iramba District

Alkalinity was also found to be positively correlated with fluoride concentration, albeit to a low extent. The Piper diagram (**Figure 7**), which was prepared in accordance with the modification by Back (1966), shows that water generally contains lower concentrations of calcium and magnesium in comparison with sodium and potassium. Bicarbonate is the dominant anion. Most of the boreholes contain water that has no dominant cation - HCO_3-type and most of the dugouts and shallow wells contain a Na-HCO_3 type of water. The predominantly Na-HCO_3 water type could be attributed to the dissolution of near-surface salts.

Stable isotopic ratios

Evaporation had an impact on the groundwater of the study area, which is characterized by a semi-arid climate. The ^{2}H and ^{18}O values range from -6.90‰ to -23.60‰ and -1.99‰ to -5.15‰ respectively. This range could be attributed to heterogeneity on the soil surface, which affects the infiltration rates of the surface water and brings about the modification of the isotopes through evaporation effects. The mean values for dugouts are -14.98 and -3.08 (n = 5); for shallow wells, -15.48 and -3.39 (n =13); and for boreholes, -18.00 and -3.84 (n =14) for ^{2}H and ^{18}O respectively (**Table 6**).

Table 6: Mean $\delta\ ^{18}O$ (‰) of the various water sources

Water Source	Mean $\delta\ ^{18}O$ (‰)
Rainfall	- 4.46
Dugouts	-3.08
Shallow wells	-3.39
Boreholes	-3.84

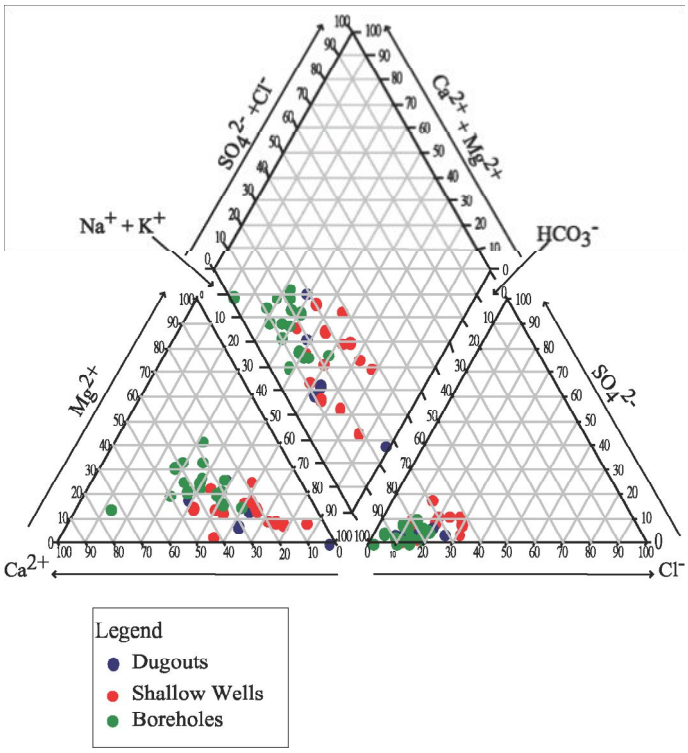


Figure 7: Piper trilinear diagram for the groundwater of the Northern Iramba District

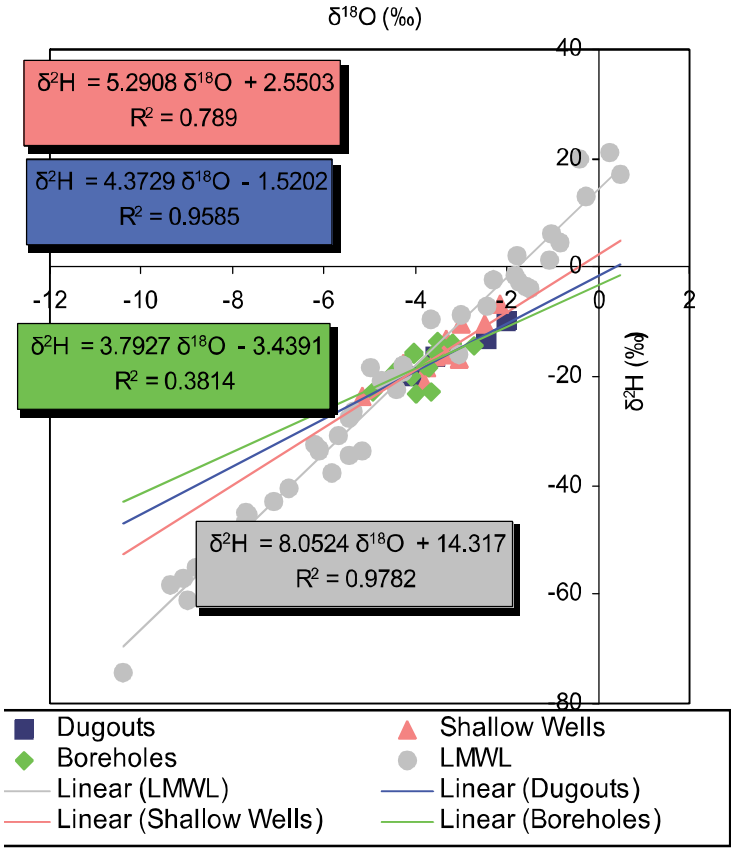


Figure 8: Relationship between δ^2H and $\delta^{18}O$ in the various water sources of the Northern Iramba District. LMWL indicates the rainfall data from the Local Meteoric Water Line

The slope of 5.3 for the shallow wells (**Figure 8**) suggests that surface water/runoff in this area has undergone evaporation before and during infiltration, which resulted in the enrichment of both ^{2}H and ^{18}O of the shallow groundwater. A comparison to the mean $\delta^{18}O$ value of the rainfall (**Table 6**) supports the observation shown in figure 8. In addition, the mean data for the dugouts and the resultant slope of 4.4 for the dugouts support the surface to subsurface evaporation processes of infiltrating water.

The mean stable isotope data for boreholes, that are less enriched than both the dugouts and shallow wells, indicate that the isotopic character of deeper groundwater may result from a mixture of evaporated surface runoff before infiltration and direct infiltrating/recharge of rainfall through bypass flow mechanisms in macropores. The bypass flow mechanism of groundwater recharge is typical in the basement fractured aquifers of central Tanzania as observed by Nkotagu (1996) at the Makutupora groundwater basin in the Dodoman craton. A relationship between $\delta\ ^{18}O$ and fluoride concentration (**Figure 9**) show the same fluoride values to vary with different $\delta\ ^{18}O$ values with no clear pattern. However, most data are concentrated between $\delta\ ^{18}O$ -3‰ and -4‰ with fluoride values at about 3 mg/ℓ. This indicates that similar processes are responsible for fluoride enrichment in the various groundwater sources. As indicated, bypass flow mechanisms may play a major role in the groundwater recharge processes within the study area.

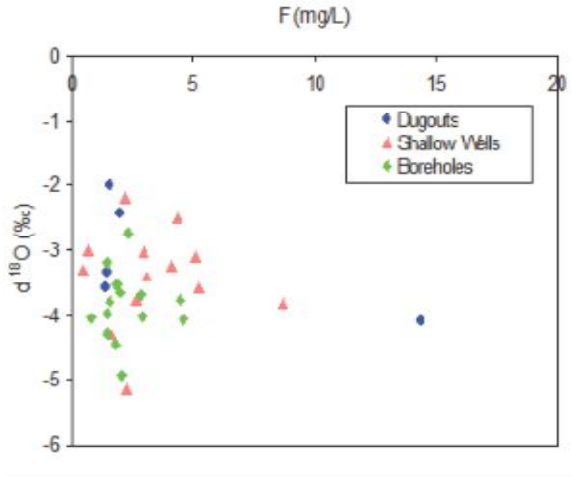


Figure 9: Relationship between $\delta^{18}O$ and fluoride concentration in the various water sources of the Northern Iramba District.

A relationship between fluoride concentrations and depths of boreholes/wells (**Figure 10**) generally shows that the groundwater from dugouts (mean depth = 0.5 m, mean [F-] = 4.15 mg/ℓ, n = 5) and shallow wells (mean depth = 6 m, mean [F-] = 3.31 mg/ℓ, n = 11) have higher concentrations of fluoride than the groundwater that was abstracted from boreholes (mean depth = 49 m, mean [F^-]= 2.17 mg/ℓ, n= 8) for the water sources with known depths. Groundwater sources that are deeper than 40 m have lower fluoride concentrations than groundwater that was abstracted at depths less than 30 m below ground level. This difference may be attributed to the leaching of near-surface salts that are formed due to the repetitive evaporation processes. The range of fluoride concentrations in shallow wells, from 0.5 to 6 mg/ℓ, at the same depths, and dugouts to a lesser extent, supports the view that fluoride leaching and subsequent infiltration of groundwater may be taking place under different heterogeneous soil conditions (**Figure 10**). The narrow range of fluoride concentrations, of about 2-3 mg/ℓ, for the groundwater that was abstracted through deeper boreholes may imply a similar or uniform process of fluoride enrichment with depth (**Figure 10**).

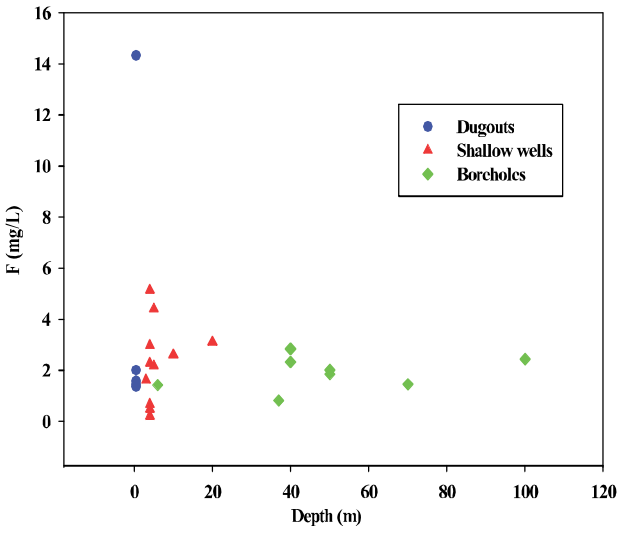


Figure 10: Variation of fluoride with depth for various water sources in the Northern Iramba District

Subsurface evapotranspiration tends to concentrate fluoride and other salts in solution. In groundwater sources that are deeper than 40 m, this effect is not as significant in comparison with the shallower groundwater sources. The dissolution of minerals through water-rock interaction contributes significantly to the release of fluoride and other elements into groundwater.

Conclusions

Fluoride concentration in 72% of the groundwater samples was found to have fluoride concentration that is above the WHO guideline value of 1.5 mg/ℓ. Four factors that bring about the chemical character of high fluoride groundwater in the study area were determined and it was found that the leaching of surface and near-surface soil salts lead to the high concentration of fluoride and other major ions in the groundwater. Mineral dissolution of CaF_2 and NaF plays an insignificant role in elevating fluoride concentrations in the groundwater of the study area. The subsurface evaporation process contributes to the elevated fluoride concentration in groundwater as indicated by the stable isotopes data. Fluoride concentration in groundwater is highly variable, suggesting the heterogeneity of basement aquifers, both in terms of hydraulic (fractured/non-fractured) and lithologic characteristics. It has been noted that geomorphology plays an insignificant role in the fluoride concentration of various groundwater sources. However, a challenge remains in respect of understanding optimum depths of the construction of wells with acceptable levels of fluoride concentration for the improvement of the quality of public water supplies.

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