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Hydrogeochemical Assessment of Groundwater Quality in Salima and Nkhotakota Districts, Malawi

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Abstract: ***This paper investigated the hydrogeochemical characteristics influencing water quality, and assessed the groundwater quality for domestic and irrigation purposes in two districts of Salima and Nkhotakota in Malawi. Data was compiled from water quality surveillance reports of water sources constructed by sponsorship from WaterAid Malawi programme. A water quality index (WQI) was used to measure suitability of groundwater for domestic purposes. Electrical conductivity, total dissolved solids and various indices were used to measure quality of water for irrigation. Anion chemistry showed a general dominance of HCO_3^-, while Ca^{2+} was the dominant cation. The pH of groundwater in Salima was neutral and of Ca-HCO_3/Na type; while in Nkhotakota it was slightly acidic and of Ca-Na/Mg type. It was determined that Ca^{2+}, Mg^{2+}, SO_4^{2-} and HCO_3^- originated from release of carbonates (calcite or dolomite) in both districts and from gypsum in Salima district only. Although turbidity, pH and EC exceeded drinking water standards, the WQI showed the water to be suitable for consumption. It was therefore recommended to educate communities on household water treatment methods. Continual monitoring of these water sources with unacceptable standards was also proposed to be a priority.***

Keywords: Hydrogeochemistry; Groundwater; Water-rock interactions; Water quality index; Malawi

1. Introduction

Groundwater is important for domestic and irrigation uses in rural parts of Malawi. Rural communities in Malawi do not access safe drinking water easily, despite abundant water resources and a wide network of surface water (Palamuleni 2002). Surface water is easily accessible but it is prone to contamination from farming and household activities. Alternatively groundwater can be made available to rural communities cheaply, is not contaminated, and can be available regardless of season (McDonald and Calow 2009). However, any disturbance to the water-rock interactions can negatively affect groundwater quality. Therefore, knowledge of groundwater hydrogeochemical evolution is vital for water quality management.

The demand for safe water in Malawi has prompted WaterAid to venture into promoting water supply and sanitation in the country. WaterAid is an international non-governmental organization that focuses on provision of portable drinking water, improved hygiene and sanitation in rural areas across the world (WaterAid 2015). WaterAid Malawi programme operates by funding its partners to construct boreholes and shallow wells, supports communities to repair broken wells and hand-pumps and trains them to maintain their own facilities in the long term. WaterAid aims to deliver quality drinking water to project beneficiaries, which conforms to quality standards of the country (WaterAid 2009).

The objectives of this study were to (1) investigate groundwater hydrogeochemical characteristics; (2) determine water-rock interaction influencing water quality and; (3) assess groundwater quality for use in households and agriculture lands under irrigation. To achieve the set objectives the study used scatter plots, USGS geochemical code PHREEQC (Parkhurst and Appelo 2013) and piper diagram as complementary tools. A water quality index (WQI) was used to determine the safety of the groundwater for human consumption (Yidana 2010). The groundwater electrical conductivity (EC) together with recommended irrigation water quality (sodium adsorption ratio (SAR), percent sodium Ion (% Na^+) and residual sodium carbonate (RSC)) and total dissolved solids (TDS), were calculated to evaluate the suitability of groundwater for irrigation activities.

2. Materials and Methods

Study Area

Salima and Nkhotakota districts boarder each other and are located in the central region of Malawi, south of Lilongwe the country's Capital (Fig 1). The two districts are located along Lake Malawi to the east. Salima district covers a land area of approximately 2,200 km^2 while Nkhotakota covers about 4,260 km^2 (Government of Malawi (GoM) 2006; GoM 2010). These districts experience a warm tropical climate, which is characterized by the rainy and dry seasons that occur from November to April and May to October, respectively. The mean annual temperature for Salima district is about 22°C. The highest temperatures in Salima are experienced in October, which at times might go as high as 33°C. The lowest temperatures are experienced between June and July. For Nkhotakota district the maximum and minimum temperatures have an average of 28.7°C and 20°C respectively. On average, Salima and Nkhotakota receive annual rainfall of about 1270mm and 1400mm, respectively (GoM 2006; GoM 2010).

Figure 1: Sketch map showing the location of study districts

The districts of Salima and Nkhotakota are found in the central region of Africa's Great Rift Valley. The Rift Valley system is separated from the Central African Plateau by the escarpments in the hilly areas. The valley has a flat terrain that generally slopes towards the lake, which has a marshy coastline comprised of sandy soils. The study area is part of the extensive basement complex that originated from the Precambrian and early Palaeozoic eras (Chilton and Smith-Carington 1984; Mapoma and Xie 2014; Mapoma et al. 2014). The basement complex lithology is widely developed by biotite and hornblende-bearing gneisses, variably modified by magnetization and boasts of minerals like hornblende, charnockite and other ecologically favourable minerals (GoM 2006; GoM 2010). The basement complex is largely weathered in plateaus and fractured in highly areas. The quaternary alluvial deposits of lowlands form the greater part of the lakeshore districts, of which Salima and Nkhotakota are part (Mapoma and Xie 2014). The deposits are characterized by superficial deposits (Dulanya et al. 2010). The alluvial aquifers are high yielding with recorded yields in excess of 10 L/s (Chimphamba et al. 2009) compared to weathered basement of the plateau areas. However, alluvial aquifers are more mineralized compared to weathered basement aquifers.

Data source

This study obtained data from water quality surveillance reports of water sources constructed with funding from WaterAid in Malawi. These surveillance reports were for the periods of April 2011, January 2012 and January, April and November of the year 2013. The groundwater data was for 59 sources in Salima district and 16 sources in Nkhotakota district. The purpose of the surveillance exercises was to determine the quality of groundwater for domestic purposes. The measured major ions were calcium (Ca^{2+}), sodium (Na^{+}), magnesium (Mg^{2+}), potassium (K^{+}), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}) and nitrate (NO_3^-); and measured trace elements were Fe^{2+} and F^-. The measured physical parameters included Total Hardness (TH), Total Suspended Solids (TSS) and Turbidity. These water parameters were measured in the Central Water laboratory of the Ministry of Agriculture, Irrigation and Water Development. Total dissolved solids (TDS), pH and electric conductivity (EC) were measured during sampling.

Drinking water quality assessment

The WQI adopted from Canadian Council of Ministers of the Environment (CCME) was used to measure safety of groundwater for domestic purposes in Salima and Nkhotakota districts. The WQI determines water quality based on three main categories of scope, frequency and amplitude (CCME 2001). Scope identifies variables falling short of required water quality standard; Frequency measures the number of failings to achieve required standards; and amplitude measures the proportion for sub standard water quality. The objectives for this study were based on the national Malawi standards for drinking water delivered from Boreholes and Protected Shallow Wells (MSB 2005), although the World Health Organization's (WHO) standards were also used to compare with accepted international standards (WHO 2011). The three elements of scope, frequency and amplitude are combined to produce a single water quality score ranging between 0 and 100; categorized in 5 descriptive categories to simplify presentation (Table 1).

Table 1: Water quality index categories and their descriptions

WQI Category	*Rank*	*Rank description*
Excellent	95 - 100	Water is close to the pristine condition
Good	80 - 94	Conditions rarely depart from natural or desirable levels
Fair	65 - 79	Conditions sometimes depart from natural or desirable levels.
Marginal	45 - 64	Conditions often depart from natural or desirable levels.
Poor	0 - 44	Conditions usually depart from natural or desirable levels.

Calculation of the WQI followed the procedure of initially calculating scope (equation 1), frequency (equation 2) and amplitude (equations 3a, b and c), before calculating the WQI (equation 4).

$$\text{Scope} = \left(\frac{\text{Number of Failed Variables}}{\text{Total Number of Variables}}\right) \times 100 \quad \text{(Equation 1)}$$

$$\text{Frequency} = \left(\frac{\text{Number of Failed Tests}}{\text{Total Number of Tests}}\right) \times 100 \quad \text{(Equation 2)}$$

$$\text{Excursion}_i = \left(\frac{\text{Failed Test Value}_i}{\text{Objective}_j}\right) - 1 \quad \text{(Equation 3a)}$$

$$\text{Normalised Sum of Excurssions (nse)} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{Number of Tests}}$$
(Equation 3b)

$$\text{Amplitude} = \left(\frac{\text{nse}}{0.01\text{nse} + 0.01} \right) \quad \text{(Equation 3c)}$$

$$\text{WQI} = 100 - \left(\frac{\sqrt{Scope^2 + Frequency^2 + 2Amplitude^2}}{1.732} \right) \text{(Equation 4)}$$

Irrigation Water Quality Assessment

The water quality for irrigation purposes was assessed using several indices that included SAR, % Na^+, and RSC. The SAR, expressed as in equation 5, has been commonly used for evaluating how appropriate groundwater is for irrigation purposes (Ayers and Westcot 1985). The $\%Na^+$ was calculated as shown in equation 6; and in both equations 5 and 6 ion concentration was in meq/L.

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\left(\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2} \right)}} \quad \text{(Equation 5)}$$

$$\%\text{Na}^+ = \left[\frac{(\text{Na}^+ + \text{K}^+)}{(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+)} \right] \times 100 \quad \text{(Equation 6)}$$

The United States Salinity Laboratory Staff (USSLS) diagram, which plots SAR against EC was also used for this assessment. Similarly, the Wilcox's diagram, which plots the EC against % Na^+ was also used for the classification. The RSC was computed using equation 7, where all concentrations were expressed in meq/L, and it evaluates the effect of HCO_3^- and CO_3^{2-} on irrigation water quality standards (Eaton 1950).

$$\text{RSC} = \left(\text{HCO}_3^- + \text{CO}_3^{2-}\right) - \left(\text{Ca}^{2+} + \text{Mg}^{2+}\right) \text{(Equation 7)}$$

3. Results and Discussion

Hydrochemistry Status

The pH ranged from 6.1 to 8.2 and had a mean of 7.3 for Salima indicating neutral water; groundwater pH for Nkhotakota ranged from 5.3 to 6.4 and a mean of 5.8 that indicated slight acidic water (Table 2). Although 75% of the water samples in Nkhotakota had pH values less than the required minimum of the Malawi standards, groundwater in Salima was within the required pH range (Table 2). The TDS in Salima varied from 40 mg/L to 1269 mg/L (mean = 326.7); and EC ranged from 74 to 2365 (mean = 640.3us/cm; Table 2). The TDS and EC values in Nkhotakota ranged from 38 mg/L to 230 mg/L (mean = 230) and 50uS/cm to 340uS/cm (mean=123) for TDS and EC respectively. The piper diagram (Fig 2) classified the groundwater in Salima as Ca-HCO_3 type water in 50.8 percent of sampling points, with Ca-Na-HCO_3 (33.9%) and Na-Ca-HCO_3 (11.9%) observed in other parts. The majority of groundwater samples in Nkhotakota were Na-Ca-HCO_3 in 48.3 percent of the samples, while Ca-Mg-HCO_3 (31%) and Ca-Na-HCO_3 (25%) groundwater types were apparent.

Table 2: Statistical summary of the hydrochemistry of groundwater for Salima and Nkhotakota districts (mg/L except where indicated)

Parameters	Salima			Nkhotakota			MSB	WHO
	Minimum	Maximum	Mean	Minimum	Maximum	Mean		
EC (µS/cm)	74	2365	640.3	50	340	122.8	3500	140
pH	6.1	8.2	7.3	5.3	6.38	5.8	6 - 9.5	6.5 - 8.5
TDS	40	1269	326.7	38	230	85.9	2000	1000
HCO_3	21	645	233.8	16	181	57.9	-	-
Cl	3.0	154	32.7	3.0	14	7.03	750	600
SO_4	0	418	41.1	2.0	7.0	3.14	800	400
NO_3	0.01	8.67	0.55	0.09	0.014	0.21	100	100
F	0.1	2.20	1.01	0.45	1.6	0.45	3.0	2.0
Na	1.0	204	38.9	3.0	16	7.56	250	200
K	0.4	17.5	3.51	1.1	6.6	2.52	-	-
Ca	6.0	220	60.84	3.0	36	10.74	200	200
Mg	2.0	39	15.02	1.0	10	3.53	150	150
Fe	0	0.75	0.11	0	1.8	0.22	3.0	1.0
TH (CaCO3)	22	672	213.9	11	131	41.13	800	500
Turbidity (NTU)	8.0	3.0	14.8	0.6	120	3.63	25	5
SS	0.01	117	3.63	0.1	16	4.46	25	-

Anion chemistry showed a general dominance of HCO_3^- in both the districts followed by Cl^- and SO_4^{2-} in that order. In Salima district, 15 percent of samples had HCO_3^- above the Malawi standards limit (MSB, 2005). However, the concentrations for Cl and SO_4^{2-} were all below the standards limit. In Nkhotakota district, all the dominant anions were below the Malawi standards limit (Table 2). Cation chemistry showed a general dominance of Ca^{2+} in both districts followed by Na^+ and Mg^{2+} in that order. In Salima district the Ca^{2+}, Na^+ and Mg^{2+} concentrations were below the Malawi standards limit. In Nkhotakota district, all the dominant cations were also below the Malawi standards limit.

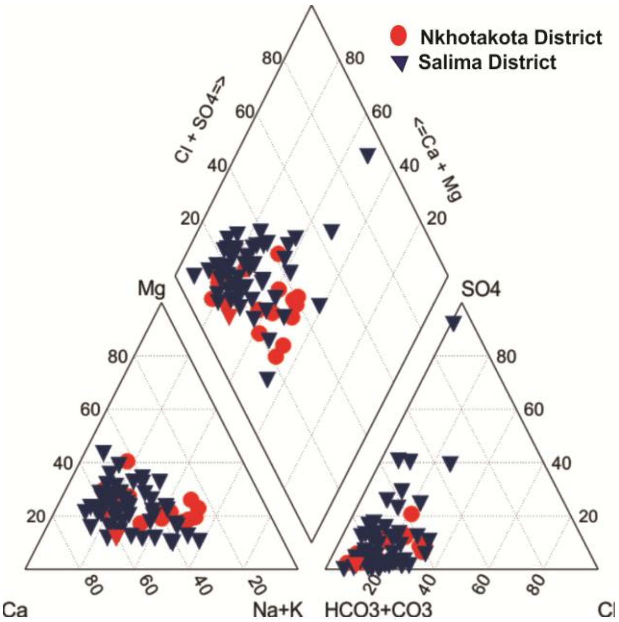

Figure 2: Piper diagram used to summarize the water types for the individual groundwater samples

Saturation Indices

Groundwater of Ca/Na-HCO$_3$ and Ca-Na/Mg-HCO$_3$ type in Salima and Nkhotakota districts respectively, suggested that calcite and dolomite were responsible for the water type. However such water quality, especially with the presence of Na$^+$, can result from ion exchange that results in release of Na$^+$ and removal of Ca^{2+} (Han et al. 2013); hence understanding the saturation levels of carbonates and other minerals was important.

Using PHREEQC inverse modeling, the SI value of calcite and dolomite in Salima district ranged from -2.99 to 0.76 (mean = -1.66) and from -6.45 to 1.07 (mean = -3.69), respectively (Fig. 3a). However, in Nkhotakota district calcite and dolomite ranged from -4.53 to -1.45 (mean = -3.25) and from -9.37 to -3.25 (mean = -6.85), respectively (Fig. 3b). Considering the mean scores in the two districts, it can be said that calcite and dolomite were in general under-saturated. Unlike in Nkhotakota where all samples had SI values below zero, a large proportion of the groundwater samples in Salima had SI results for dolomite (64%) and calcite (56%) that were less than zero (Fig. 3). Gypsum and Fluorite were other minerals of interest and their SI values showed that they were all under-saturated in both districts. The SI value of gypsum and fluorite in Salima district ranged from -5.52 to -0.73 (mean = -2.91) and from -5.81 to -0.44 (mean = -1.45), respectively. In Nkhotakota district gypsum and fluorite SI values ranged from -4.32 to -3.11 (SI$_{mean}$ = -6.85) and from -5.81 to -0.92 (SI$_{mean}$ = -2.71), respectively. The SI results were in overall below zero indicating that all the minerals (calcite, dolomite, gypsum and fluorite) were under-saturated in these samples and could continue to dissolve along the groundwater flow path (Fig. 3). There was a strong positive correlation between gypsum and TDS in Salima district, which showed release of gypsum into the groundwater and that additional Ca^{2+} from gypsum, were responsible for saturation of calcite and dolomite in some samples.

Calcite and dolomite SI followed a positive linear trend that was characterized by a correlation coefficient of 0.99 in both districts of Salima and Nkhotakota. This showed that the mineral phases were changing in a similar trend, which is evidence that the reactions of the two minerals were controlled by similar hydrogeochemical process. The SI of gypsum varied from -2.26 to -0.91 (SI$_{mean}$ = -1.56), suggesting release of gypsum.

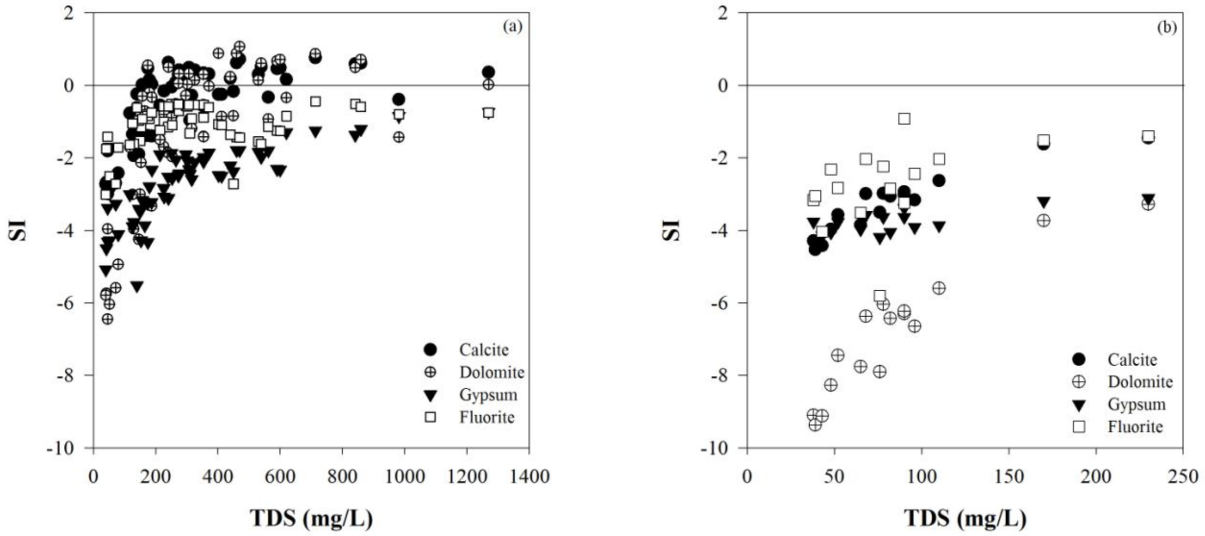

Figure 3: Scatterplot of TDS versus SI for Salima district (a) and Nkhotakota district (b).

The SI values of calcite and dolomite in Salima district had a medium correlation with TDS; while in Nkhotakota district there was a very high correlation. Additionally, the concentrations of Ca^{2+}, Mg^{2+} and HCO$_3^-$ were highly correlated with calcite and dolomite in Nkhotakota district, but also had a medium correlation in Salima district. This supports the interpretation that calcite and dolomite were still dissolving in Nkhotakota district; while in Salima district calcite and dolomite were still dissolving in some areas but not all.

In contrast, SI for gypsum showed undersaturation values in both districts, but was positively and highly correlated with TDS in Salima district than in Nkhotakota district (Fig. 3). This also supports the earlier expectation that gypsum was released into the groundwater resulting in increased concentration of Ca^{2+} in Salima district. The continued release of gypsum explained high Ca^{2+} and SO_4^{2-} concentrations in the groundwater.

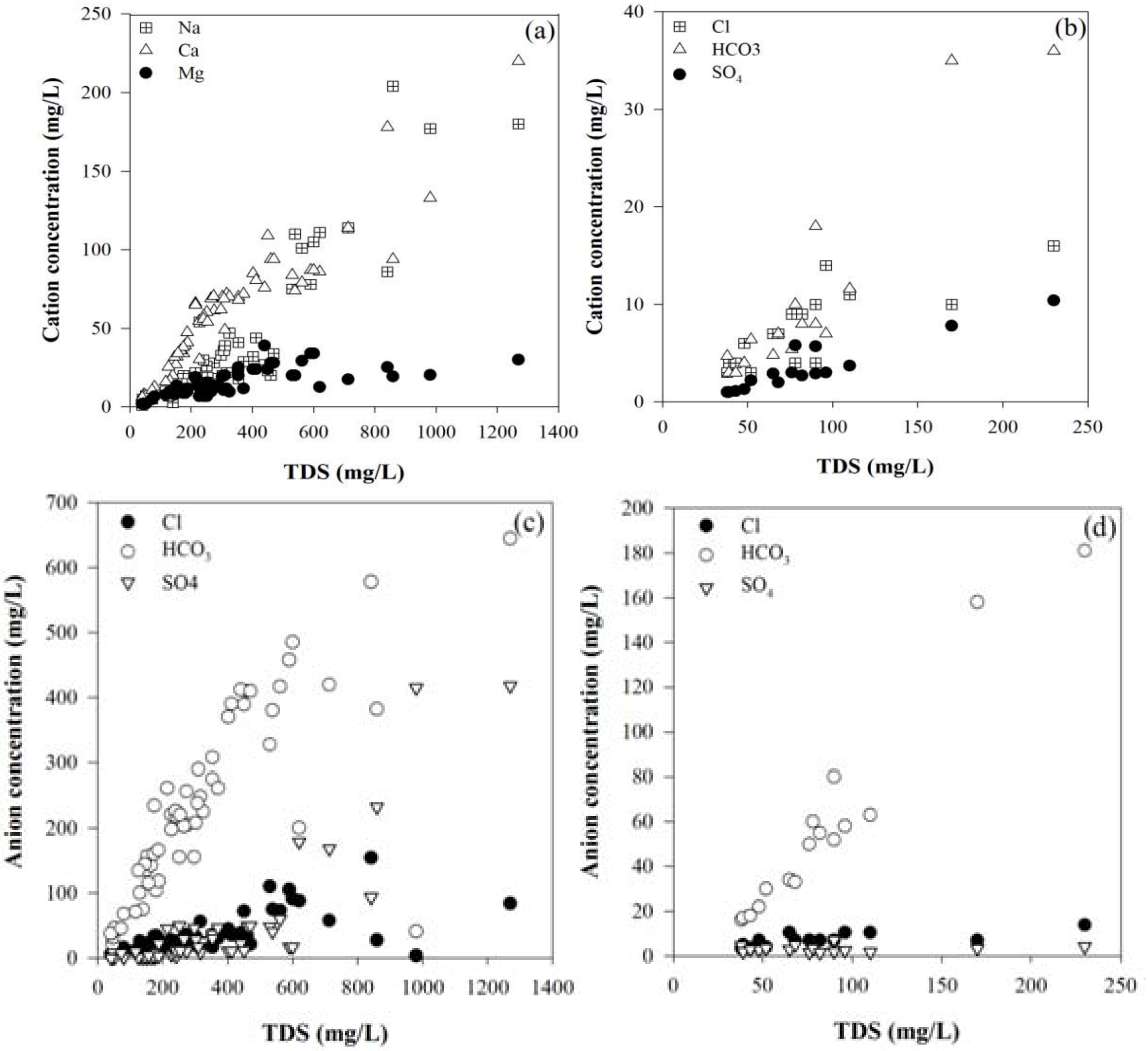

Figure 4: Scatterplot of TDS versus major ion concentrations for Salima district (a and c) and Nkhotakota district (b and d).

Hydrogeochemical Evolution Processes

Hydrogeochemical evolution processes have in previous studies (Han et al. 2013; Li et al. 2014) demonstrated that the relationship between TDS and the major ions can explain the character of the groundwater. In Salima district the linear relationship for cations with TDS was very good especially for Ca^{2+} (R^2 = 0.865) and Na^+ (R^2 = 0.823); however Ca^{2+} had a higher rate of increase in the form of slope than Na^+ (Fig. 4a). In Nkhotakota district the scenario was similar with the correlation between the concentration of Ca^{2+} and TDS (R^2 = 0.869) being very high, and also a high rate of increase than the other cations (Fig. 4b). In Nkhotakota district the correlation of Mg^{2+} and TDS (R^2 = 0.855) was equally as high as that for Ca^{2+} and TDS, but had a lower slope value; while Na^+ and TDS (R^2 = 0.607) had a medium value correlation. For anions in Salima district SO_4^{2-} and TDS showed the highest correlation (R^2 = 0.689) followed by the correlation between HCO_3^- and TDS (R^2 = 0.579; Fig 4c). In Nkhotakota district the anions correlation exhibited a high relationship between HCO_3^- and TDS (R^2 = 0.952) followed by correlation between Cl- and TDS (R^2 = 0.488; Fig 4d).

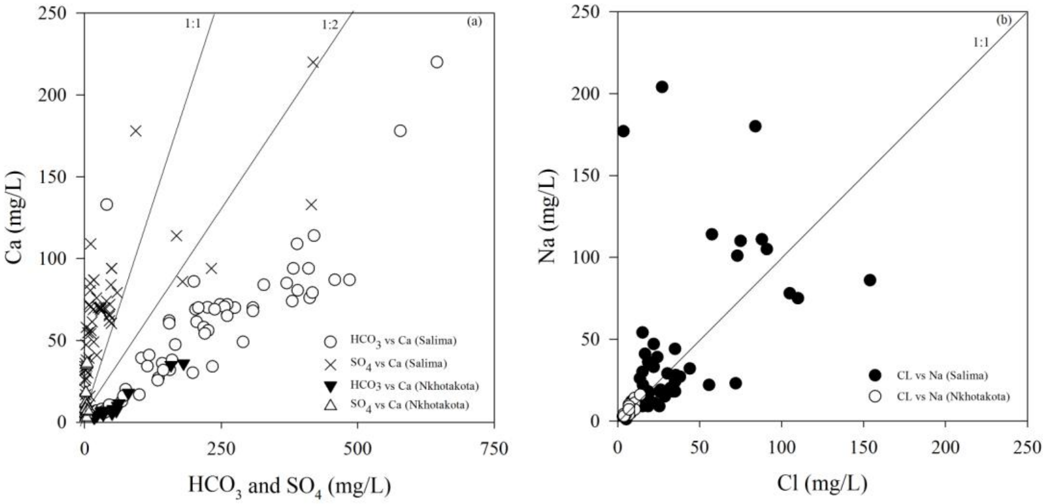

Figure 5: Scatter plot of HCO_3 and SO_4 versus Ca (a) and Cl versus Na (b)

The correlations between the major ions and TDS and the saturation indices of minerals can suggest the chemical reactions occurring along the flow path. In Salima district the possible chemical reactions were involving the dissolution of gypsum (reaction 1), carbonates (reactions 2 and 3), halite and fluorite.

$$CaSO_4 = Ca^{2+} + SO_4^{2-} \quad \text{(Reaction 1)}$$

If Ca^{2+} and SO_4^{2-} were released by gypsum only, then $[Ca^{2+}]/[SO_4^{2-}]$ would be 1:1. Although Fig. 5a shows a positive relationship between Ca and SO_4 and that in Salima district Ca^{2+} was positively correlated with SO_4^{2-} (R^2 = 0.506), the ratios were not falling close to the 1:1 gypsum line. This observance suggested that gypsum is not the main source of Ca^{2+} in both the districts.

The two main elements associated with calcite and dolomite (carbonates) were Ca^{2+} and Mg^{2+}. The SI's for calcite and dolomite were all undersaturated in Nkhotakota district but not in Salima district. Its noteworthy that calcite is known to have a faster rate of dissolution than all the other carbonates hence likely to be the highest source of Ca^{2+} (Nyirenda et al. 2015). The dissolution of calcite pH<5 is dependent solely on the pH via reaction 2 while the dissolution at pH>5 occurs as indicated by reaction 3 (Plummer et al. 1979).

$$CaCO_3^- + H^+ = Ca^{2+} + HCO_3^- \quad \text{(Reaction 2)}$$

$$CaCO_3^- + H_2O + CO_2 = Ca^{2+} + 2HCO_3^- \quad \text{(Reaction 3)}$$

Nevertheless, when Ca^{2+} and HCO_3^- are released by calcite alone, then $[Ca^{2+}]/[HCO_3^-]$ would be between 1:1 to 1:2 as indicated by reactions 2 and 3. All the samples in the two districts were plotted below the line of 1:2, suggesting that calcite is not the sole supplier of Ca^{2+} (Fig. 5a). There was a positive correlation between the concentration of Ca^{2+} and HCO_3^- in both districts of Salima (R^2 = 0.681) and Nkhotakota (R^2 = 0.957). Furthermore, a corresponding increase between HCO_3^- and TDS was observed (Fig. 4), but SI for calcite was negative suggesting that release of calcite was still a possible supplier of HCO_3^- in the groundwater for both districts. Similarly, the the groundwater was undersaturated with respect to dolomite in both districts, suggesting dissolution of dolomite as a source of Ca^{2+} and Mg^{2+}. In fact, the sum of Ca^{2+} and Mg^{2+} increased with HCO_3^- suggesting release of dolomite dissolution may be an additional contributor of Ca^{2+} and Mg^{2+} in ground-waters for both districts.

So far it has been determined that Ca^{2+}, Mg^{2+}, SO_4^{2-}, and HCO_3^- originated from release of carbonates (calcite or dolomite) in both districts and from gypsum in Salima district only. Additional source of Ca^{2+} in both districts was fluorite dissolution (reaction 4), since fluorite was undersaturated. However in the two districts the groundwater samples showed the presence of Na^+ and Cl^- that may have resulted from dissolution of halite (Reaction 5).

$$CaF_2 = Ca^{2+} + 2F^- \quad \text{(Reaction 4)}$$

$$NaCl = Na^+ + Cl^- \quad \text{(Reaction 5)}$$

Theoretically, if Na^+ and Cl^- have a single source in the form of halite, then $[Na^+]/[Cl^-]$ in mmol/L should be equal to 1 (Li et al. 2013). All samples in Nkhotakota district and most samples in Salima district are plotted below the 1:1 line (Fig 5b), which suggests that the Cl^- content was higher than Na^+. When samples are plotted below the 1:1 line, as in our study, the dissolution of halite is assumed not to be the only source of Na+ and Cl^-, and other reactions influencing the contents of Na^+ and Cl^- may have occurred as well (Li et al. 2014). Cation exchange (R6 and R7) may explain the deficiency of Na^+. The cation exchange makes Na^+ in groundwater adsorbed onto the surface of the aquifer media, resulting in the decrease of Na^+ in the water and forcing the samples to be plotted below the 1:1 line.

$$2Na^+ + CaX_2 = Ca^{2+} + 2NaX \quad \text{(Reaction 6)}$$

$$2Na^+ + MgX_2 = Mg^{2+} + 2NaX \quad \text{(Reaction 7)}$$

Drinking Water Quality Assessment

In terms of WQI (Table 3), pH was the only variable that failed to meet the objective, because it was less than the minimum standard in 12 out of 16 stations (Table 3). Based on the WHO objectives the WQI was categorized as good, because the standards are more stringent than the Malawi standards. Turbidity failed in 9 sampling points, while fluorine and iron failed in a single sampling point each. The WQI results in Nkhotakota district were categorized as good (88) using Malawi standards objective, with a failure in 3 variables namely Turbidity, Ca^{2+} and TDS (one sampling point each). For the WHO standard based objective the WQI was marginal (60) with 9 out of 13 variables failing. The variables that failed included Turbidity in 20 out of 59 samples; pH and conductivity failed in 10 out of 59 samples; F^- failed in three out of 59 samples; hardness and SO_4^{2-} did not meet the objective in two out of 59 samples; while TDS, Ca^{2+} and Na^+ failed in one sampling point out of 59.

Table 3: Drinking Water Quality Index results

Summary	Salima		Nkhotakota	
	MoIWD	WHO	MoIWD	WHO
Number of variables tested	14	13	14	13
Number of variables that failed	3	9	1	4
Scope	21	69	7	31
Frequency	0	6	5	13
Amplitude	1	8	0	6
WQI	88	60	95	80
Categorization	Good	Marginal	Excellent	Good

TDS and TH are also important parameters in assessing water quality for human consumption. TDS expresses the degree of salinity of a medium, while TH is a measure of dissolved Ca^{2+} and Mg^{2+} in water and is expressed as $CaCO_3$ (Mitra et al. 2007). According to the level of TDS (Fig. 6), groundwater in both the districts was classified as fresh (TDS<1000 mg/L); only one sample in Salima district had brackish water (1000<TDS<10000 mg/L). Regarding TH, Nkhotakota district had over 80 percent of the groundwater as soft water and the worst recording was categorized as slightly soft (Fig. 6). In Salima district almost 40 percent of groundwater samples were categorized as less than slightly soft, and 60 percent of the groundwater samples were categorized as hard water.

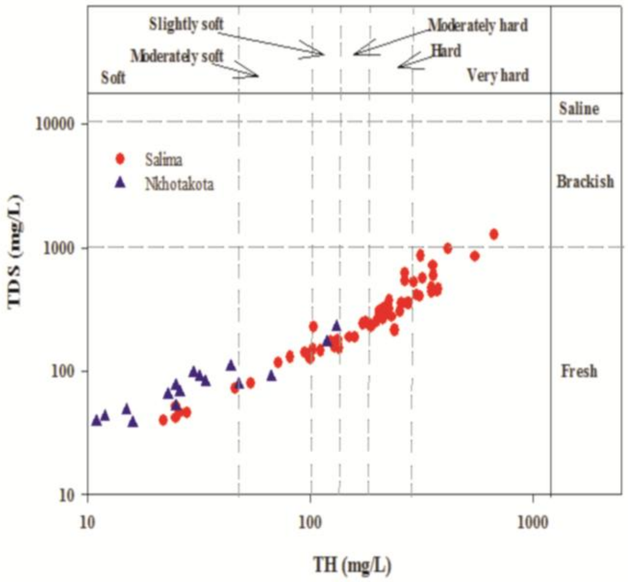

Figure 6: Plot of TH versus TDS

Groundwater Quality for Irrigation

The TDS specifically is categorized into three categories with respect to content for the water to be ideal for irrigation purpose, when the irrigation water contains TDS lower than 1000 mg/L it is categorized as ideal, fair if it ranges between 1000 and 2000 mg/L, and not suitable if it's more than 2000 mg/L. TDS for all water samples from both Salima and Khotakota was considered to be ideal for Irrigation.

Groundwater resources with RSC values less than 1.25meq/l is appropriate for irrigated agriculture. Any value ranging from 1.25 and 2.5meq/l compromise the irrigation water quality; while RSC in water exceeding 2.5meq/l is considered not appropriate for use in crop production (Wanda et al. 2013). In this study, RSC range for all the groundwater samples were less than 2.5meq/l. Salima District had a range of -7.04 to 3.01meq/l (mean RSC=-0.10meq/l) and 0.13 to 1.01meq/l in Nkhotakota District (mean RSC 0.12meq/l). All the samples from Nkhotakota were suitable for irrigated agriculture, because they had RSC<1.25meq/l.

Soil salinity is an important parameter that determines quality of soil for crop production. This soil salinity can be influenced by water being used to irrigate the crops; as such to measure influence of groundwater on soil salinity EC and SAR were used. The computed SAR for Salima district ranged from 0.10 to 0.5 (average 1.04) and for Nkhotakota SAR ranged from 0.21 to 1.12 (average 0.56). According to the Wilcox diagram (Fig. 7a) results for the SAR in both Salima and Nkhotakota district were within S1 (Low), therefore the ground water quality had low sodium (alkali) hazard and the water is suitable for irrigation purpose.

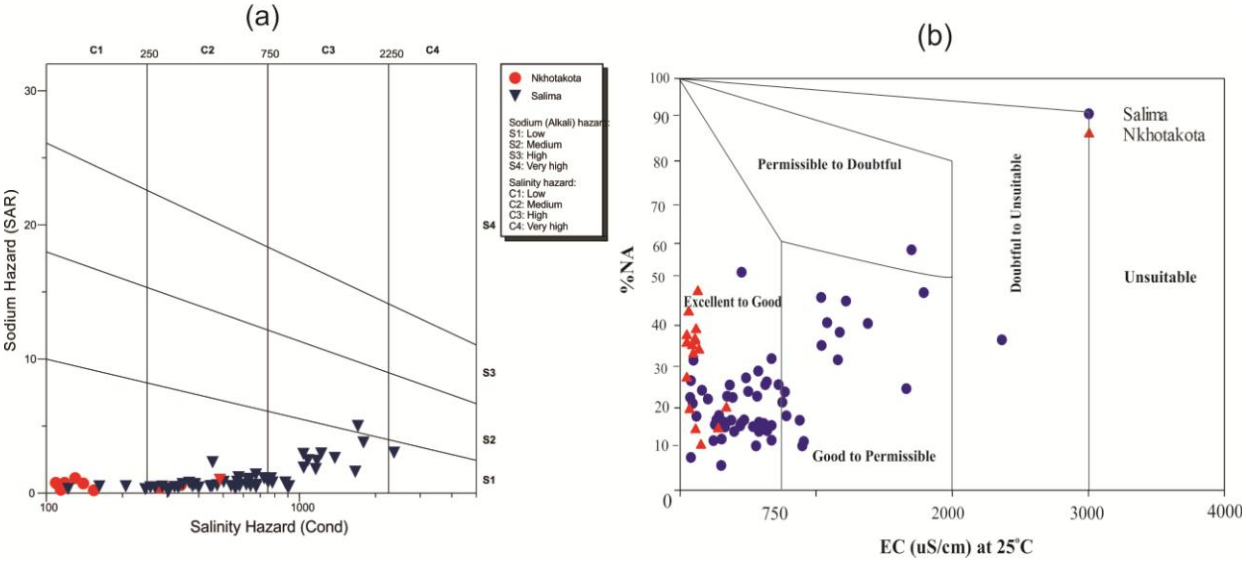

Figure 7 Wilcox diagram (a) and EC versus %Na (b)

The amount of salt available in water for irrigation affects soil productivity for plant growth through osmotic pressure (Wanda et al. 2013). There is a direct relation between the osmotic pressure and amount of salt in the water, also known as salinity hazard. Plant growth is affected directly due to salt content in the irrigation water; this also affects the permeability and aeration, resulting into an indirect impact on the crop growth. As such EC is vital in assessing the appropriateness of irrigation water as it affects water availability to plants, higher EC value indicate that less water is available to plants. Based on EC values from the sampled districts, Nkhotakota could be classified as having 100% groundwater excellent to good for irrigation. However in Salima district the EC is classified as having 71.1% excellent to good (C1), 27.3% good to permissible (C2) and 1.6% doubtful to unsuitable (C3) waters for irrigation purposes respectively.

The concentration of Na^+ is a good indicator of water quality for irrigation because of the reaction between sodium and the soil, which reduces the soil permeability. The concentration of Na^+ is usually presented as percent sodium (% Na). In the study area % Na^+ ranged between 4.97% to 58.34% for Salima District and 10.92% to 48.21% for Nkhotakota (Fig. 7b). The % Na^+ shows that the water was excellent to good for irrigation (% $Na^+ < 60\%$) in both the districts.

4. Conclusion

This study aimed to investigate the hydrogeochemical characteristics, determine the water-rock interaction influencing the water quality; and assess the quality of groundwater for direct human consumption and irrigation uses in Salima and Nkhotakota districts. The study has established that groundwater in Salima district is neutral to alkaline and mostly of $Ca\text{-}HCO_3/Na\text{-}HCO_3$ type; while in Nkhotakota district the groundwater is slightly acidic and of $Ca\text{-}Na/Mg\text{-}HCO_3$ type. This shows the predominance of Ca over Na and Mg while HCO_3 dominating the anionic group The water type and chemistry in both districts suggests that calcium carbonate minerals are responsible for the water type in the study areas. The saturation index mean values for calcite and dolomite were generally undersaturated in both districts. Unlike in Nkhotakota where all samples had negative SI values, the groundwater samples in Salima had SI results for dolomite (64%) and calcite (56%) that were undersaturated. Gypsum and fluorite were undersaturated in both Salima and Nkhotakota districts. The results showed that these minerals were still being released into the groundwater as it flowed along its path. The relationship between TDS and the major ions shows a linear correlation. This study has determined that Ca^{2+}, Mg^{2+}, SO_4^{2-}, and HCO_3^- originate from release of carbonates (calcite or dolomite) in both districts and from gypsum in Salima district only. Additional source of Ca^{2+} in both districts could be from fluorite dissolution.

Groundwater in the two districts is fit for direct human consumption as indicated by the WQI based on both the Malawi standards and WHO standards. Despite the suitability of water for human consumption pH and turbidity in Nkhotakota district exceeded the standards limits. In Salima district, several samples raised a concern with regards to turbidity, pH and EC. The groundwater samples were found to be mostly suitable for agriculture use. This paper recommends that WaterAid in Malawi should educate communities on household water treatment such as boiling and use of simple filters, due to the unacceptable turbidity levels. Turbidity is known to provide an environment for pathogens to settle and cause diseases such as diarrhea to water consumers. Even though, pH has no direct harm for human consumption it is related to other aspects of water quality such that if acidic it may lead to corrosion of pipes, and in cases that the pH is alkaline (not acidic) it can affect disinfection of water by chlorine. Since this study identified that the water is slightly acidic, it is thus further recommended to conduct frequent monitoring of such water sources to observe Iron levels in the water, which could result from corrosion of borehole metal pipes. If the iron levels increase changing the pipes of the water source would be encouraged.

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