

GEOCHE
WATER R
GROUNDW

DANIEL B. MKANDAWIRE

Thyolo, Malawi

Dissertation submitted to Ndata School of Climate and Earth Sciences of the Malawi University of Science and Technology in partial fulfilment of the requirements for the Bachelor of Science degree in Earth Sciences

JULY, 2021

GEOCHEMICAL AND MINERALOGICAL ASSESSMENTS OF WATER ROCK INTERACTION AND ITS IMPLICATIONS ON THE GROUNDWATER QUALITY IN AN AQUIFER: A CASE STUDY OF T/A CHIMALIRO AREA

DISSERTATION APPROVED BY:

SUPERVISOR:
MZEE W. NYIRONGO Signature: _____

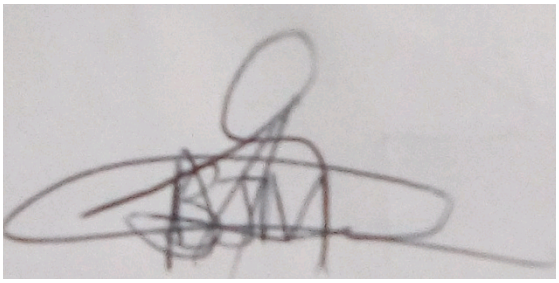
ASSESSOR:

Signature: _____

GEOCHEMICAL AND MINERALOGICAL ASSESSMENTS OF WATER ROCK INTERACTION AND ITS IMPLICATIONS ON THE GROUNDWATER QUALITY IN AN AQUIFER: A CASE STUDY OF T/A CHIMALIRO AREA

DECLARATION

I **DANIEL MKANDAWIRE** declare that this research project represents my own work and that it has never been submitted to this institution for any academic purpose. All sources of information have been appropriately acknowledged.

SIGNATURE: 

GEOCHEMICAL AND MINERALOGICAL ASSESSMENTS OF WATER ROCK INTERACTION AND ITS IMPLICATIONS ON THE GROUNDWATER QUALITY IN AN AQUIFER: A CASE STUDY OF T/A CHIMALIRO AREA

DISCLAIMER

This document describes work undertaken as part of a programme of study at Ndata School of Climate and Earth Sciences of the Malawi University of Science and Technology. All views and opinions expressed therein remain the sole responsibility of the author(s), and do not necessarily represent those of the School.

COPYRIGHT STATEMENT:

GEOCHEMICAL AND MINERALOGICAL ASSESSMENTS OF WATER ROCK INTERACTION AND ITS IMPLICATIONS ON THE GROUNDWATER QUALITY IN AN AQUIFER: A CASE STUDY OF T/A CHIMALIRO AREA

This copy of the dissertation has been supplied on condition that anyone who consults it is understo

ABSTRACT

Contamination of groundwater is a widespread issue around the globe and the water quality is highly dependent on the geology as well as anthropogenic interventions in the area (Hellens, 2013). Groundwater is used intensively for domestic purposes in rural areas of Malawi where Over 82% of burgeoning 17.5 million of the country's population live in rural areas that are heavily dependent upon groundwater for drinking water supply (Upton, Dochartaigh, Chunga, & Bellwood-Howard, 2020) of which T/A Chimaliro in Thyolo district is one of them. Six groundwater samples and 2 rock samples were collected to evaluate the hydro-chemical characteristics and the impact of water–rock interaction on the chemistry of groundwater using classical geochemical and statistical tools. The total dissolved solids (TDS) are all fresh water (below 530ppm). The distribution of the major ions is the order of Ca^{2+}> Mg^{2+} > Na^{+}> K^{+} and HCO_3^{-}> Cl^{-}>SO_4^{2-}. The entire water samples were collected from boreholes which draw groundwater from the fractured basement aquifer. Ionic abundance plot is of high Ca^{2+} + Mg^{2+} over alkalis and high weak acids over strong acids is suggestive of CaMg(HCO_3^{-}) type trends of concentrations (Piper, 1944). Gibbs ratio's showed that two main processes prevailed, chemical weathering (carbonate dissolution) of rock-forming minerals, especially the carbonates (in five samples shown by the use of a piper diagram and scatter plots) and evaporation (on one sample). This is also proved by the hydro-chemical signatures and correlation relationships of the different elements. The obtained results revealed that about 100% of the samples are suitable for drinking purposes with respect to Malawi standards but according to WHO 33.33% of the samples with respect to iron concentrations. After all the analysis the fractured basement aquifer has not affected the hydro-geochemistry of the groundwater for it to have calcium and magnesium bicarbonate type because it is made up ferromagnesian minerals according to (Envans, 1965) and (Habgood, Holt, & Walshaw, 1973) which was also verified by the rock samples which were collected along the Luchenza River.

ACKNOWLEDGEMENTS

First and for most I would like to thank Almighty God for the gracious life. I express my gratitude with respects and infinite thanks to my beloved parents Mr. and Mrs. Mkandawire for being the great pillar, comforter, wise advisor and encourager over my life. Appreciations should be extended to my beloved elder sisters Lizzie, Veronica, Vickness and Vaireen Mkandawire who were always there to support me to stand still in many aspects of life.

I grateful to my supervisor Mr. W. Nyirongo for endless and tireless support. You took time out of your busy schedule to help me and provide me with valuable insights in the writing process and throughout the course of study presented in this dissertation.

Lastly, I thank following; Dereck Makowa for the laptop wise friendly advise since first year; Florence Chirwa and Emily Moyo for the help during sampling; Berthia for the help in GIS; Ramsey Chima, Christos Livila, Takondwa Sawasawa Luzana Kantangwala, and Yamiko Gombachika for sleepless nights together in group disscussions; and to the entire class of earth sciences for all the support you have rendered.

Table of Contents

1 INTRODUCTION 1
1.1 1.1 BACKGROUND 1
1.2 PROBLEM STATEMENT 2
1.3 RESEARCH OBJECTIVES 2
1.3.1 MAIN OBJECTIVE 2
1.3.2 SPECIFIC OBJECTIVES 2
1.4 RESEARCH QUESTIONS 3
1.5 SIGNIFICANCE OF STUDY 3
2 LITERATURE REVIEW 4
2.1 GENERAL OVERVIEW OF GROUNDWATER QUALITY 4
2.2 DETERMINATION FACTOR OF WATER QUALITY 5
2.3 FACTORS AFFECTING THE GROUNDWATER QUALITY 6
2.3.1 CHEMICAL PROCESSES 7
3 METHODOLOGY 12
3.1 TYPE OF STUDY 12
3.2 SETTING AND STUDY SITE 14
3.2.1 STUDY AREA MAP 14
3.2.2 GEOLOGY OF MALAWI 15
3.2.3 GEOLOGY OF THYOLO 16
3.3 SAMPLE TYPES 19
3.4 SAMPLE COLLECTION 19
3.5 SAMPLE ANALYSIS 21

3.5.1 Chemical Analysis of Selected Borehole Water Samples.....21
3.5.2 Mineralogical Analysis of Selected rock Samples.....22
3.6 DATA ANALYSIS.....22
4 RESULTS AND DISCUSSION.....23
4.1 DATA ANALYSIS.....26
4.1.1 GIBBS DIAGRAM.....26
4.1.2 PIPER DIAGRAMS.....27
4.1.3 SCATER PLOTS.....29
4.1.4 WATER QUALITY.....33
4.1.5 ANALYSIS CONLUSION.....37
5 CONCLUSION AND RECOMMENDATION.....38
6 References.....39
7 APPENDICES.....43
7.1 PICTURES FROM SAMPLE COLLECTION.....43

ACRONYMS/ ABBREVIATIONS

µs/m: Microsecond per meter, unit of electrical conductivity

mg/l: Milligram per litre

ppm: parts per million

pH: Hydrogen ion activity

EC: Electrical conductivity

TDS: Total Dissolved Solids

MS: Malawi standards

WHO: World Healthy Orgarnisation

LIST OF FIGURES

Figure 1 showing an extract of T/A Chimaliro from Malawi.....14
Figure 2 Showing sampling points in T/A Chimaliro..... 15
Figure 3 showing the geology of Malawi (Smith Carington & Chilton, 1983).....16
Figure 4 Map showing the geology of T/A Chimaliro..... 18
Figure 5 Showing Gibbs diagram..... 27
Figure 6 showing a sample piper diagram showing hydrogeochemical facies (Piper, 1944). 28
Figure 7 showing the water types of the water samples collected.....29
Figure 8 showing a scatter graph of (Ca2+ + Mg2+) vs (SO42- + HCO3-)..... 30
Figure 9 Showing Na+ vs Ca2+ scatter graph.....31
Figure 10 Show a scatter graph of Na+ vs Cl-.....32
Figure 11 showing scatter graph of Na+ vs HCO3-..... 33
Figure 12 showing the electrical conductivity of water samples with the MS and WHO values for comparison..... 34
Figure 13 showing the TDS values of water samples with that of MS and WHO.....34
Figure 14 showing values of major anions (HCO3-, Cl- and SO42-) and that of MS and WHO. 35
Figure 15 showing concentrations of Nitrate and its accepted limits set up by WHO and MS... 36
Figure 16 showing graph of major cations and their WHO and MS limits..... 36
Figure 17 showing graph of minor cations and their WHO and MS limits..... 37

Figure 18 showing water sampling at a water point and measurement of the pH and temperature 43
Figure 19 showing rock sampling 44

LIST OF TABLES

Table 1 showing field data of water samples 19
Table 2 Showing rock sample field data 20
Table 3 Showing data from water analysis 23
Table 4 Showing the centrality and variability of data 24
Table 5 Showing data from rock analysis collected along the Luchenza River 26

1 INTRODUCTION

1.1 1.1 BACKGROUND

According to (Sarikhani & Nagaraju, 2011) groundwater chemistry is largely a function of the mineral composition of the aquifer through which it flows. As a ground water moves along its path from recharge to discharge areas, a variety of hydro-geochemical processes altered its chemical composition. The hydro-geochemical processes and hydro-geochemistry of the ground water vary spatially and temporally, depending on the geology and chemical characteristics of the aquifer. Groundwater contains minerals carried in solution, the type and concentration of which depends upon several factors like soluble products of rock weathering and decomposition in addition to external polluting agencies and changes in space and time. As a result of chemical and biochemical interaction between groundwater and contaminants from urban, industrial and agricultural activities along with geological materials through which it flows, it contains a wide variety of dissolved inorganic chemical constituents in various concentrations. The character of groundwater in different aquifers over space and time proved to be an important technique in solving different geochemical problems (Cheboterev, 1955) and (Srinivasamoorthy, et al., 2008)

The study assessed and analyzed the water/rock interaction in the area of T/A Chimaliro and established how this interaction has affected the groundwater quality by using the geochemical approach. The essence of this assessment was to analyze the impact of lithology on the water quality as groundwater flows in the subsurface. According to (Habgood, Holt, & Walshaw, 1973) the geology of the Thyolo area of Malawi shows that is underlain by the basement complex which mostly is composed of pyroxene-hornblende-biotite gneiss and charnockitic gneiss and granulite. The geology of Thyolo is highly metamorphosed has led to the rocks having low porosity and permeability due to the compaction which reduced intergranular spaces during metamorphism furthermore the basement complex in this area is very highly faulted according to (Smith Carington & Chilton, 1983). The basement complex is the aquifer

of the area because it is highly Fractured hence it is called the fractured basement aquifer so the pre

1.2 PROBLEM STATEMENT

There is no any research which was done in this area on the impacts of the geology on the quality of groundwater since the boreholes were drilled without any quality assessment which may result in people consuming water which is contaminated though there might be many sources of contamination but this study has assessed the geological factor on how it has affected or contributed to the quality of water since geological contamination of groundwater is critical and diverstating for example at the lower Paral in India and upper Colorado river in USA according to (Apodaca, Jeffrey, & Michelle, 2002). So this study has assessed the relationship of the geology of the area of T/A Chimaliro to quality of groundwater used in the area and has deduced whether it is susceptible to groundwater contamination in future.

1.3 RESEARCH OBJECTIVES

1.3.1 MAIN OBJECTIVE

- Assessing the significance of geological formation on the groundwater quality using geochemical approaches.

1.3.2 SPECIFIC OBJECTIVES

- To elucidate the mineralogy of rocks in the area of T/A Chimaliro.
- To analyze the chemical composition of groundwater in the area of T/A Chimaliro.
- To establish the relationship between water and rock chemistry and its impacts on the groundwater quality for domestic use.

1.4 RESEARCH QUESTIONS

- What is the mineralogy and geochemistry makeup of the rocks in the area?
- What is the chemical composition of groundwater on each borehole selected in the area?
- Deduce the relationship between the geology of the area and ground water and what is its impact on the groundwater quality in the area.

1.5 SIGNIFICANCE OF STUDY

The significance of this study was to deduce the relationship of the geology of the area of T/A Chima

2 LITERATURE REVIEW

2.1 GENERAL OVERVIEW OF GROUNDWATER QUALITY

Groundwater quality is based on the behavior of physical, biological and chemical parameters that are influenced by geological formations, atmospheric precipitation, inland surface water, and geochemical processes as they are in contact with the rock and the various anthropogenic activities (Saravanan, Srinivasamoorthy, Prakash, Gopinath, & Suma, 2015). Water chemistry provides valuable information to determine the origin, transit time, flow patterns and water regimes, geological structure, and mineralogy of aquifers, as well as hydrogeochemical processes. Specific water quality is required to meet both domestic and irrigation needs. Their monitoring and evaluation are essential to design preventive measures on human health, animal life, and vegetation (Salcedo, Garrido, Vicenta, Martínez, & Ocampo, 2017).In addition, groundwater (Bruckmann & Clauser, 2020) often provides that main source of freshwater used for drinking, domestic, agricultural, industrial, and ecological supplies worldwide. Thus, preservation of groundwater quality is a growing concern globally (Mehrdad & Thomas, 2020). It is important to measure and understand the processes controlling the chemical composition of groundwater for the assessment of quality and potential future use. Management should be aimed at determination of a balanced set of solutions to ensure sustainability and socioeconomics (Danapour, Hojberg, Jensen, & Atisen, 2019). Generally, groundwater pollution is divided into natural and artificial causes (Teresa, et al., 2014). Water quality parameters are divided into three classes, which include chemical, physical, and biological. Often measured parameters include dissolve ions and other substances, while physical parameters may include the color, turbidity, odor, temperature, and taste, and biological may include coliform and

bacteria may provide some indication of the level of the suitability for drinking water quality (Batabya

2.2 DETERMINATION FACTOR OF WATER QUALITY

When assessing water quality it is important to know what the water is intended to be used for, as some waters will be suitable for crop irrigation, but not for human consumption. For instance the presence of waterborne microbes can make a drinking water supply unpotable, but it may be satisfactory for the irrigation of a vineyard. So this study was there for the assessment of the impacts of the geology on the groundwater quality for human consumption purposes. Over 82% of Malawi's burgeoning 17.5 million population live in rural areas that are heavily dependent upon groundwater for drinking water supply (Upton, Dochartaigh, Chunga, & Bellwood-Howard, 2020). The comprehensive mapping of rural water supplies in Malawi indicate international aid programs have drilled nearly 60,000 boreholes and wells, most without prior hydrogeological knowledge or assessment of potential geo-hazards, with 24.5% resulting in poor performance and another 14.1% resulting in failure and abandonment (Rivett, et al., 2018) so due to lack of the hydrogeological knowledge of the water supply points (boreholes) people might be consuming water that is contaminated due to the chemical weathering of the aquifer that is why this is necessary for people to be aware if they are consuming good quality water and to be able to depict whether the area is susceptible to groundwater contamination due to geological factors since the contamination is very hazardous for it comes with it diseases which mostly are incurable and difficult to control for they maybe accumulating and come as a surprise with healthy related issues which may drawdown the development of the area and the country because the government may focus to mitigate the health issues so there is a need of groundwater monitoring to prevent the adverse impacts that may come due to ignorance of the hydrogeology.

2.3 FACTORS AFFECTING THE GROUNDWATER QUALITY

Groundwater scarcity and contamination in aquifers is likely affected by changing land use such as construction (Davidson, Holt, & Blainey, 2019), agriculture and changes in

population, and industrial development activities at city boundaries but hydrogeological properties, ex

Though there are several factors that affect the groundwater quality but this study has focused on the geological factor that has been analyzed by using the rock-water interaction that happens in the subsurface and where the end result is the lithology altered and the groundwater quality affected. So looking at the rock-water interaction groundwater chemistry is largely a function of mineral composition, the formation through which it flows due to rock-water interaction. Evaporation and concentration, dilution due to precipitation also can change the chemical composition of groundwater but rock-water interaction is the major process because solid phases (inorganic and organic matter) are the primary sources and inks of dissolved constituents of groundwater. During groundwater movement along its path from recharge to discharge areas, a variety of chemical reactions with solid phases take place. These chemical reactions will vary spatially and temporally, depending on the chemical nature of the initial water, geological formations and residence time. The resulting concentrations of major ions of groundwater can be used to identify the intensity of rock-water interaction and chemical reactions. (Elango, Karman, & Senthil Kumar, 2003) Have inferred that carbonate weathering and dissolution, silicate weathering and ion exchange processes are responsible for groundwater chemistry in Lower Palar River Basin, India. (Apodaca, Jeffrey, & Michelle, 2002) Have inferred that hydrogeochemical processes such as dissolution, ion exchange processes and the residence time along the flow path control the chemical composition of groundwater in the shallow alluvial aquifers of the Upper Colorado River, USA. Hence, knowledge on rock-water interaction that control groundwater chemical evolution will lead to improved understanding of hydrogeochemical characteristics of an aquifer. This would contribute in the effective management and utilization of groundwater resources.

2.3.1 CHEMICAL PROCESSES

Generally different chemical processes occur during rock-water interaction, which include dissolution/precipitation, ion exchange processes, oxidation and reduction. Rock types are broadly classified as igneous, metamorphic and sedimentary. Minerals present in these rocks will completely or partially dissolve in water according to the

resistance of chemical weathering (i.e. the most abundant minerals in the fracture basement aquifer Types of chemical weathering which are chemical processes influenced by rock-water interaction which end up in affecting the groundwater chemistry which have been explained below.

2.3.1.1 Dissolution/ precipitation of minerals

Mineral dissolution and precipitation involves transfer of mass to a phase or from a phase (Deutsch, 1997). Here, in this context mass transfer takes place between rock types and groundwater, which is called as dissolution and precipitation. Dissolution starts when groundwater tends to move toward equilibrium. This process continues until groundwater is saturated with those particular mineral components. At equilibrium concentration values, the mineral may continue to dissolve, that excess mineral components may combine in the solution to form precipitates of that particular mineral, and this reaction is called precipitation (Deutsch, 1997). Chemical equilibrium of groundwater for a particular mineral can be identified by calculating saturation indices. If the SI values are less than zero it will take more mineral into the solution, which is called dissolution

SI =

Where IAP is ion activity product, and K_s; is solubility product of the mineral. (The use of SI is best limited to soluble simple salts like carbonate minerals.) Carbonate weathering, silicate weathering, halite, gypsum dissolution and precipitation are common in an aquifer system. (Rajmohan & Elango, 2004) Reported that the concentrations of the major ions increases mainly due to dissolution of minerals deposited during the preceding dry season in a part of Palar and Cheyyar River Basins.

2.3.1.1.1 Carbonate weathering and dissolution

If calcium and magnesium are the dominant ions found in groundwater it reveals that dissolution of carbonate minerals is responsible for them. During infiltration or along the flow, groundwater may dissolve the $CaCO_3$, and $CaMg(CO_3)_2$ present in the rocks

will increase the concentration of calcium ions in groundwater. (Datta & Tyagi, 1996) Explained that i

$CO_2+H_2O \rightarrow H_2CO_3$ …1

Hence making the water acidic

$CaCO_3+H_2CO_3 \rightarrow Ca^{2+}+2HCO_3^-$ [Dissolution of calcite] …..2

$CaMg(CO_3)_2 + 2\ H_2CO_3 \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-$ ……3

This process leads to the increase in calcium, magnesium and bicarbonate ions in the area.

If carbonate weathering and silicate weathering takes place, bicarbonate is generally dominant among anions in groundwater. During infiltration of rainwater and irrigated water, the carbonate minerals available along the path will be dissolved depending on the availability of dissolved CO_2 and carbonic acid (Eq. (I)). During the recharge process HCO_3^- and Ca will be released to groundwater. Similarly, silicate weathering also increases the concentration of HCO_3 in groundwater.

2.3.1.1.2 Silicate weathering processes

If bicarbonate and sulfate ions are dominant than calcium and magnesium that means silicate weathering is dominant (Elango, Karman, & Senthil Kumar, 2003). Similarly, sodium is also high in groundwater. In general, 1: I relationship between Na and CI implies halite dissolution, whereas increased concentration of Na than CI is typically interpreted as Na released from silicate weathering as shown in equation 4 below (Mayback, 1987).

$2NaAlSi_3O_g$ [Albite] $+2H_2CO_3+9H_2O \rightarrow Al_2Si_2O_5(OH)_4$ [Kaolinite] $+2Na+ 4H_4SiO_4+2HCO_3$

2.3.1.2 Ion exchange processes

Ion exchange is a type of adsorption/desorption phenomenon. Clay minerals are the most common ion exchangers in soil and aquifer system. Cations present in the clay and groundwater are easily exchangeable than anion. The pH of a solution also

controls the exchange processes. If huge amount of Na content is reduced from groundwater, it is at

2.3.1.3 Oxidation/reduction processes

Lot of reactions in groundwater involves the transfer of electrons between dissolved and solid constituents. Electron loss results in oxidation and electron gain results in reduction. The most important oxidizing agents in groundwater are dissolved oxygen, Oxo-anions such as nitrate and sulfate and water itself. Reducing agents include a wide variety of organic compounds, inorganic sulfides such as pyrite andiron silicates. At least one of the following groups will be available in groundwater. Sulfate and iron are common constituents in soils and groundwater that participates in the oxidation and reduction reaction. These reactions readily reflect changes in surrounding Eh/pH conditions. In groundwater systems iron occurs in one of two oxidation states: reduced soluble divalent ferrous iron (Fe^{2+}) or oxidized insoluble trivalent ferric iron (Fe^{3+}). Similarly, the sulfate ions present in water may get reduced due to reduction process

(Eq. 2). If the concentrations of sulfate and iron in groundwater are very low and eh of the groundwater samples are also in reduced condition then the ions might have reduced due to reduction. However, in some areas the lack of source or least occurrence of source of sulfate and iron might be the reason for the low concentration. (Dissolution of gypsum as in Eq. 2, which can supply sulfate to the groundwater.)

$2Fe^{2+} + 3H_2O \longleftrightarrow Fe^{3+} + O_3 + 6H+ + 2e^-$ ……1

$H_2O + CaSO_4.2H_2O \longrightarrow Ca^{2+} + SO^{2-} + 3H_2O$ ……..2

2.3.1.4 Hydrolysis

Hydrolysis is a chemical process in which a molecule is cleaved into two parts by the addition of a molecule of water. This is distinct from a hydration reaction, in which water molecules are added to a substance, but no cleavage occurs. Due to hydrolysis, rock and soil materials are decomposed into different products. (Malov, 2004) Had reported that the principal role in the removal of Ca from rocks was probably played by the hydrolysis of calcium aluminosilicates that are in nonequilibrium state with all types of ground waters present in Vendian sandy-clayey rocks aquifer. Had reported that the most characteristic process is the hydrolysis of sodium aluminosilicates.

So looking at the chemical weathering might be the supplier or extractor of chemical constituent dep

3 METHODOLOGY

3.1 TYPE OF STUDY

This is the scientific study which is about investigating how the groundwater quality has been affected by the geology of the area using the geochemical approach.

The study involved the assessment of physical and chemical parameters of groundwater from water points in relation to the geology of T/A chimaliro. Generally, the project involved the following three main steps: Sample collection, Sample treatment and Laboratory analysis. Water and rock samples were collected from six water point and two points respectively (water from Boreholes and rocks along the river) and Available standard data (physical and chemical) from WHO and MBS was compared with the data from the study area.

Water and rock samples were collected from six boreholes and two points along the river within the study area in May, 2021. The co-ordinates of the sampling points were recorded using the Global Positioning System (GPS) of the smart phone. Figure 2 shows the location of the sample collection points. Identification names were allotted to each of the eight sampling points in this study and such names were used in the discussions in place of actual names of location. Samples were taken from a pump outlet pipe through which water was in continuous flow where water was allowed to flow for two minutes before taking the sample according to the standard sampling procedure (Clesceri & A., 1995). To prevent unnecessary aeration while the sample was being taken, the bottle was filled to within 15 mm of the top of the neck. The bottle was closed and properly labelled with the given code. Water parameters that are considered to have a significant relationship with the geology of the area were

selected for the study. The parameters include pH, TDS, EC, chloride, sulfate, bicarbonate, carbonat

For the unstable parameters such as pH, EC, TDS and temperature, in situ measurements were measured. This was carried out using a portable Multiprobe parameter (Aqua-Read AM200) meter. Water samples were collected in two clean one liter plastic bottles at each water point where one of the two at each water point was acidified and the other not and then transported to a standard laboratory (southern water laboratory, Ministry of Forestry and Natural Resources) for further analysis within 24 hours from the time of sample collection. Bicarbonate, Chloride, Calcium and Magnesium where analysed using titration method; Sodium and Potassium was measured by a frame photometer and lastly Sulphate, Nitrate and Iron was measure by UV/VIS Spectrophotometer.

Laboratory results of water samples were subjected to statistical analysis. Descriptive analysis covered minimum, maximum, mean, standard deviation of all the parameters in the data sets. Graphs of parameters were derived from Excel and GCD kit softwares so in order to assess the potability of the water and geological impact on the composition of groundwater. The results were then compared with standards set by regulatory bodies such as WHO and MS

3.2 SETTING AND STUDY SITE

3.2.1 STUDY AREA MAP

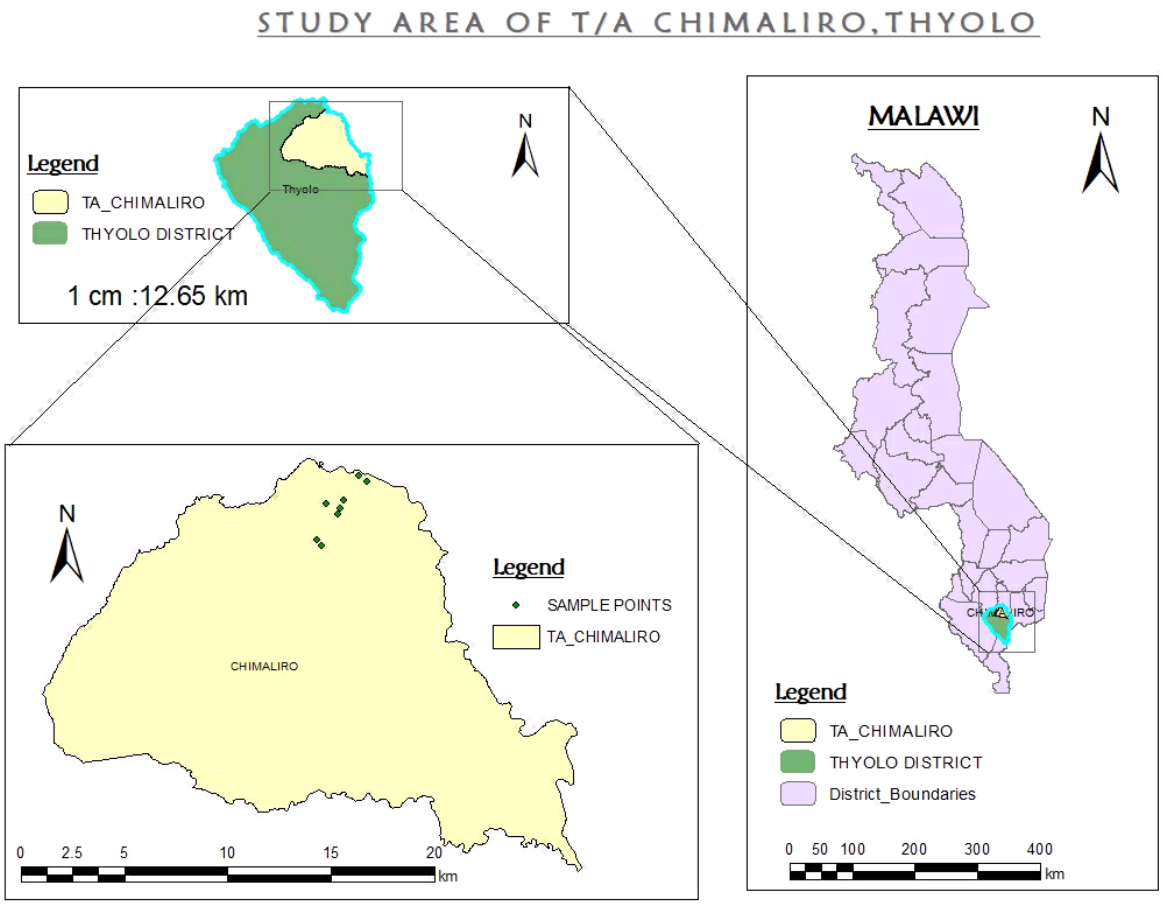


Figure 1 showing an extract of T/A Chimaliro from Malawi

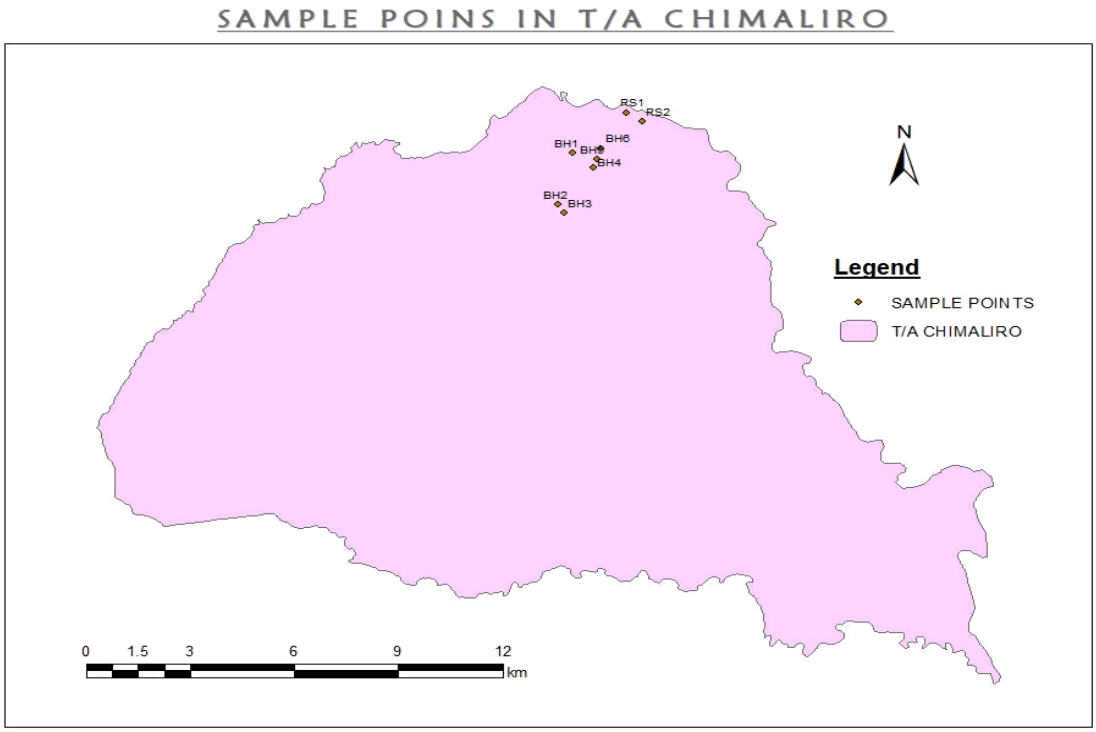


Figure 2 Showing sampling points in T/A Chimaliro

Where those labeled BH are water points (boreholes) while those labeled RS points along the Luchenza River where rock samples were collected.

3.2.2 GEOLOGY OF MALAWI

According to (Smith - Clington & Chilton, 1983) the greater part of Malawi is underlain

by crystalline / metamorphic and igneous rocks of Precambrian to Lower Palaeozoic age referred to



Figure 3 showing the geology of Malawi (Smith Carington & Chilton, 1983)

3.2.3 GEOLOGY OF THYOLO

This study was done in an area of T/A Chimaliro in Thyolo district. According to (Hol73) Thyolo district occupies 1600km^2 area of Malawi and is in the southern region of Malawi and the greater part of the area is underlain by high grade metamorphosed basement complex, frequently migimatic gneisses and granulites which are referred to as Malawi Basement complex and which lie within the Precambrian to lower Paleozoic Mozambique Belt.

According to (Habgood, Holt, & Walshaw, 1973) the geology is described with the greater part of the area is underlain by highgrade, frequently migimatic gneisses and granulites which are referred to the Malawi basement complex. The gneisses and granulites have undergone regional metamorphism under amphibolite to granulite facies conditions. The hornblend bearing gneisses are considered to represent downgraded charnockiticrocks and both rock types occur in close association. The regional metamorphism was followed by widespread migmatization and slightly later syenitization. There is a swarm of dolerite dykes cuts the basement complex rocks trends consistently on a NE – SW trend lastly the superficial deposits underlies the Shire valley plain and mask the basement complex in the extreme northeast. The basement complex is the aquifer in Thyolo and its able to store water because it is highly faulted and intruded hence it is called the fractured basement aquifer.

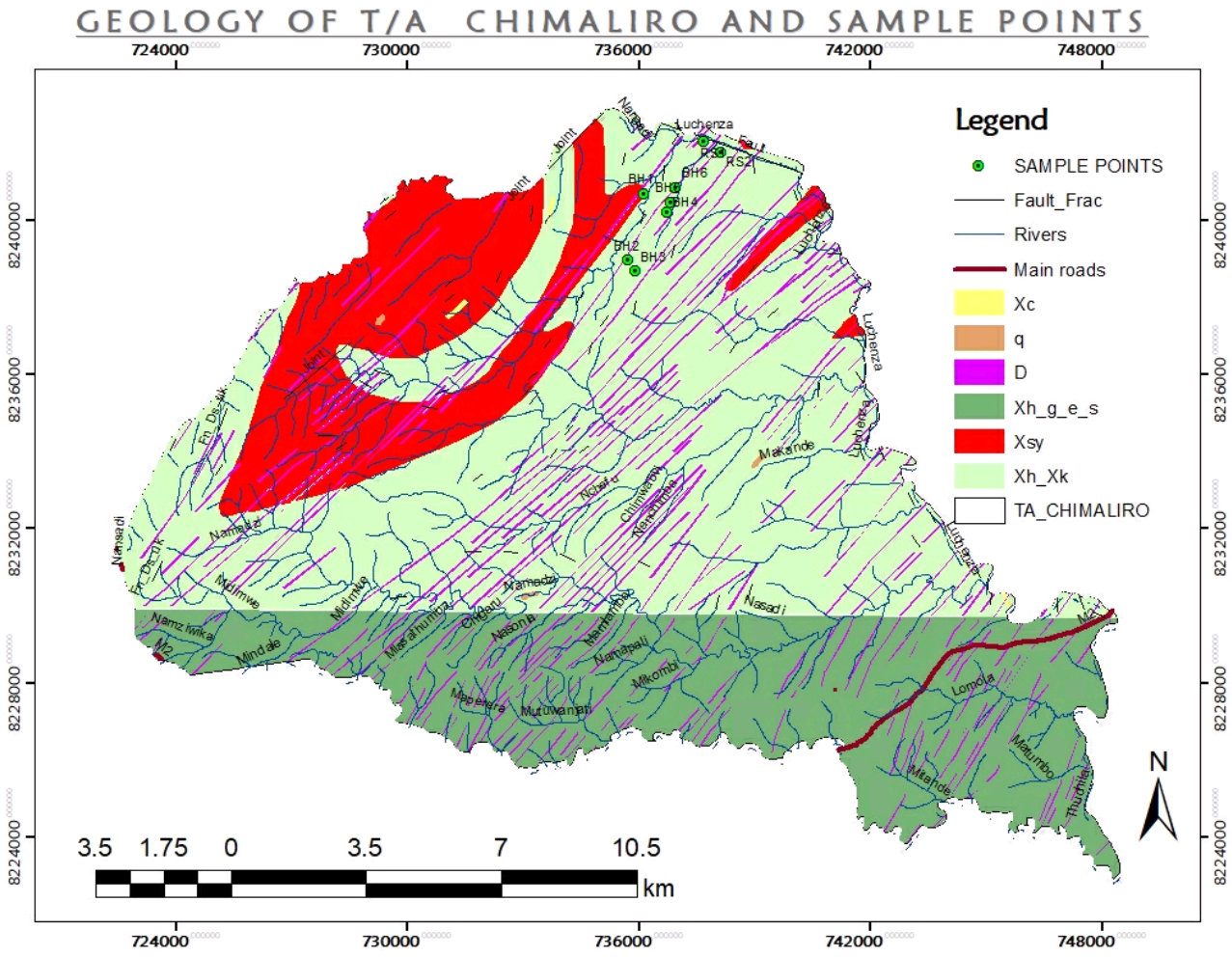


Figure 4 Map showing the geology of T/A Chimaliro

Figure 4 is the geology of T/A Chimaliro extracted from the shape files of the geology of Thyolo and S

3.3 SAMPLE TYPES

In this study there was the collection of water samples from boreholes and rock samples surrounding each borehole where the water samples were being taken.

3.4 SAMPLE COLLECTION

The study used purposive sampling technique where six boreholes were selected basing in the difference in geology to deduce the relationship between the geology and groundwater chemistry. Water and rock samples were collected in May 2021 in sterilized polyethene plastic bottles and bags respectively from six boreholes in six different locations (villages) within the area of T/A Chimaliro. Two bottles and plastic bags of samples (referring to water and rock samples respectively) were collected at each sample point. The borehole water was pumped and ran for two minutes after which the 500 ml pre-sterilized capped polythene plastic bottles were carefully uncapped and filled with water. The bottles were then transported to the Chemistry Laboratory of Chancellor College, University of Malawi for analysis. The samples collected from various sites were labeled as shown in Table 1 for water samples and table 2 for rock samples.

Table 1 showing field data of water samples

Name of location of borehole	Water sample Code	Date borehole was constructed	Depth of Borehole (m)	GPS location (UTM) and elevation
Nanthereza Kadewere	BH 1	12 February, 2002	30m	36L E 736147.7m N 8240701.0m Elevation : 818m
Mangazi	BH 2	1 January, 2002	27m	36L E 735712.0m

				N 8238979.4m Elevation : 839m
Mangazi	BH 3	N/A	N/A	36L E 735904.8m N 8238690.8m Elevation :852m
M'mina	BH 4	N/A	N/A	36L E 736726.8m N 8240205.9m Elevation : 823m
M'mina	BH 5	23 July, 1998	N/A	36L E 736837.5 N 8240483.5 Elevation : 819m
M'mina	BH 6	2021	N/A	36L E 736969.5 N 8240854.2 Elevation : 806m

Table 2 Showing rock sample field data

Name of location of borehole	Rock sample Code	GPS location and elevation
Mosania	RS 1	36L E 737696m N 8242044 m

		Elevation :766m
M'mina	RS 2	36L E 738134m N 8241753m Elevation :773

3.5 SAMPLE ANALYSIS

This study involved collecting water and rock samples from which geochemical and mineralogical data was extracted in the laboratory where several chemical parameters were considered which are major cations e.g. Mg^{2+}, Ca^{2+}, Na^{+} and K^{+}; major anions Cl^{-}, CO_3^{2-}, HCO_3^{-}, SO_4^{2-} which were used to analyze if the there was a water-rock interaction and quality of the groundwater (other chemical parameters were also analyzed like trace elements e.g. As^{3+}, Fe^{2+}, Al^{3+} and F^{-}) by piper diagrams and scatter plots and by comparing the chemical parameters' concentrations with the national and international standards which were set.

3.5.1 Chemical Analysis of Selected Borehole Water Samples

The water samples from each borehole were examined in terms of chemical properties using WHO standards method of analysis. The water pH, total dissolved solids and temperature were measured at the point of collection. Other parameters such as nitrate (NO_3^{-}),, chloride (Cl^{-}), sulfate(SO_4^{2-}), carbonate(CO_3^{2-}), bicarbonate(HCO_3^{-}), calcium(Ca^{2+}), magnesium(Mg^{2+}), sodium(Na^{+}), potassium(K^{+}), iron(Fe^{2+}) were analyzed at the laboratory. Instruments were; Multmeter which was used to measure the following; Temperature, pH, EC and TDS; Titration method which was used to analyse the following; Bicarbonate, Chloride, Calcium and Magnesium; Frame Photometer which was used to measure Sodium and Potassium; UV/VIS Spectrophotometer which was used to measure Sulphate, Nitrate and Iron.

3.5.2 Mineralogical Analysis of Selected rock Samples

The rock samples collected from the outcrops which are along Luchenza river and were examined by the use of mineral physical properties to identify they rocks and the minerals there in.

3.6 DATA ANALYSIS

The geochemical and mineralogical data that was extracted from the water and rock samples collected have been analyzed by the use of the Gibbs diagram, bar charts, scatter plots and piper diagrams. The major chemical parameters were the ones that were used to plot the water samples on both the piper diagrams and scatterplots to know if there is any water–rock interaction and evaluate what kind of water – rock interaction occurred that led to the present status of the water quality.

4 RESULTS AND DISCUSSION

Water samples underwent a physical and chemical analysis where the results have been shown in the table 3 on the other hand the mineralogical analysis was done on

rocks by analyzing their physical properties.

Table 3 Showing data from water analysis

SAMPLE IDENTITY	**Nanthereza**	**Mangazi**	**Mangazi**	**M'mina**	**M'mina**	**M'mina**	**PERMISSIBLE LIMITS SET**	
DATE SAMPLED	19/05/ 2021	19/05/ 2021	19/05/ 2021	19/ 05/ 2021	19/05/ 2021	19/05/ 2021		
SAMPLE SOURCE	BH1	BH2	BH3	BH4	BH5	BH6	MS	WHO
pH Value	7.71	7.45	7.56	7.54	7.4	7.31	6.0-9.5	6.0-8.5
CONDUCTIVITY (µs/cm at 25˚C)	727	575	437	465	480	1136	3500	1500
TOTAL DISSOLVED SOLIDS, mg/l	368	292	220	229	236	558	1000	2000
CARBONATE (as CO_3^{2-}), mg/l	6	4	2	13	8	6	-	-
BICARBONATE (as HCO_3^-), mg/l	284	220	156	179	184	462	-	500
CHLORIDE (as Cl^-), mg/l	36	31	24	27	32	74	250	250
SULPHATE (as SO_4^{2-}), mg/l	56	44	32	18	13	38	400	250
NITRATE (as NO_3^-), mg/l	0.34	0.5	0.14	0.21	0.11	0.11	50	45

SODIUM (as Na^{+}), mg/l	32	28	22	24	28	68	500	200
POTASSIUM (as K^{+}), mg/l	0.6	0.3	0.8	0.6	0.9	0.4	-	12
CALCIUM (as Ca^{++}), mg/l	79	64	54	48	54	102	200	75
MAGNESIUM (as Mg^{++}), mg/l	18	12	8	10	8	42	150	50
IRON (Fe^{++}), mg/l	0.17	0.21	1.1	0.4	0.31	0.42	3	0.3
TEMPERATURE (°C)	31.2	28.6	26.4	28.2	29.1	27.5	-	-

Table Showing the centrality and variability of data

SAMPLE IDENTITY	MEAN	MEDIAN	STANDARD DEVIATION
pH Values	7.495	7.495	0.139821
CONDUCTIVITY (µs/cm at 25˚C)	636.6667	527.5	266.5248
TOTAL DISSOLVED SOLIDS, mg/l	317.1667	264	130.4
CARBONATE (as CO_3^{2-}), mg/l	6.5	6	3.781534
BICARBONATE (as	247.5	202	114.1889

HCO_3^-), mg/l			
CHLORIDE (as Cl^-), mg/l	37.33333	31.5	18.43547
SULPHATE (as SO_4^{2-}), mg/l	33.5	35	16.12141
NITRATE (as NO_3^-), mg/l	0.235	0.175	0.156301
SODIUM (as Na^+), mg/l	33.66667	28	17.1775
POTASSIUM (as K^+), mg/l	0.6	0.6	0.228035
CALCIUM (as Ca^{++}), mg/l	66.83333	59	20.38055
MAGNESIUM (as Mg^{++}), mg/l	16.33333	11	13.10979
IRON (Fe^{++}), mg/l	0.435	0.355	0.340632
TEMPERATURE (°C)	28.5	28.4	1.622344

The data of iron, potassium and pH is the only one which is centralized and minute variation shows that each of these data have been affected mainly by one factor since all the boreholes were taken on the same lithology while for nitrate is anthropogenic and is also centralized so this may be so because the water samples were collected from area with people of the same agricultural practices. The data that is more dispersed showing maybe affected by local and global factors which may be from the leaching, aquifer of the study area and maybe from the neighboring aquifer bordering with this aquifer

Table 5 Showing data from rock analysis collected along the Luchenza River

ROCK CODE	ROCK NAME AFTER PHYSICAL PROPERTY ANALYSIS
R1	Dolerite intrunsions and chanockitic gneiss

R2	Quarzo feldsparthic granulites

4.1 DATA ANALYSIS

This section involves the analysis of the data by the use of graphical representation to determine if there was water-rock interaction and what kind of interaction that is occuring in the area. This was achieved by the use of the following; gibbs diagram, piper plot and scater plots.

4.1.1 GIBBS DIAGRAM

Gibbs diagram is widely used to establish the relationship of water composition and aquifer lithological characteristics. Three distinct fields such as precipitation dominance, evaporation dominance and rock–water interaction dominance areas are shown in the Gibbs diagram. The predominant samples fall in the rock–water interaction dominance and one sample in evaporation dominance field of the Gibbs diagram as shown in Figure 5. The rock–water interaction dominance field indicates the interaction between rock chemistry and the chemistry of the percolated waters under the subsurface. Hence the groundwater has chemically interacted with rocks along its pathway from recharge through the aquifers to discharge (in this case water points in the T/A Chimaliro area) which has a huge influence on the groundwater chemistry.

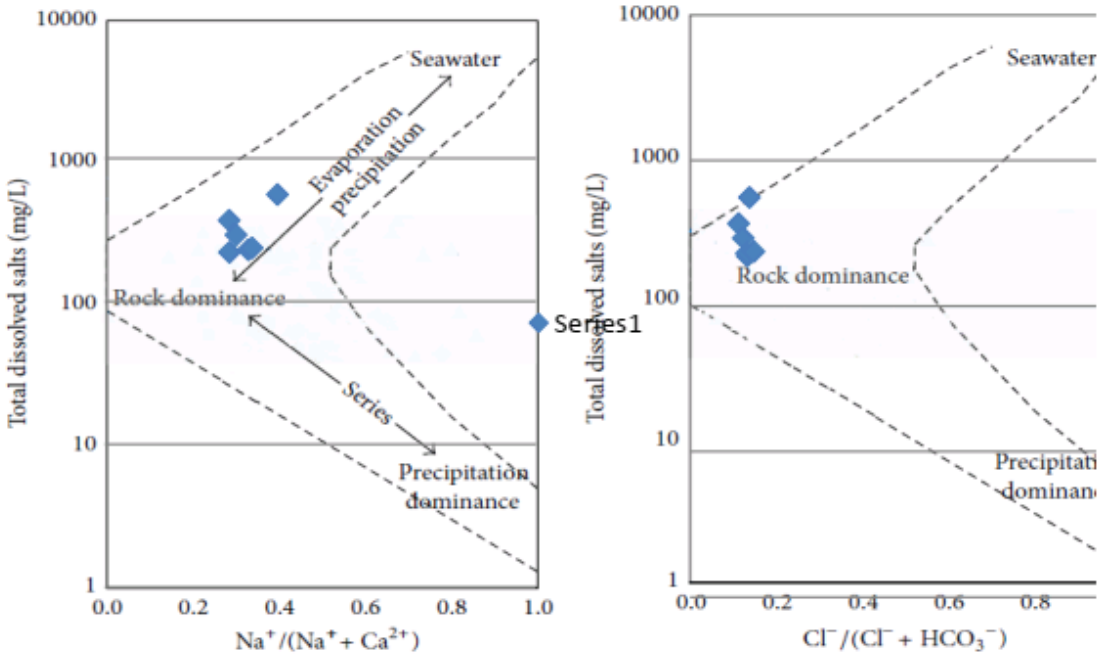


Figure 5 Showing Gibbs diagram

Gibbs diagram showing what factor contributed to chemistry of the water sample points.

4.1.2 PIPER DIAGRAMS

Piper diagram is extensively used to understand problems concerning the geochemical evolution of groundwater. This diagram consists of three distinct fields including two triangular fields and a diamond-shaped field showing hydrogeological facies as shown in the figure 6 below.

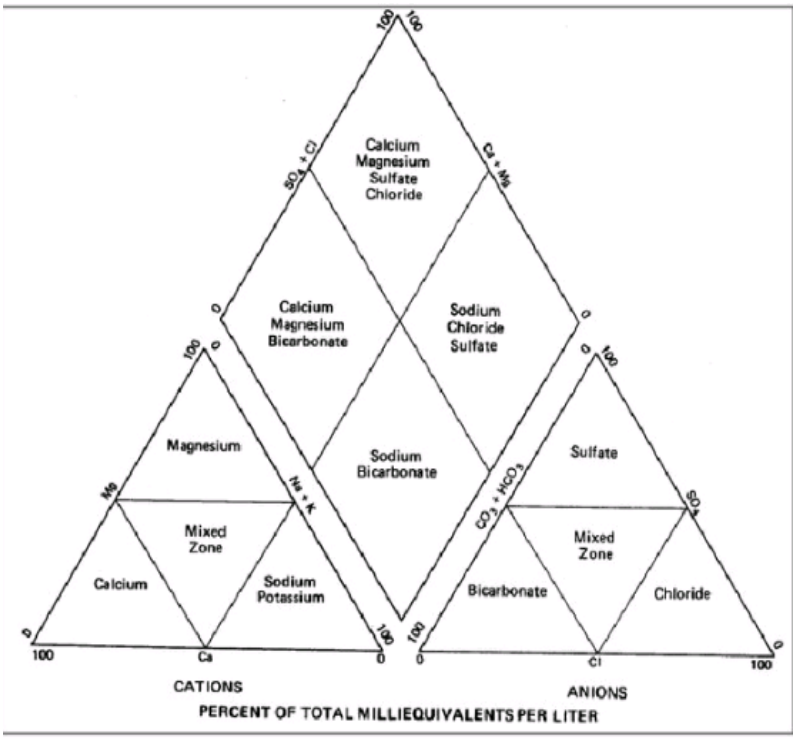


Figure 6 showing a sample piper diagram showing hydrogeochemical facies (Piper, 1944)

The cations expressed as percentage of total cations in meq/l as a single point on the left triangle while anions plot in the right triangle (Piper, 1944). Each point is then projected into the upper field along a line parallel to the upper margin of the field and the point where the extension intersects indicates the character of the water as represented by the relationship among $Na^+ + K^+$, $Ca^{2+} + Mg^{2+}$, $CO_3^- + HCO_3^-$ and Cl^-, SO_4^{2-} ions. Similarities and differences among groundwater samples can be revealed from the trilinear diagram because water of similar qualities will tend to plot together

as groups. GW Chart software was used for the plotting of piper trilinear diagram. The piper diagram

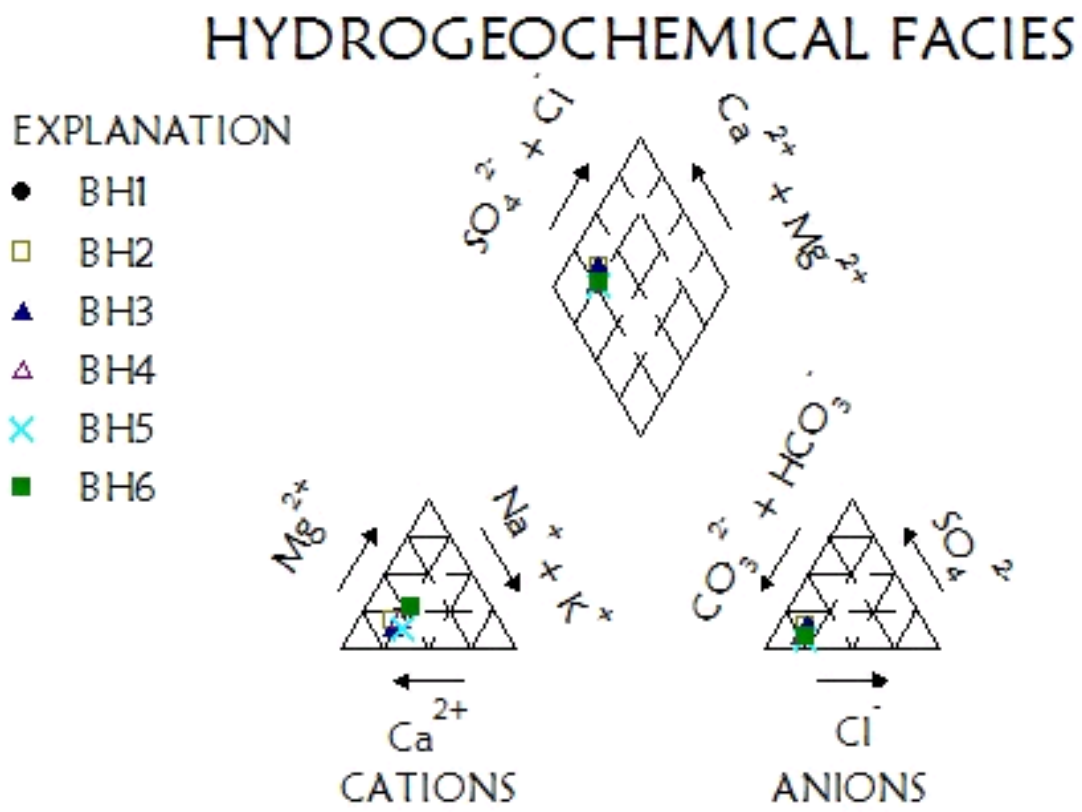


Figure 7 showing the water types of the water samples collected

4.1.3 SCATER PLOTS

There are several scatter plots that have been plotted to deduce what kind of water rock interaction t

4.1.3.1 THE (Ca^{2+} + Mg^{2+}) vs (SO_4^{2-} + HCO_3^-) SCATTER PLOT

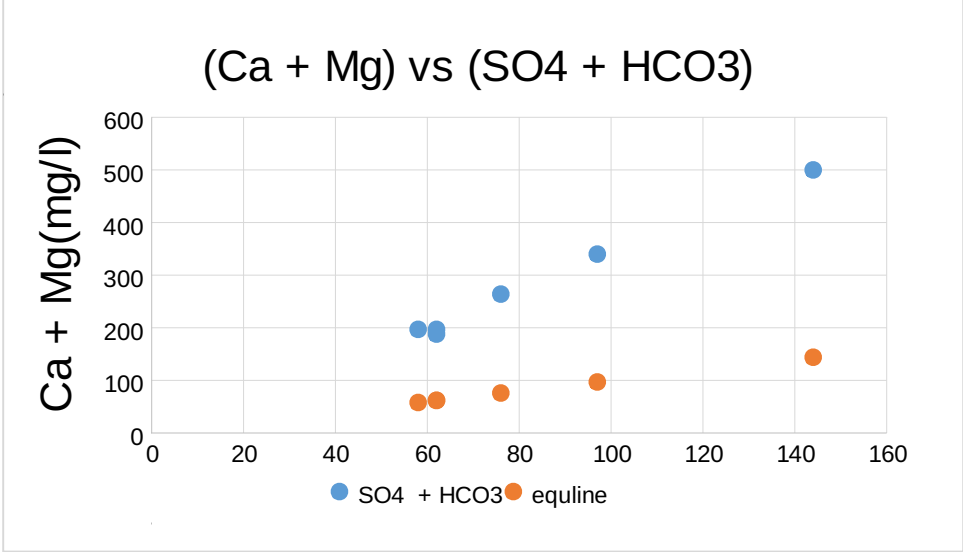


Figure 8 showing a scatter graph of (Ca2+ + Mg2+) vs (SO42- +

Datta & Tyagi, 996) Explained hat in the (Ca + Mg) vs. (HCO_3+ O_4) scatter iagram, the ionic oncentrations alling above the equiline result from carbonate weathering, while those falling along the equiline are due to both carbonate weathering and those below the equiline are a result of silicate weathering. So according figure 8 this shows that the ground water chemistry is affected by carbonate weathering which depicts water interacting carbonate rocks of which are not present in the aquifer of T/A Chimaliro because it mostly contain gneisses with mostly mafic and minimal felsic silicate minerals (Habgood, Holt, & Walshaw, 1973) which was confirmed by the rocks collected in T/A Chimaliro on outcrops found in Luchenza River which are ; the biotite-hornblend gneisses; chanockitic gneisses; doleritic dykes ; and quartzo-feldspathic granulites, in addition to that aquifer is overlain by clay soil which is a silicate mineral hence low infiltration since clay has low permeability this shows that the aquifer is mainly recharged by percolation from another storage which has carbonate rocks which is contributing to the high levels of (Ca^{2+} +Mg^{2+}) and HCO_3^- If bicarbonate and sulfate ions are dominant than calcium and magnesium that means silicate weathering is dominant (Elango, Karman, & Senthil Kumar, 2003). Similarly, sodium is also high in groundwater such that it exceeds the 1:1 ratio of sodium ions to chloride ion and since $Na^+ \approx Cl^-$ show halite dissolution as illustrated in figure 10 hence

there no silicate weathering in the aquifer that may affect groundwater in the area so the groundwate

4.1.3.2 THE SODIUM VS CALCIUM PLOT

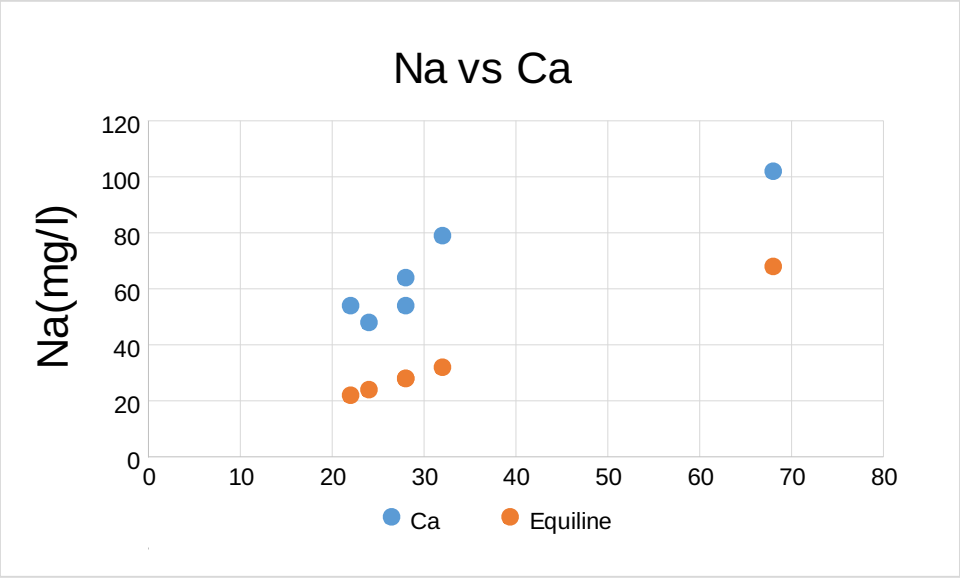


Figure 9 Showing Na+ vs Ca2+ scatter graph

Figure 9 is Na^{+} vs Ca^{2+} scatter diagram shows that Ca/Na ion exchange also increased the concentration of Ca^{2+} in groundwater due to high [Ca^{2+}] over [Na^{+}] however complimenting this data with that in figure 10 this high [Ca^{2+}] cannot be attributed just to ion exchange since [Na^{+}] is slightly less to [Cl^{-}] which can be negligible.

4.1.3.3 THE SODIUM VS CHLORIDE PLOT

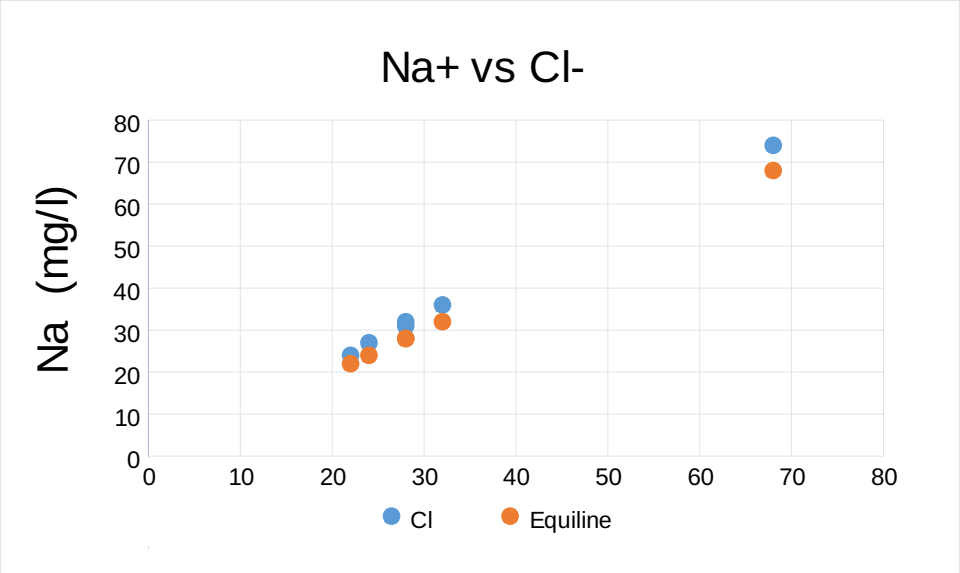


Figure 10 Show a scatter graph of Na+ vs Cl-

Figure 10 is a sodium vs. chloride scatter plot that shows a ratio of sodium to chloride concentrations in water samples which is approximately 1:1 ratio where there is a minute difference between the two. The groundwater of this kind is derived from halite dissolution which cannot be attributed to the geology of T/A Chimaliro because of the absence of halite minerals or rock salt hence this water might be affected by a other lithology which are along its pathway but not of this aquifer depending on the geology of the study area as the geology explained by (Envans, 1965) and (Habgood, Holt, & Walshaw, 1973).

4.1.3.4 THE SODIUM VS BICARBONATE PLOT

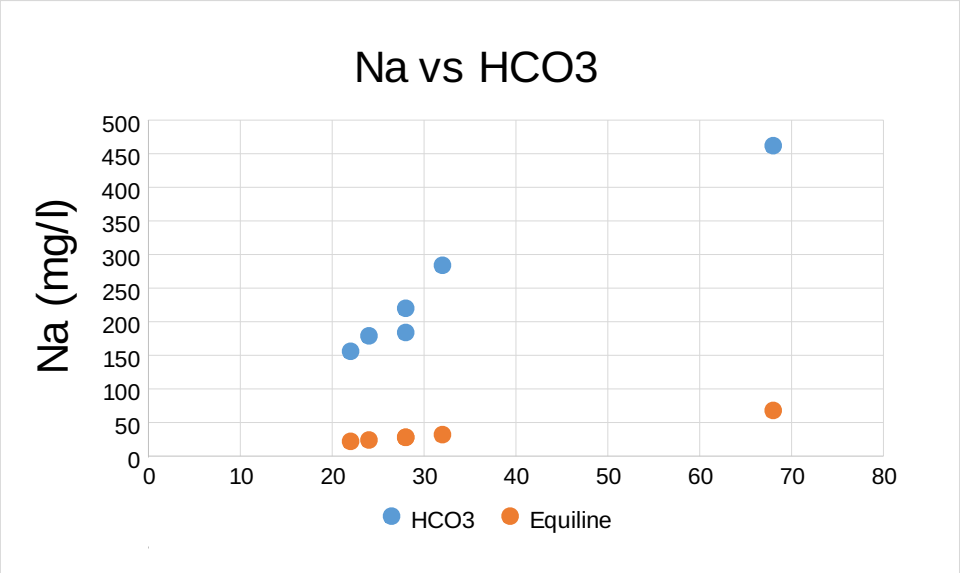


Figure 11 showing scatter graph of Na+ vs HCO3-

Figure 11 is a Na^+ vs. HCO_3^- scatter plot showing increased concentration of bicarbonate with respect to sodium. This shows that the carbonate dissolution is very high with respect to halite dissolution as illustrated in figure 10 the sodium and chloride ions in the groundwater are due to halite since $Na^+ \approx Cl^-$ though sodium is slightly lower than the chloride ion concentration which can be attributed to a minute/negligible ion exchange process.

4.1.4 WATER QUALITY

All the water samples have not exceeded the Malawi standards (MS) for boreholes & protected shallow wells but that of WHO in terms of HCO_3^- concentrations of BH6 and iron concentration of BH3, BH4, BH5 and BH6 exceeded the WHO permissible limits. The water is chemically interacting with the rocks in the aquifer at the minimal rate but is not occurring only in this aquifer but the other aquifers surrounding due to the water

compositions which are strange to the aquifer in the study area. This was shown in bar charts below

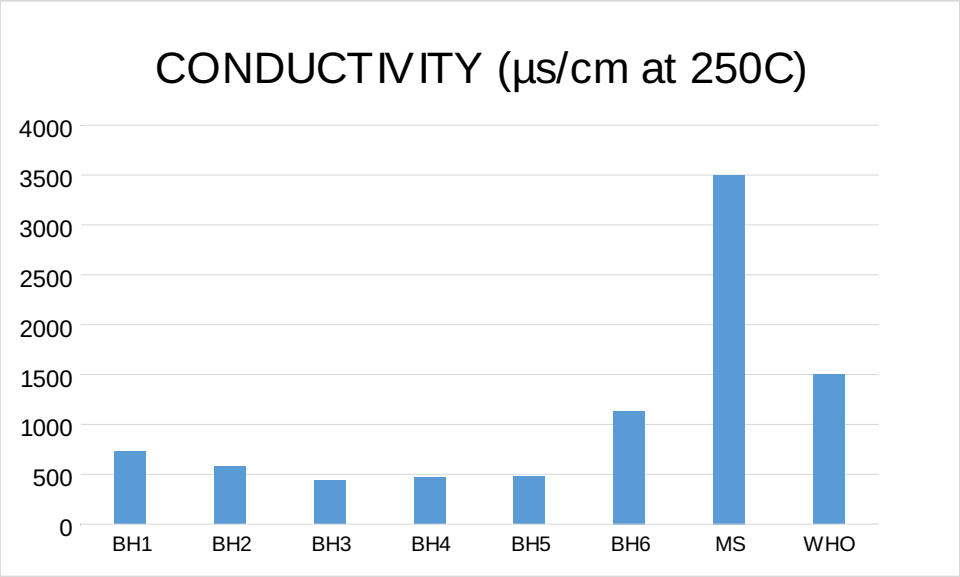


Figure 12 showing the electrical conductivity of water samples with the MS and WHO values for comparison

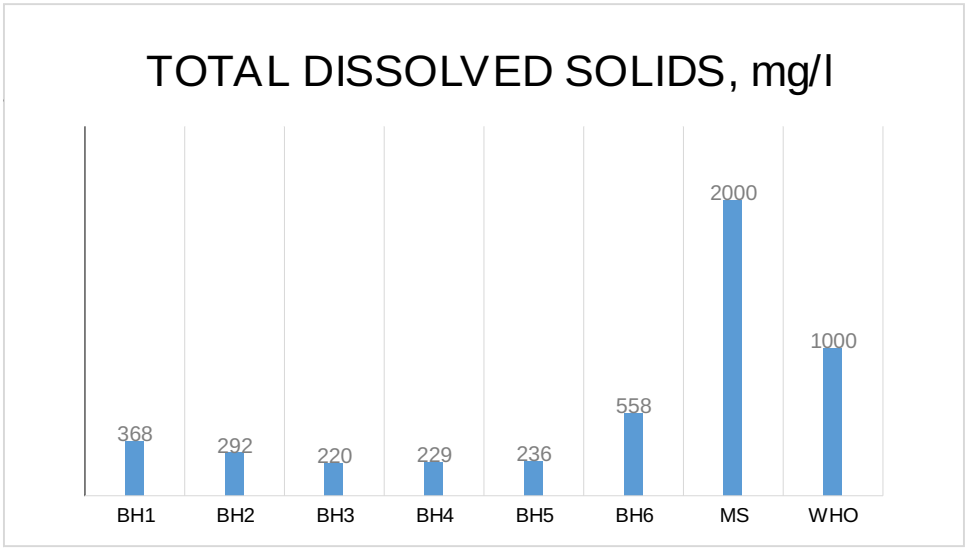


Figure 13 showing the TDS values of water samples with that of MS and WHO

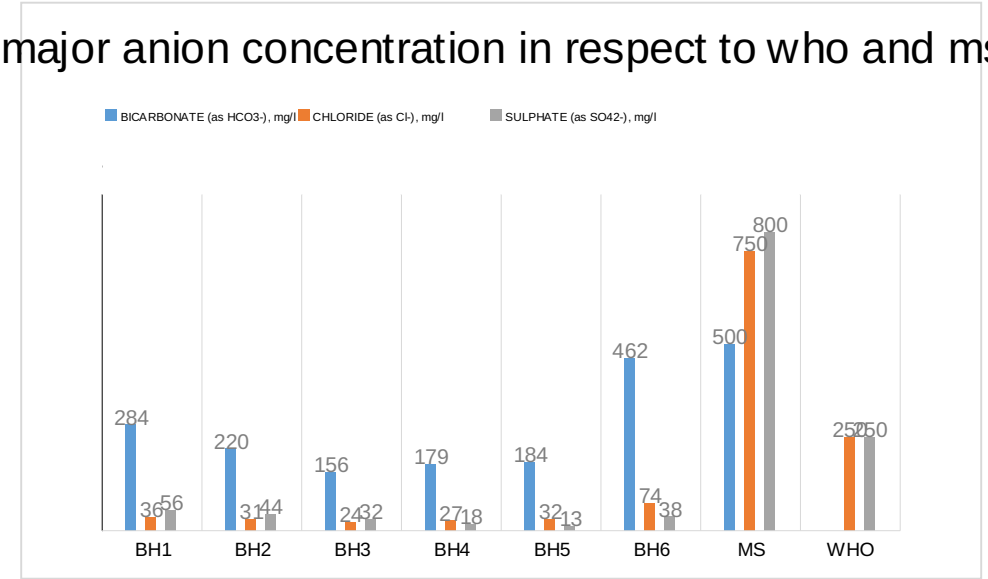


Figure 14 showing values of major anions (HCO3-, Cl- and SO42-) and that of MS and WHO.

All these major anions concentration have not exceeded the permissible limits of both MS and WHO however [HCO_3^-] on BH6 is close to the WHO standard and although on other boreholes is not close they are large relatively to other anions which might a result of leaching or groundwater flowing from a nearby aquifer which is the weathered basement containing rocks of carbonate origin since so the study recommends a further study on the groundwater flow of the area and implement monitoring programs in the area checking anion concentrations and deducing remediation measures.

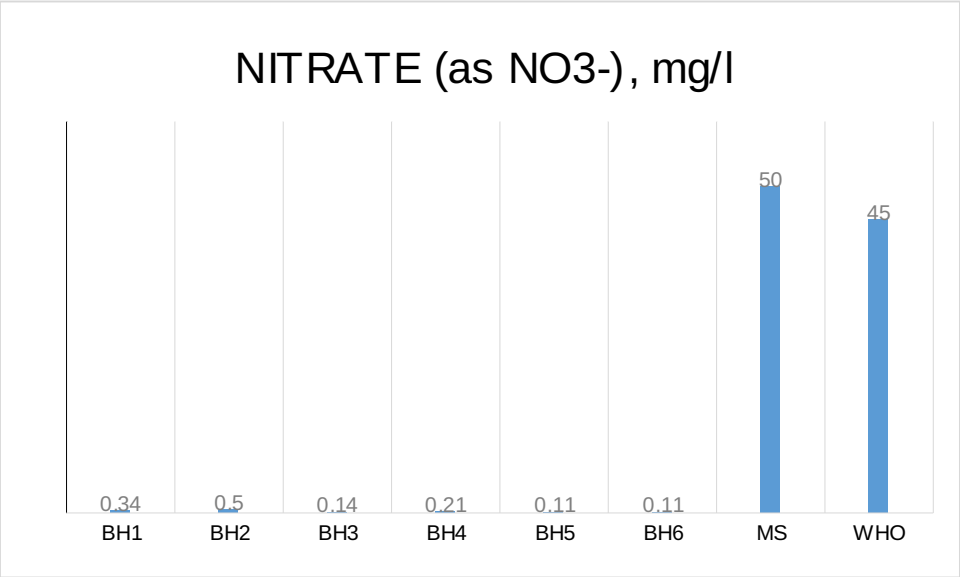


Figure 15 showing concentrations of Nitrate and its accepted limits set up by WHO and MS.

The nitrate concentrations have not exceed the both the WHO and MS permissible limits. The minute concentrations of nitrate in borehole water shows there was

insignificant anthropogenic contamination

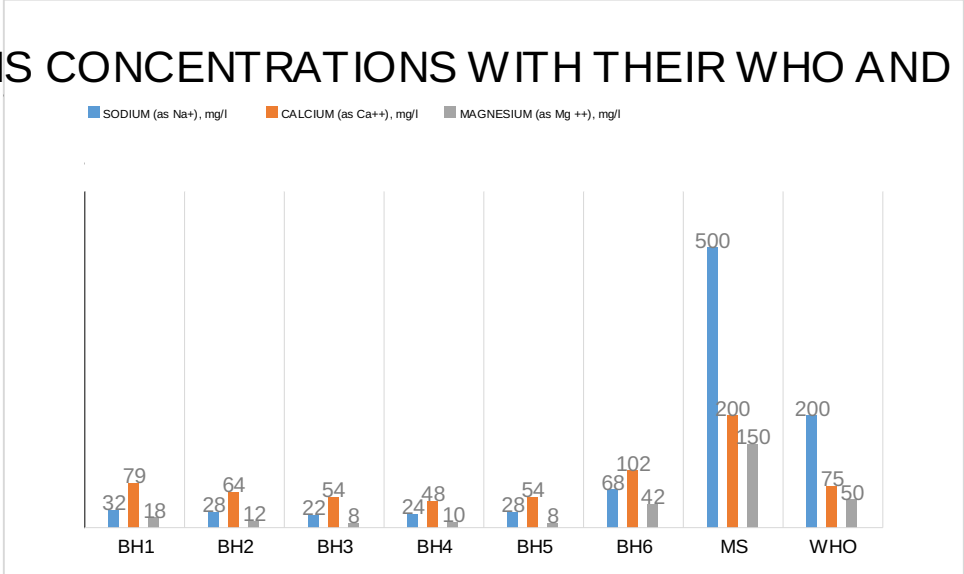


Figure 16 showing graph of major cations and their WHO and MS limits.

The calcium concentrations for BH1 and BH6 exceed the permissible limits set by WHO only which calls for the further study on groundwater flow to identify where exactly is the contamination is originating as shown by figure

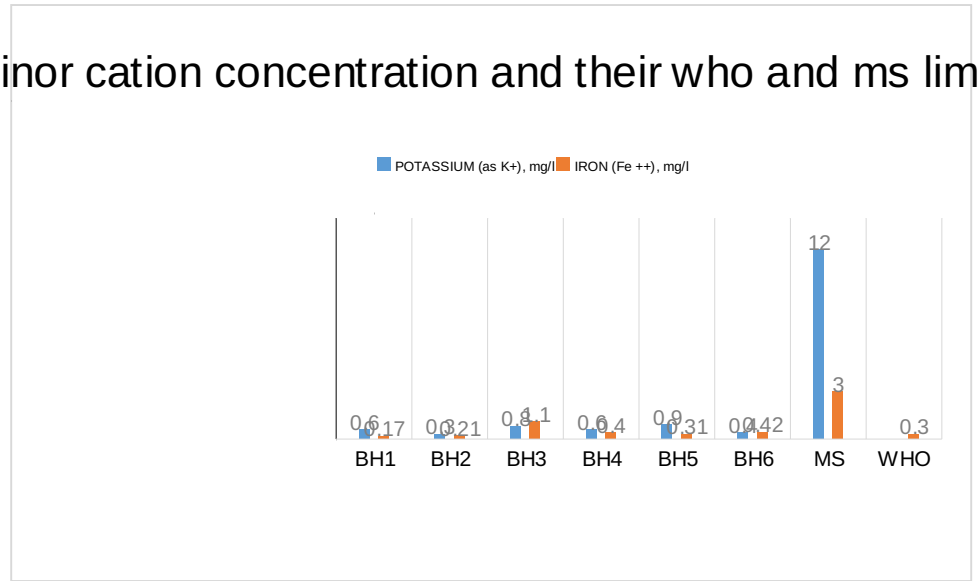


Figure 17 showing graph of minor cations and their WHO and MS

The iron concentrtions of only borehole 1 and 2 do not exceed the WHO permissible limit which can be caused by lithology T/A Chimaliro because it ferromagnesian (minerals which easily undergoes chemical weathering) which might contribute the groundwater chemistry in small quantities as seen because interacts within the fractures

4.1.5 ANALYSIS CONLUSION

The hydrogeochemistry of the groundwater has not been affected by the aquifer since water type shows carbonate dissolution which cannot happen in the aquifer for it is ferromagnesian but it is only the ferric composition is the one can be attributed to the aquifer due to its composition however from the Gibbs diagram in figure 4.1.1.1 show that the groundwater chemistry is predominantly affected by the water-rock interaction hence this interation may have occurred along the pathway into the aquifer as groundwater is flow.

5 CONCLUSION AND RECOMMENDATION

There is minimal water-rock interaction in the aquifer that is in T/A Chimaliro however the groundwater is also affected by the lthologies surrounding the study area aquifer or by leaching of the chemical constituents from the soil which interacts with the groundwater as it flows into the aquifer in T/A Chimaliro and this increases the chemical constituents (CaMg (HCO_3)). The study recommends on; assessing the ground water flow to know were the groundwater is coming from and make remediation measures to reduce contaminants; mornitoring measures for checking increment of the ions; and the area is a good site for engineering structures due to the properties of aquifer which are resistant to weathering though fractured.

6 References

Apodaca, L., Jeffrey, B., & Michelle, C. (2002). Water quality in shallow alluvial aquifers, Upper Colorado River basin, Colorado,. *1997. J. Am. Wat. Res. Ass.*, 133-143.

Appelo, C., & Postma, D. (2005). *Geochemistry, Groundwater and Pollution.* Amsterdam, The Netherlands: CRC Press.

Arnold, T. L., Bexfield, L. M., Musgrove, M., Lindsey, B. D., Stackelberg, P. E., Barlow, J. R., . . . Belitz, K. (2017). *Groundwater-quality data from the National Water-Quality Assessment Project, January through December 2014 and select quality-control data from May 2012 through December 2014.* Virginia: U.S. Geological Survey.

Batabyal, A., & Chakraborty, S. (2016). Hydrogeochemistry and Water Quality Index in the Assessm

Bäumle, R., Himmelsbach, T., & Noell, U. (2018). Hydrogeology and Geochemistry of a Tectonically Controlled, Deep-Seated and Semi-Fossil Aquifer in the Zambezi Region (Namibia). *Hydrogeol. J.*, 27, 885–914.

Bruckmann, J., & Clauser, C. (2020). Ensemble-Based Stochastic Permeability and Flow Simulation of a Sparsely Sampled Hard-rock Aquifer Supported by High Performance Computing. *Hydrogeol. J.*

Cheboterev. (1955). Geochim. Cosmochim. Acta 8. *Metamorphism of natural waters in the crust ofweathering-I*, 22–48.

Clesceri, L. S., & A., G. (1995). *Standard Methods for the Examination of Water and Wastewater.* Washington D.C.: American Publish Health Association.

Danapour, M., Hojberg, A., Jensen, K., & Atisen, S. (2019). Assessment of Regional Inter-basin Groundwater Flow Using Both Simlpe and Highly Parametrized Optimization Schemes. *Hydrogeol. J.*, 27, 1929–1947.

Datta, P., & Tyagi, S. (1996). Major ion chemistry of groundwater in Delhi area: Chemical weathering processes and groundwater flow regime. *J. Geol. Soc. India*, 47, 179-188.

Davidson, G., Holt, H., & Blainey, J. (2019). Geochemical Assessment of the Degree of Isolation of Edge-of-aquifer Groundwater Along a Fringe of the Southern High Plains Aquifer, USA. *Hydrogeol. J.*, 27, 1817–1825.

Deutsch, W. (1997). *Groundwater Geochemistry: Fundamentals and Applications to Contamination.* New York.: Lewis Publishers.

Elango, L., Karman, R., & Senthil Kumar, M. (2003). Major ion chemistry and identification of hydrogeochemical processe of groundwater in a part of Kancheepuram district, Tamil Nadu, India. *Environ. Geosci.*, 157-166.

Envans, R. K. (1965). *THE GEOLOGY OF THE SHIRE HIGHLANDS.* Zomba: The

Government printer.

Gibbs, R. (1970). Mechanisms controlling world water chemistry. *Science*, 170,795-840.

Habgood, F., Holt, D. N., & Walshaw, R. D. (1973). *The Geology Of The Thyolo Area.* Zomba: The Government Printer.

Hellens, A. V. (2013). *Groundwater quality of Malawi– fluoride and nitrate of the Zomba-Phalombe plain.* Swedish University of Agricultural Sciences.

Ismail, C., Boutheina, F., & Mammou, A. B. (2010). Identification of major sources controlling groundwater chemistry from a multilayered aquifer system. *Chemical Speciation & Bioavailability*, 183-189.

Malov, A. (2004). Water-rock interaction in vendian sandy-clayey rocks of the Mezen Syneclise. . *Lithol. Min. Resour.* , 345-356.

Mayback, M. (1987). Global chemical weathering of surficial rocks estimated from river dissolved loads. *Am. J. Sci.*, 287,401-428.

Mehrdad, B., & Thomas, H. (2020). Effects of Upscaling Temporal Resolution of Groundwater Flow and Transport of Boundary on the Performance of Nitrate-Transport Models at the Regional Management Scale. *Hydrogeol. J.*, 28, 1299–1322.

Piper, A. M. (1944). A graphical interpretation of water - analysis. Trans. Am. Geophys.Union. 914-928.

Rajmohan, N., & Elango, L. (2004). Identification and evolution of hydrogeochemical processes in the groundwater environment in a part of the Palar and Cheyyar River Basins,Southern India. *Environ. Geol.*, 47-61.

Rivett, M., Budimir, L., Mannix, N., Miller, A., Addison, M., Moyo, P., . . . al., e. (2018). To boldly go beyond the world of hand-pumped groundwater supply? Sci. Total Environment. *Responding to salinity in a rural African alluvial valley aquifer system*, 1005-1024.

Salcedo, E., Garrido, S., Vicenta, M., Martínez, M., & Ocampo, A. (2017). Hydrogeochemistry and w

Saravanan, K., Srinivasamoorthy, K., Prakash, R., Gopinath, S., & Suma, C. (2015). An Evaluation of hydrogeochemistry of groundwater in upper vellar sub-basin using mineral stability and solute transport modelling. *Aquat. Procedia*, 1119–1125.

Sarikhani, R., & Nagaraju, D. (2011, January). Hydro geochemical and rock water interaction studies in East of Kurdistan, N-W of Iran. *Environmental Sciences and Research, I*, 16-22.

Smith - Clington, A. K., & Chilton, P. J. (1983). *Groudwater resources of Malawi.* REPUBLIC OF MALAWI DEPARTMENT OF LANDS, VALUATION AND WATER.

Smith Carington, A. K., & Chilton, P. J. (1983). *GROUNDWATER RESOURCES MALAWI.* ZOMBA: OVERSEAS DEVELOPMENT ADMINISTRATION INSTITUTE OF GEOLOGICAL SCIENCES.

Srinivasamoorthy, K., Chidambaram, S., Prasanna, M. V., Vasanthavihar, M., John, P., & Anandhan, P. (2008). Identification of major sources controlling groundwaterchemistry from a hard rock terrain – A case study from Metturtaluk, Salem district, Tamil Nadu, India. *Earth Syst. Sci. 117*, 49–58.

Teresa, C., Marini, L., Schott, J., Mavromatic, V., Apollaro, C., Rinder, T., . . . Oelkers, E. (2014). Dissolution rates of actiolite and chlorite from a whole-rock experimental study of metabaslt dissolution from 2 </=pH >/=12 at 25C. *Chem. Geol.*, 390, 100–108.

Upton, K., Dochartaigh, B., Chunga, B., & Bellwood-Howard, I. (2020, October 19). *Hydrogeology of Malawi. British Geological Survey.* Retrieved from Africa Groundwater Atlas: http://earthwise.bgs.ac.uk/index.php/Hydrogeology_of_Malawi

7 APPENDICES

7.1 PICTURES FROM SAMPLE COLLECTION



Figure 18 showing water sampling at a water point and measurement of the pH and temperature.



Figure 19 showing rock sampling