

PHYSICAL AND CHEMICAL CHARACTERISTICS OF GROUNDWATER AND SURFACE WATER IN THE LAKE CHILWA BASIN, MALAWI

BLESSINGS MLOTHA
(ESC-023-17)

RESEARCH DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE AWARD OF THE
BACHELOR OF SCIENCE DEGREE IN EARTH SCIENCES

MALAWI UNIVERSITY OF SCIENCE AND TECHNOLOGY
NDATA SCHOOL OF CLIMATE AND EARTH SCIENCE
DEPARTMENT OF EARTH SCIENCE
Supervisor
(Mr. Wilson Tchongwe)
July, 2021

DISSERTATION APPROVED BY:

SUPERVISOR

Title, Initials, Name Signature:

ASSESSOR

Title, Initials, Name Signature:

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

COPYRIGHT STATEMENT

This copy of the dissertation has been supplied on condition that anyone who consults it is understood to recognize that its copyright rests with its author and that no quotation from the dissertation and no information derived from it may be published without acknowledgement.

ABSTRACT

The physical and chemical properties of groundwater, streams and Lake Chilwa water were measured in the Lake Chilwa Basin in southern Malawi. The goal was to trace the origin of salinity in groundwater and Lake Chilwa water and their relationship to water-rock interactions and alluvial deposits respectively. Groundwater around the Lake Chilwa Basin are highly saline which has led to water shortages because of poor water quality. The hypothesize of the research was that highly saline groundwater and Lake Chilwa water results from water-rock interactions and alluvial deposits respectively or highly saline groundwater and Lake Chilwa water does not result from water-rock interactions and alluvial deposits respectively. The main objective was achieved from the following specific objectives: measuring the physical and chemical properties of water from tributaries, and groundwater, assessing the major ion concentrations of boreholes and Lake Chilwa water and investigating the major types of rocks within Lake Chilwa basin that may contribute to salinity of the lake and groundwater. Groundwater from 16 boreholes, 5 stream water samples and 3 samples from Lake Chilwa were collected using standard methods and investigated for temperature, pH, electrical conductivity and total dissolved solids (TDS). The expected results were that groundwater and Lake Chilwa water have higher ionic concentrations of HCO_3^-, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, F^-, NO_3^-, SO_4^{2-} and SiO_2 than stream water because of weathering of silicate minerals and alluvial deposits respectively. Quality of streams water is adequate, and base flow to perennial streams is supported by shallow groundwater, efforts should be made to map shallow fresh groundwater aquifers for domestic and industrial use.

ACKNOLEDGEMENT

I truly thank my Supervisor Mr. W. Tchogwe for the time spent for guiding me during my research p

Table of Contents

CHAPTER 1 1
1.1 Introduction 1
1.2 Problem statement 1
1.3 Research questions 2
1.4 Research hypothesis 2
1.5 Research objectives 2
1.5.1 Main objective 2

1.5.2 Specific objective....2
1.6 Significance of the study....3
CHAPTER 2:....4
2.1 Literature review on water quality worldwide....4
2.2 literature review on surface and groundwater: Lake Chilwa basin....6
CHAPTER 3....7
3.0 Methodology....7
3.1 Study Area....7
3.2 Topography and geology....8
3.3 Sample collection....12
3.4 Measurements and sample analysis....13
CHAPTER 4:....14
4.0 Results....14
4.1 Physical parameters....14
4.2 Chemical parameters....19
CHAPTER 5....20
5.0 Discussion....20
5.1 Water quality and surface water....20
5.2 Ionic evolution of groundwater and surface waters....26
CHAPTER 6....28
6.0 Conclusions....28
REFERENCES....29

ACRONYMS/ABBREVIATIONS

WHO: World Health Organization

MBS: Malawi Bureau of Standards

TDS: total dissolved solids

FAO: Food and Agricultural Organization

WQI: Water Quality Index

EC: Electrical Conductivity

LIST OF FIGURES

Figure 1. Malawi on the world map, framed area representing the study area. Source; world map from Wikipedia and map of Malawi from ESRI world map..... 17

Figure 2. Map of Malawi showing river drainage; the solid rectangle is the location of the study area. The map shows Lake Chilwa and groundwater and surface water sampling locations. Shape files provided by Geological Survey Department, Malawi... 19

Figure 3. Digital elevation map of the study area. Source: ETOPO1 Global Elevation data..... 20

Figure 4: Geological map of the study area. Source: Geological Survey Department of Malawi..... 21

Figure 5. Plot of concentrations of total dissolved solids (TDS) for groundwater and surface water in the Lake Chilwa Basin. Also shown on the plot are the bars representing World Health Organization (WHO) and Malawi Bureau of Standards (MBS) maximum permissible..... 32

Figure 6: Plots of concentrations of cations (a) Na+ and (b) K+ for groundwater and surface water in the Lake Chilwa Basin. Also shown on the plot are bars representing World Health Organization (WHO) and Malawi Bureau of Standards (MBS) maximum permissible concentrations in drinking water (WHO, 2008)..... 34

Figure 7: Plots of concentrations of (a) F- (b) Cl-, (c) NO3-, and (d) HCO3- for groundwater and surface water in the Lake Chilwa Basin. Also shown on the plots are bars representing World Health Organization (WHO) maximum permissible concentrations in drinking water (WHO, 2008)..... 37

Figure 8: Piper plot showing ionic proportions for groundwater and surface water in the Lake Chilwa Basin.....38

LIST OF TABLES

Table 1: Summary statistics of the physical parameters of water samples. pH,

temperature (°C), electrical conductivity (EC) (µS/cm) and Total Dissolved Salts (TDS). GW is grou
..... 24

Table 2: Summary statistics of the chemical parameters of water samples. All values are in mg/L, GW is groundwater, LW is lake water, SW is stream water, Min is minimum value, Max is maximum value and SD is the standard deviation..... 26

Table 3: Results of the Physical analyses of water samples from Lake Chilwa Basin.. 28

Table 4: Results of the Chemical analyses of water samples from Lake Chilwa Basin. 29

Table 5: Water Quality Standards. World Health Organization (WHO) Drinking Water Guidelines (WHO, 2008) and Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005)..... 31

Table 6: showing charge balance, alkalinity, SI fluorite, and SI halite..... 45

CHAPTER 1

1.1 Introduction

Globally, groundwater and surface water are the major sources of water for domestic, agricultural and industrial purposes. Approximately one third of the world's population use groundwater for domestic use (Nickson et al., 2005). The World Health Organization (WHO) (2004) report that having safe drinking water is an internationally accepted human right. However, groundwater resources are under constant threat of salinization which is a worldwide concern (Rajmohan et al., 1997; Dar et al., 2011; Ebrahimi and Vilcáez, 2018a&b). Lake Chilwa is the second-largest lake in Malawi after Lake Malawi. It is in eastern Zomba District, near the border with Mozambique. Approximately 60 km long and 40 km wide, the lake is surrounded by extensive wetlands. There is a large island in the middle of the lake called Chisi Island (Missi, 2018). The lake has no outlet, and the level of water is greatly affected by seasonal rains and summer evaporation (Saka, 2006). In 1968, the lake disappeared during exceptionally dry weather. When David Livingstone visited the lake in 1859, he reported that its southern boundary reached as far as the Mulanje Massif, which would have made the lake at least 20 miles longer than it is today (Wilson 2014).

1.2 Problem statement

High water salinity in Lake Chilwa and groundwater around Lake Chilwa is a major water quality problem (Davis, 1969; Monjerezi, 2011). The Lake Chilwa Basin in southern Malawi has saline ground water and surface waters and water use is impaired by high concentrations of solutes (Food and Agricultural Organization (FAO), 2005). Boreholes which tap groundwater with high salinity are frequently abandoned in favor of open unprotected shallow hand dug holes in dry river beds or surface water (Bath, 1980). High levels of other physico-chemical parameters (EC, TDS and turbidity) at several sites suggest that the water sources are grossly contaminated with salts and minerals, hence causing diarrhea and abdominal pain when human consume without treatment (Chidya et al., 2016). However, the expansion of groundwater supplies countrywide and the improvement of drinking water quality remains a national priority (Government of Malawi (GOM), 1995).

1.3 Research questions

- Do the rocks within Lake Chilwa basin have impact on the increased levels of salts and minerals in the lake and groundwater?
- Does alluvial deposits in Lake Chilwa have impacts on salinity increase in the Lake?

1.4 Research hypothesis

- Highly saline groundwater and Lake Chilwa water results from water-rock interactions and alluvial deposits respectively.
- Highly saline groundwater and Lake Chilwa water does not results from water-rock interactions and alluvial deposits respectively.

1.5 Research objectives

1.5.1 Main objective

To trace the origin of salinity in groundwater and Lake Chilwa water based on rock types and alluvial deposits.

1.5.2 Specific objective

- To measure the physical properties of water from, tributaries, and groundwater.
- To assess the major ion concentrations of boreholes and Lake Chilwa water.
- To investigate the major types of rocks within Lake Chilwa basin that may contribute to salinity of the lake and groundwater.

1.6 Significance of the study

The results of this study is useful to bridge the information gap needed in addressing groundwater and surface water quality, as well as providing a foundation for groundwater monitoring. Groundwater monitoring is important as it provides groundwater quality information, such as identification of specific chemical species and associated concentrations that impair groundwater and surface water quality. Such

information can help decision makers better understand the water quality and their potential effects

CHAPTER 2:

2.1 Literature review on water quality worldwide

Sheikh, et al has explained, Physical, chemical, ionic, biological studies that were conducted at (Maharashtra State, India). It is positioned on south east corner of Maharashtra. Nagzari dam is situated at Nagzari village of Kinwat quality of Nagzari dam. Water is used to determine the nutrient status of the water with reference to drinking water quality as well as irrigational purpose. Also observe the seasonal variations of selected water parameters and identify the pollution sources dam. The physical and chemical parameters were analyzed as per APHA revealed that there were fewer variations in the physicochemical, ionic, heavy metals analysis of the present water quality parameters undertaken and results received through the entire

one year of study showed that the status of water quality is quite normal and within the permissible

T. M. Heidtke, A. M. Asce and W. C. Sonzogni have studied, results from a study of water quality planning and management alternatives for the Great Lakes are used to identify cost-effective pollution control strategies. Mathematical models and other systems analysis techniques are applied to estimate pollution loadings, specific water quality problem areas, costs and pollutant reductions offered through alternative management strategies. A determination of how these alternatives may be expected to achieve water quality objectives for the Great Lakes is made. Data from a diversity of Great Lakes research efforts are compiled, integrated, and used to project local and lake wide water quality conditions over the next twenty years. A set of management tools, including a near shore water quality index and a series of environmental quality maps, are developed to promote communication and interpretation of Great Lakes water quality data among technical and nontechnical interests. Findings from the study support a staged approach to pollution control, whereby the most cost effective programs are implemented and their results assessed before more expensive control measures are undertaken.

Tandel, et al have studied, the water quality index is a single number that expresses the quality of water by integrating the water quality variables. Its purpose is to provide a simple and concise method for expressing the water quality for different usage. The present work deals with the monitoring of variation of seasonal water quality index of some strategically selected surface water bodies. The index improves the comprehension of general water quality issues, communicates water quality status and illustrates the need for and the effectiveness of protective practices. It is found that in all cases the change in WQI value follow a similar trend throughout the study period. The lake water is found of good quality (WQI - 67.7 to 78.5) during both seasons. However, it is found that water quality of lake deteriorates slightly from winter to summer season on account of the increase in microbial activity as well as increase in pollutants concentration due to water evaporation

Islam et al have studied, the purpose of this study was to assess the hydrological properties and water quality characteristics of Chini Lake in Pahang, Malaysia. A total of seven sampling stations were established at the main Feeder Rivers of Chini Lake for measurement of stream flow. A total of 10 monitoring stations covering the study area were selected for water sampling. Fourteen water quality parameters were analyzed

based on in-situ and ex-situ analysis for two seasons and laboratory analyses were carried out acc

2.2 literature review on surface and groundwater: Lake Chilwa basin

Groundwater in Malawi is, according to a study made by groundwater consultants Bee Pee and SRK Consultants (SADC, 2002), estimated to supply about 3 million people in rural areas making out about 29 % of the rural domestic water supplies. As groundwater is transported through layers of sand and gravel it is normally clean from anthropogenic pollution. However, due to weathering processes, high contents of different chemical compounds might be accounted for depending on the geological constitution of the area (BGS, 2004). Most of the water supplies of the rural areas of Malawi are derived from shallow hand dug wells or hand pumped boreholes. According to a study made by the BGS (2004), little documentation on the chemical parameters of aquifer groundwater has been done. However, FAO (2005) stated in a report that the areas around Lake Chilwa have saline waters and water consumption is limited due to high concentrations of iron, fluoride, sulphate, nitrate and TDS. Boreholes which tap groundwater with high salinity are frequently abandoned in favor of open unprotected shallow hand dug holes in dry river beds or surface water (Bath, 1980). High levels of other physico-chemical and microbiological parameters (EC, TDS, turbidity, fecal coliform and fecal streptococci) at several sites suggest that the water sources are grossly contaminated with bacteria, hence not suitable for human consumption without treatment (Chidya et al., 2016). There are no dedicated studies on the impact of rocks and alluvial deposits on the increased level of solutes in groundwater and Lake Chilwa water.

CHAPTER 3

3.0 Methodology

3.1 Study Area

Lake Chilwa Basin (latitude 15º 20'S, longitude 35º 40'E) is a close basin of about 7500km^2 located in the southern Malawi and includes portion of north eastern Mozambique as shown in Figure 1. The Lake Chilwa Basin covers three administrative districts: Phalombe has about 73,880 hectares, Machinga has about 11,200 hectares and Zomba has about 185,174 hectares of land (Sagona, 2016). The Lake Chirwa Basin is bounded to the west by the Chikala Hills, Zomba and Malosa Mountains, the Shire highlands and Chiradzulu Mountain. These highlands give rise to the Domasi River, Likangala River, Thondwe River and Namadzi River. The basin is bounded to the south-east by the Mulanje and Michesi mountains which give rise to the Phalombe River and Sombani River. To the east lie the hills and mountains of Mozambique which give rise to Mnembo River and Mbugwe River (Njaya, 2011). Among the seven rivers only Domasi River and Likangala River are perennial, the rest dry up during the dry season.

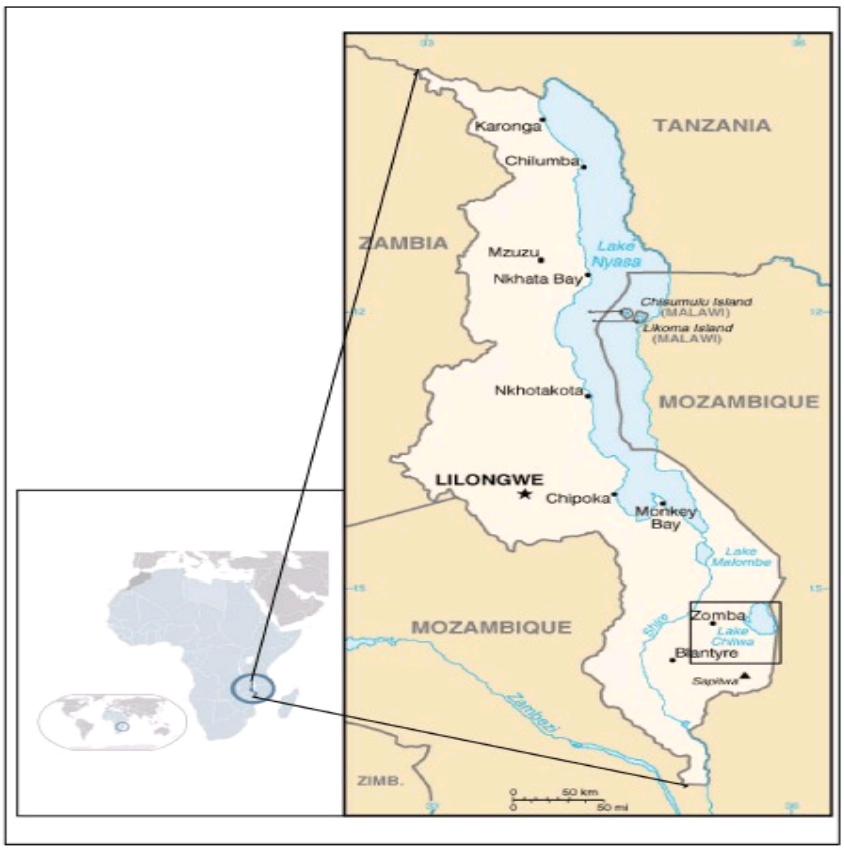


Figure 1. Malawi on the world map, framed area representing the study area. Source; world map from Wikipedia and map of Malawi from ESRI world map.

3.2 Topography and geology

The topography of the Lake Chilwa Basin is made up of uplands and lowlands (Figure 3). The Lake Chilwa Basin is a tectonic depression of post-cretaceous age that has been progressively filled with sand, silt and various sediments from the denudation of the surrounding highlands (Sagona, 2016). The uplands have deep, well drained sandy soils. Derived from the weathering of gneisses, while the lowlands have very deep soils with variable drainage in fluvial, colluvial and lacustrine deposits (Morgan and Kalk, 1970).

The Lake Chilwa Basin as shown in Figure 4 is characterized by (1) crystalline metamorphic and igneous rocks of Precambrian to lower Paleozoic age referred to as the basement complex (Carter and Bennett, 1973; Chilton and Smith-Carington, 1984; Mapoma and Xie, 2014). The major lithological units of the basement complex are charnockites and granulites. Charnockites include orthopyroxene granite, quartz, feldspar, syenite and others, whereas granulites include pyroxene, biotite, garnet, calcium plagioclase and quartz, (2) the Chilwa alkaline intrudes the Precambrian basement and is divided into 4 lithological units: basanite, granite and syenite,

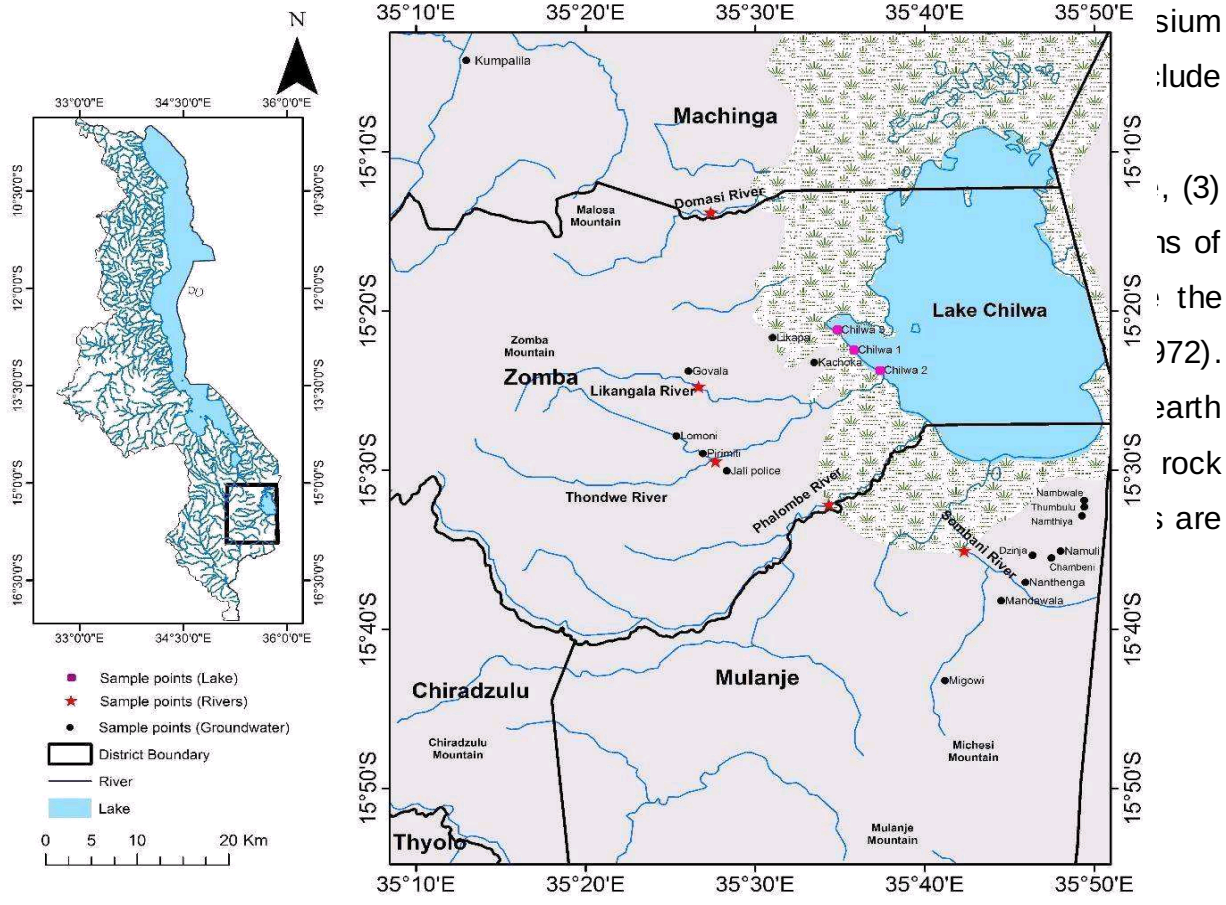


Figure 2. Map of Malawi showing river drainage; the solid rectangle is the location of the study area. The map shows Lake Chilwa and groundwater and surface water sampling locations. Shape files provided by Geological Survey Department, Malawi.

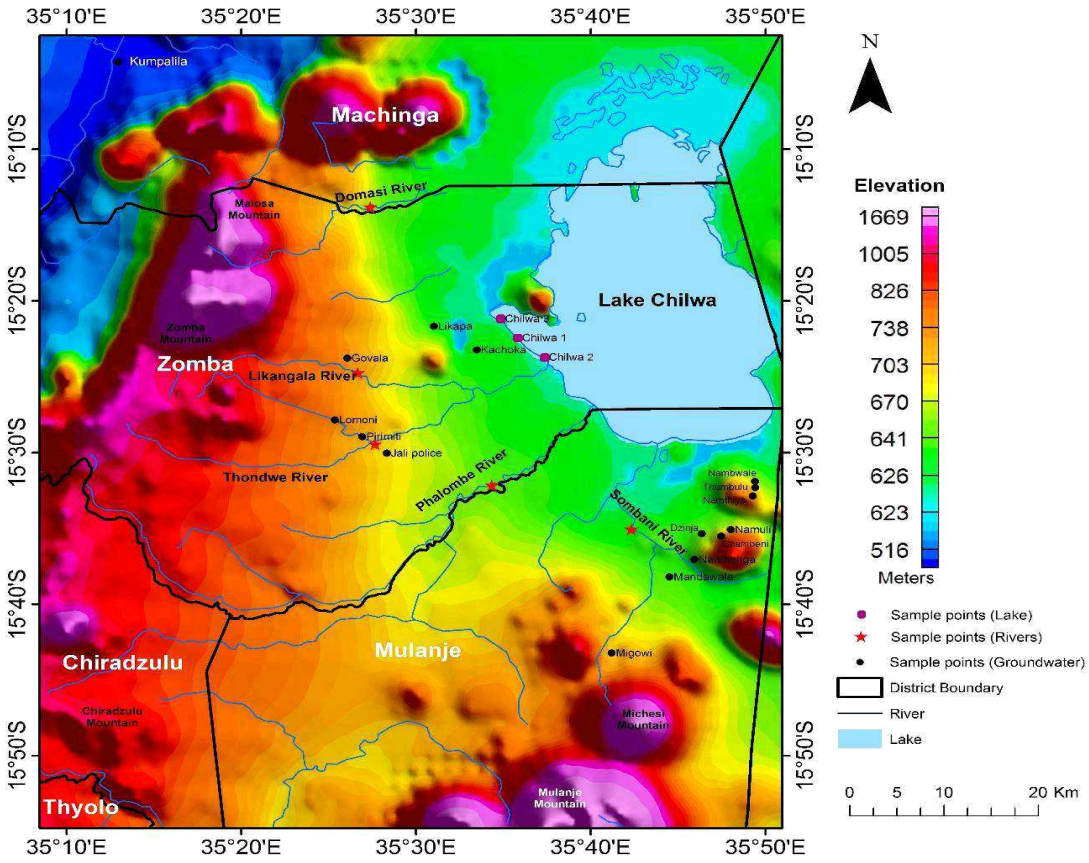


Figure 3. Digital elevation map of the study area. Source: ETOPO1 Global Elevation data.

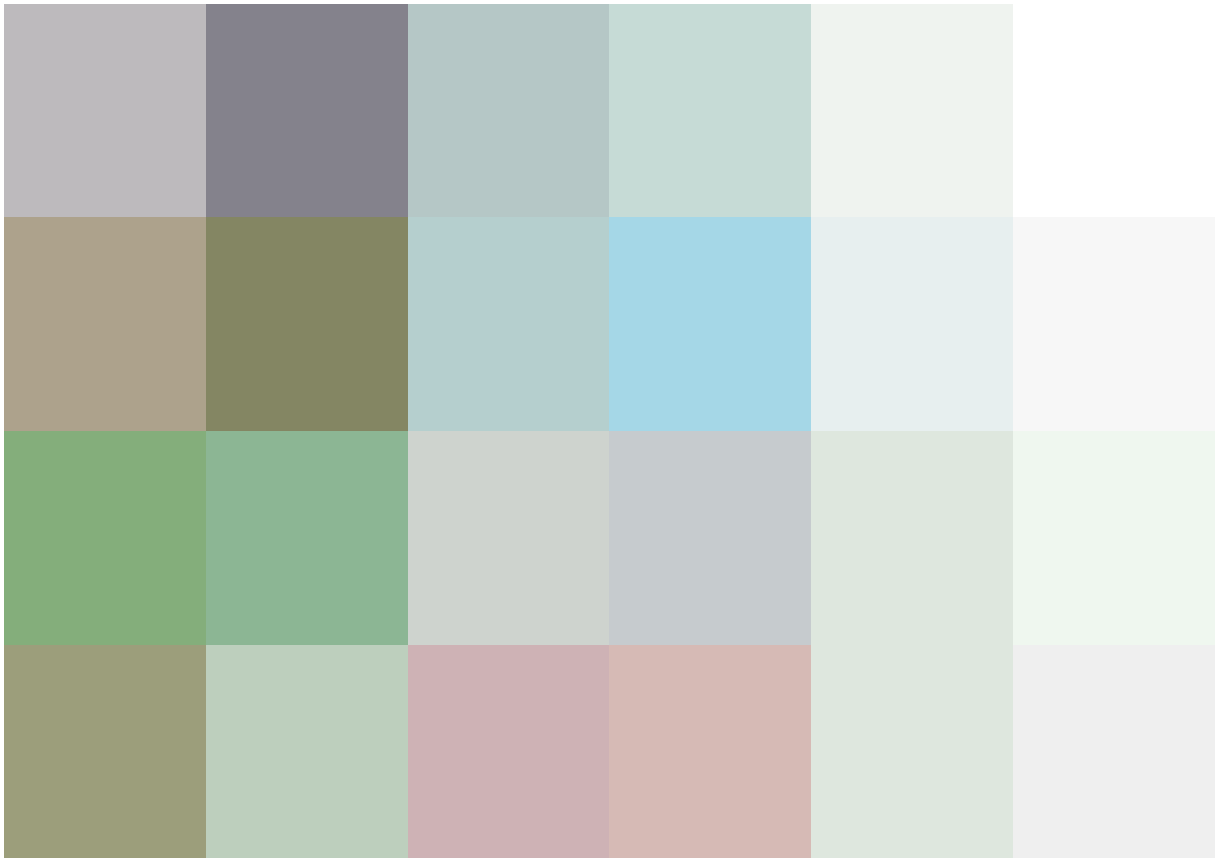


Figure 4: Geological map of the study area. Source: Geological Survey Department of Malawi.

3.3 Sample collection

Water samples were collected from boreholes, streams and Lake Chilwa using standard sampling procedures (APHA, 1985). Water sample collection was conducted from May 6th, 2021 to May 20th, 2021. Groundwater samples were collected from the following boreholes: Dzinja, Namthiya, Nthumbulu, Nambwale, Namuli, Chambeni, Nanthenga, Mandawala, Migowi, Likapa, Govala, Kachoka, Pirimiti, Jali police, Lomoni and Kumpalila (Figure 2). Groundwater samples were collected by hand pumping after

purging three estimated casing volumes.

All stream water samples were collected under bridges from the following streams: Domasi, Likangala, Thondwe, Phalombe and Sombani. Lake water samples were collected from the western side of Lake Chilwa along the shore from three locations (Figure 2). Stream water and lake water samples were collected using grab technique.

All water samples were filtered through a 0.45 µM nylon filter during collection. The sample bottles were rinsed three times with the filtered water sample to be collected and then filled and capped. Filtered water for cations analysis were collected in 60 mL polypropylene bottles, acidified to a pH < 2 with high purity nitric acid (Apha, 1989), and stored in cooler box. Samples for anions and silica analyses were collected unacidified in 30 mL polypropylene bottles and stored in a cooler box as described by Missi, (2018).

Rock samples were not collected from my study areas instead I used the geology of lake Chilwa which maps the rock types that are associated with lake Chilwa basin since the research was targeting the effects of rocks on a large scale.

3.4 Measurements and sample analysis

Water temperature, pH, electrical conductivity (EC) and total dissolved solids (TDS) were measured in situ at each borehole during purging using potable multi-meter probe (HANNA instrument model 991300N). The probe of the meter was dipped in the container receiving the pumped water and readings will be taken after stabilization (Apha, 1989). For surface water, the probe will be immersed in the water and readings were recorded after stabilization (Missi, 2018). The rest parameters (F^-, Cl^-, SO_4^{2-}, NO_3^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^- and SiO_2) were determined at ministry of forestry and natural resources

(southern water laboratory).

Instruments and method used in the lab were as follows: Mult meter was used to measure the following; Temperature, pH, EC and TDS. Titration method was used to analyse the following; Bicarbonate, Chloride, Calcium and Magnesium. Frame Photometer was used to measure Sodium and Potassium. UV/VIS Spectrophotometer was used to measure Sulphate, Nitrate and Iron (Hatch Company, 1992).

CHAPTER 4:

4.0 Results

4.1 Physical parameters

Summary statistics of the physical and chemical parameters of water samples results are presented in Table 1 while results of the physical and chemical analysis of water samples are presented in Table 2. The pH of groundwater ranged from 6.71 to 7.12 and averaged 6.9±0.3. The pH of lake water samples was more alkaline which ranged from 8.39 to 8.78 and averaged 8.6±0.3. Stream water samples had an average pH of 7.55±0.3 and ranged from 7.35 to 7.98.

The temperature of groundwater, lake water and stream water samples ranged from 27.1 to 29.9°C, 27.4 to 27.8°C and 22.1 to 28.9 °C, respectively and averaged 28.2±0.9, 27.6±0.5 and 26.2±3.4 °C, respectively. For groundwater the EC averaged 2416±604 µS/cm and ranged from 1563 to 3496 µS/cm. For the lake water samples and stream water samples, the EC ranged from 3002 to 3576 and 870 to 950 µS/cm, respectively and averaged 3309.7±289 and 925.4±55 µS/cm, respectively. The conductance of the stream water samples might be lower than those obtained by Missi (2018) and I suggest this to be so due to time and space. I collected my samples at the middle of the rainy season when the volume of water has greatly increased resulting to low concentration of salts in the water.

The average TDS concentration for groundwater samples was 1469 ±387 mg/L and ranged from 856 to 2238 mg/L. The average TDS concentration for Lake Chilwa samples was 1947 ±189 mg/L and ranged from 1771 to 2146 mg/L. For Stream water samples, the TDS averaged 553.8±23 and ranged from 467 to 608 mg/L. Groundwater and fresh stream water samples EC and TDS results seems to be much lower than those of the Lake Chilwa water. This is because the lake is a sink without a surface outlet for all sediments from catchment rivers and run-offs (Mumba et al.,1999; Saka, 2006). However, the TDS concentration shown in table 2 is the measured TDS, which includes all the dissolved solutes contained in the water.

		pH	Temp.(°c)	EC (µS/cm)	TDS (mg/l)
GW	Min	6.71	27.1	1563	856
	Max	7.12	29.9	3496	2238
	Mean	6.9	28.2	2416.6	1469
	SD	0.14	0.88	594.6	399
LW	Min	8.39	27.4	3002	1771
	Max	8.78	27.8	3576	2146
	Mean	8.6	27.6	3309.7	1947
	SD	0.2	0.2	289.2	188.6
SW	Min	7.35	22.1	870	467
	Max	7.98	28.9	950	608
	Mean	7.55	26.2	925.4	553.8
	SD	0.25	3.1	33.1	58.4

Table 1: Summary statistics of the physical parameters of water samples. pH, temperature (°C), electrical conductivity (EC) (µS/cm) and Total Dissolved Salts (TDS). GW is groundwater, LW is lake water, SW is stream water, Minis minimum value, Max is maximum value and SD is the standard deviation.

		Na^+ (mg/l)	K^+ (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	F^- (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (mg/l)	SiC (mg
GW	Min	52.6	0.5	13.8	36.5	0.6	21.6	0.4	27.6	301	75

	Max	188	3.6	164	220	39.7	198	22.1	64	1428	114
	Mean	100.2	1.6	56.5	92.8	8.6	91.8	5	42.9	551.8	93
	SD	42.3	0.9	46.8	46.2	11.4	57.4	5.6	12.2	383	9.7
LW	Min	320.1	12.3	6.1	17.6	41.12	320.5	2.11	17.1	253	90
	Max	358	12.6	15.4	19.3	43	388	16.5	62	298	94
	Mean	338.8	12.6	9.6	18.4	42	351.4	10.9	32.4	282	92.
	SD	19	0.3	5.1	1.6	0.9	34.1	7.7	25.6	16.3	2.1
SW	Min	20.2	1.2	1.3	2.4	0.8	20.2	1.2	11.5	26.3	75
	Max	82	4.6	3.4	102	2.8	82	4.2	31	294	90
	Mean	42.8	3.6	2.4	2.7	2.1	42.8	2.04	19.4	99.8	80.
	SD	29.8	0.8	0.7	43.4	0.8	29.8	1.2	10.1	110.8	5.8

Table 2: Summary statistics of the chemical parameters of water samples. All values are in mg/L, GW is groundwater, LW is lake water, SW is stream water, Min is minimum value, Max is maximum value and SD is the standard deviation.

SampleID	**Station ID**	**pH**	**Temp.(** °c)	**EC (µs/cm at 25**°C)	**TDS (mg/l)**
Pt 1 BH	Dzinja	6.89	27.2	2953	1517
Pt 2 BH	Namthiya	6.91	27.4	2313	1240
Pt 3 BH	Thumbulu	6.93	29.9	2746	1453
Pt 4 BH	Nambwale	6.78	28.7	1941	1026
Pt 5 BH	Namuli	6.72	29.1	3496	2238
Pt 6 BH	Chambeni	7.12	28.9	3206	2053
Pt 7 BH	Nanthenga	6.86	28.6	2817	1804

Pt 8 BH	Mandawala	7.11	29.7	3060	1986
Pt 9 BH	Migowi	6.83	27.8	1765	1125
Pt 10 BH	Likapa	7.04	27.7	1563	856
Pt 11 BH	Govala	6.79	27.1	1613	1040
Pt 12 BH	Kachoka	6.89	28	2360	1512
Pt 13 BH	Pirimiti	6.94	27.4	1961	1260
Pt 14 BH	Jali police	7.11	27.9	2680	1716
Pt 15 BH	Lomoni	6.71	27.5	2201	1410
Pt 17 BH	Kumpalila	7.12	27.6	1990	1275
Pt 1 SW	L. Chilwa	8.39	27.8	3576	1771
Pt 7 SW	L. Chilwa 2	8.78	27.5	3351	2146
Pt 8 SW	L. Chilwa 3	8.65	27.4	3002	1924
Pt 2 SW	Phalombe R	7.53	28.9	920	529
Pt 3 SW	Sombani R	7.44	23.8	950	608
Pt 4 SW	Thondwe R	7.98	28.9	941	604
Pt 5 SW	Likangala R	7.45	27.4	870	561
Pt 6 SW	Domasi R	7.35	22.1	946	467

Table 3: Results of the Physical analyses of water samples from Lake Chilwa Basin

SampleID	Station ID	Na^+ (mg/l)	K^+ (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	F^- (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (mg/l)
Pt 1 BH	Dzinja	148	0.8	164	220	6.2	168	3.4	36	1428
Pt 2 BH	Namthiya	128	1.6	128	142	5.6	148	1.4	44	1120
Pt 3 BH	Thumbulu	188	2.6	132	148	2.2	198	3.2	64	1298
Pt 4 BH	Nambwale	164	0.7	92	110	1.4	198	6.1	46	640
Pt 5 BH	Namuli	96	2.2	42.3	80.5	32.2	105.1	6.9	41.7	394
Pt 6 BH	Chambeni	129.3	1.9	25.9	76.9	17.4	96.9	9.6	56.8	357
Pt 7 BH	Nanthenga	130.8	1.8	32.5	100.4	39.7	76.3	1.4	28.9	314
Pt 8 BH	Mandawala	61.8	1.9	34.1	66.4	6.1	62.7	4.9	59	326
Pt 9 BH	Migowi	82.3	1.9	13.8	68.5	1.3	47.9	1.2	59.1	325
Pt 10 BH	Likapa	92	0.6	72	118	3.4	102	1.2	54	674
Pt 11 BH	Govala	67.1	2.1	20.4	67.9	0.6	61.6	0.9	34.9	317
Pt 12 BH	Kachoka	63.4	0.5	26.8	53.1	3.1	33.6	1.8	37.4	342
Pt 13 BH	Pirimiti	52.6	1.1	33.5	68.7	1.9	45.1	0.4	37.6	301
Pt 14 BH	Jali police	77.3	0.6	25.4	36.5	5.9	55.1	11.5	30.1	314
Pt 15 BH	Lomoni	53.1	3.6	34.1	71.8	5.8	49.9	3.5	27.6	336
Pt 17 BH	Kumpalila	70.1	1.8	27.9	55.9	5.1	21.6	22.1	29.7	342

Pt 1 SW	L. Chilwa	358	12.6	15.4	18.4	41.12	388	2.11	62	298
Pt 7 SW	L. Chilwa 2	338.4	12.5	7.2	19.3	43	345.6	16.5	18.1	296
Pt 8 SW	L. Chilwa 3	320.1	12.3	6.1	17.6	41.9	320.5	14.2	17.1	253
Pt 2 SW	Phalombe R	82	3.4	3.4	42	2.8	82	4.2	30	294
Pt 3 SW	Sombani R	23.1	4.6	2.5	3.4	0.8	23.1	1.2	12.7	86.7
Pt 4 SW	Thondwe R	20.6	4.2	2.5	2.4	2.7	20.6	1.4	11.8	40.1
Pt 5 SW	Likangala R	20.2	3.2	2.3	2.7	2.3	20.2	1.6	11.5	52.1
Pt 6 SW	Domasi R	68	1.2	1.3	102	2.1	68	1.8	31	26.3

Table 4: Results of the Chemical analyses of water samples from Lake Chilwa Basin.

4.2 Chemical parameters

Among the cations, the concentrations of Na^+, K^+, $Mg^{2+}$and Ca^{2+} for groundwater ranged from 52.6 to 188, 0.5 to 3.6, 13.8 to 164 and 36.5 to 220 mg/L and averaged 100.2 ± 33.3, 1.6 ± 0.9, 56.5 ± 7.1 and 92.8 ± 25.2 mg/L, respectively. For lake water, the concentrations of Na^+, K^+, $Mg^{2+}$and Ca^{2+} ranged from 320.1 to 358, 12.3 to 12.6, 6.1 to 15.4 and 17.6 to 19.3 mg/L and averaged 338.8±9.9, 12.6±0.6, 9.6±2.3 and 18.4±2.0 mg/L, respectively. For stream water samples, the concentrations of Na^+, K^+, $Mg^{2+}$and Ca^{2+} ranged from 20.2 to 82, 1.2 to 4.6, 1.3 to 3.4 and 2.1 to 102 mg/L and averaged 42.8±11.6, 3.6±3.3, 2.4±0.6 and 2.7±0.5 mg/L, respectively. The order of abundance of the cations for the groundwater and the lake water samples is $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$, respectively. The order of abundance of the cations for the stream water samples is $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$.

The concentration of SiO2 in groundwater, lake water and stream water samples averaged 93±9.4, 92.3±1.0 and 80.8±16.0 mg/L and ranged from 75.0 to 114.0, 90.0 to 94.0 and 75.0 to 90.0 mg/L, respectively. The concentration of Na^+, K^+, F^-, Cl^-, SO_4^{2-} and SiO_2 is highest in the lake water samples than in groundwater samples and stream water samples due to same reason that Lake Chilwa is a sink with no outlet (Saka, 2006).

CHAPTER 5

5.0 DISCUSSION

5.1 Water quality and surface water

Water quality was determined upon specific standards depending upon its suitability for different purpose. The table 5 below show the drinking water standards (Table 3) of the WHO (2008) and the Malawi Bureau of Standards (MBS) (MBS, 2005) was the basis for the water quality evaluation.

Constituent	**Unit**	**WHO Guideline**	**MBS Guideline**
Total Dissolved Solid (TDS)	mg/L	1000	1000
Sodium	mg/L	Not stated	200
Potassium	mg/L	10	10
Magnesium	mg/L	150	150
Calcium	mg/L	200	200
Flouride	mg/L	1.5	2
Chloride	mg/L	250	250
Nitrate	mg/L	50	50
Sulfate	mg/L	400	400

Bicarbonate	mg/L	300	Not stated

Table 5: Water Quality Standards. World Health Organization (WHO) Drinking Water Guidelines (WHO, 2008) and Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005).

The pH of lake water and stream water with the means of 8.6±0.2 and 7.55±0.2, respectively indicates that the lake water and surface water are alkaline and pH values of groundwater in the Lake Chilwa Basin averaged 6.9±0.2 which indicates slightly acidic. The pH values of the water in the Lake Chilwa Basin are within the maximum permissible limit of 6 to 9 as prescribed for drinking water by WHO (2008) and MBS (2005).

Missi (2018) and Saka (2006) reported that electrical conductivity(EC) is strongly correlated with sodium ions and the major ions in Lake Chilwa are sodium, chloride and bicarbonates. The latter is responsible for the alkaline pH of the water (8-9). TDS for groundwater, lake water and stream water in the Lake Chilwa Basin range from 467 to 2238 mg/L. As per TDS classification, groundwater and lake water is distasteful (TDS >1000 mg/L) water type except Likapa borehole which has the TDS of 856 mg/l, whereas streams have fresh water type with TDS < 1000 mg/L (Freeze and Cherry, 1979). All the groundwater and lake water samples of the Lake Chilwa Basin exceed the prescribed limit of 1000 mg/L (Figure 5) except Likapa borehole, based on the TDS concentration allowed for drinking water. Stream water samples are below the MPL. High TDS concentrations decreases palatability of water and causes gastrointestinal irritation to consumers (Garg et al., 2009 and Missi, 2018).

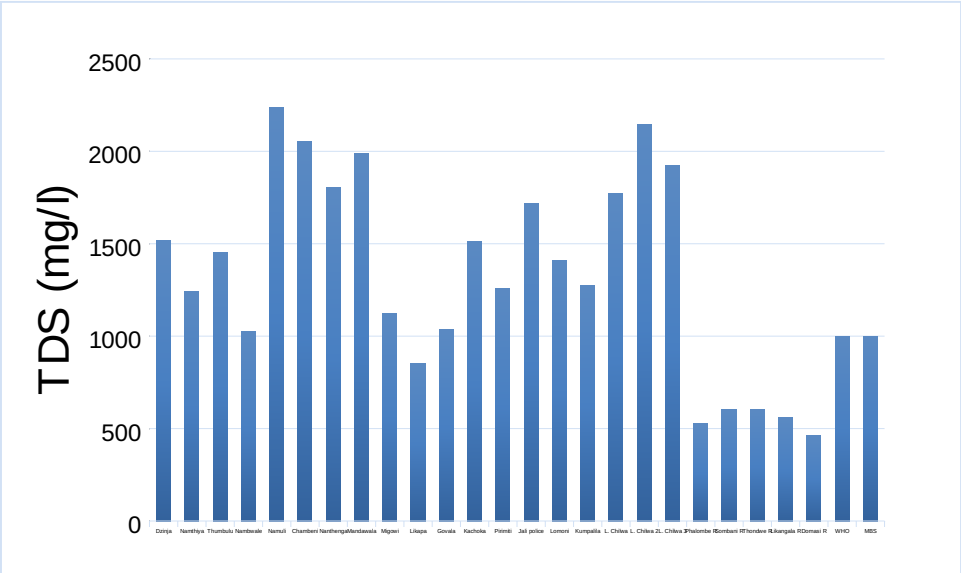
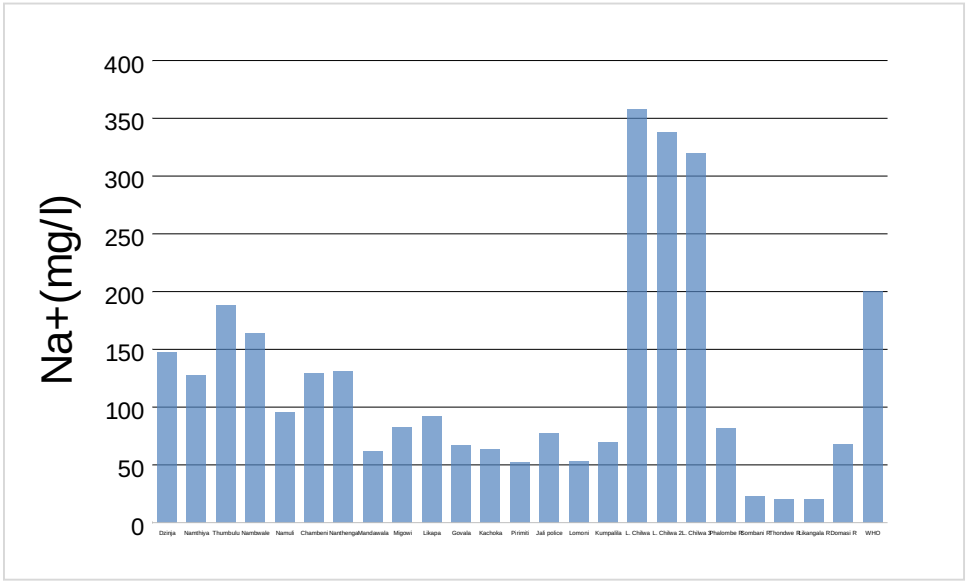


Figure 5. Plot of concentrations of total dissolved solids (TDS) for groundwater and surface water in the Lake Chilwa Basin. Also shown on the plot are the bars representing World Health Organization (WHO) and Malawi Bureau of Standards (MBS) maximum permissible

According to WHO (2008) and MBS (2005) guidelines, MPL for Na^+ in drinking water is 200 mg/L. Sodium concentrations in all the groundwater and stream water samples are below the MPL and the concentrations of Na^+ in the lake water samples exceed the MPL (Figure 6). This is consistent with earlier findings (Saka, 2006 and Missi, 2018). However, Na^+ concentrations are found to be higher than any other cations (Ca^{2+}, Mg^{2+} and K^+) in most samples. The cations Na^+, Ca^{2+}, Mg^{2+} and K^+ are significant constituents of silicate rocks (Freeze and Cherry, 1979) and hence Na+ in groundwater in the Lake Chilwa Basin is considered to originate from silicate (albite) weathering. A secondary source of Na^+ is halite, concentrated in the soil zone by evaporation and leached into the groundwater by infiltrating rain. Elevated Na^+ concentrations maybe due to dissolution of sodium bicarbonate or albite. Another possible reason for the higher Na^+ concentration could be cation exchange where Ca^{2+} from groundwater is adsorbed on clay materials in exchange of Na^+. Excess Na^+ water makes water unsuitable for drinking because it causes severe health problems like hypertension (Holden, 1970). The concentration of K^+ in groundwater and stream water samples is less than 10 mg/L which is the MPL as per WHO (2008) and MBS (2005). However, the concentration of K^+ in lake waters exceeds the MPL of 10 mg/L (Figure 6b). The low levels of K^+ in groundwater could be the consequence of its tendency to be retained in clay minerals and to contribute in the formation of secondary minerals (Zhu and Zhang, 2007). Micas (muscovite and biotite) are major constituents of the sediments / volcanic clastic sediment in the area and therefore responsible for K^+ in the groundwater.

a)



b)

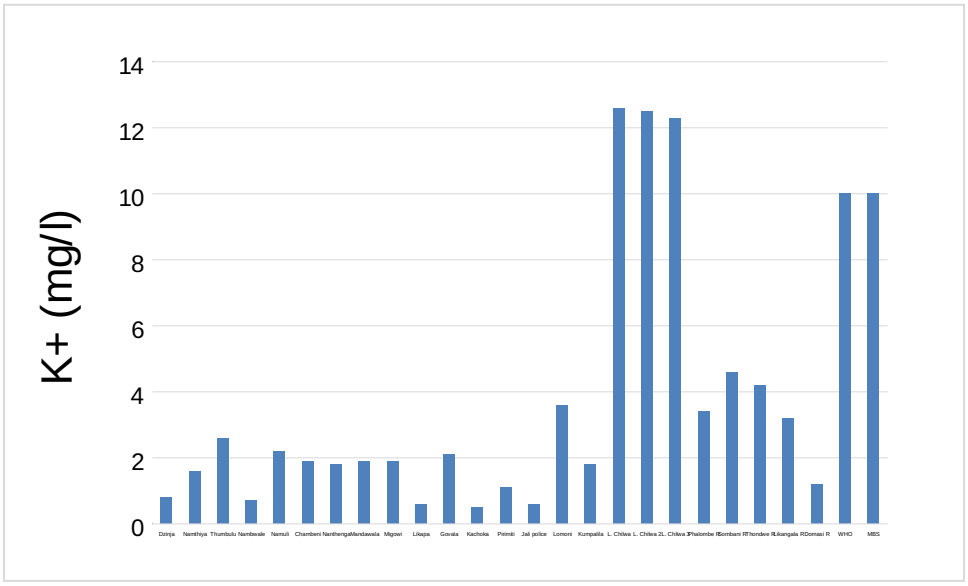


Figure 6: Plots of concentrations of cations (a) Na+ and (b) K+ for groundwater and

surface water in the Lake Chilwa Basin. Also shown on the plot are bars representing World Health

The concentration of Mg^{2+} in groundwater, lake water and stream water ranges from 1.3 to 42.1 mg/L and are within the prescribed limit for drinking water specified as 150 mg/L (WHO, 2008; MBS, 2005). The Mg^{2+}in groundwater probably comes from biotite [$K(Mg,Fe)_3(AlSi_3)O_{10}(OH,F)_2$] and hornblende [$Ca_2(MgFeAl)_5(AlSi)8O_{22}$], which are constituents of the aquifers in the study area. All groundwater samples, lake water samples and stream water samples have Ca^{2+} concentrations below the MPL of 200 mg/L as prescribed by WHO (2008). The Ca-feldspars (anorthite) ($CaAl_2Si_2O_8$) are considered the main source of calcium, releasing Ca^{2+} in the presence of carbonic acid (H_2CO_3) generated in the soil zone. Other possible sources of Ca^{2+} in the groundwaters include dissolution of the mineral hornblende and pyroxenes (Ganyaglo et al., 2017)

Fluoride may be an essential element for humans (WHO, 2004). Deficiency in drinking water (<0.5 mg/L) leads to dental caries (Edmunds and Smedley, 1996). High intake (>1.5 mg/L) results in physiological disorders, skeletal and dental fluorosis (Latha et al., 1999). Fourteen groundwater samples, all lake water samples and four stream water samples have F^- concentrations that exceed the permissible limit of 1.5 mg/L and 2 mg/L as prescribed by WHO (2008) and MBS (2005), respectively as shown in figure 7(a). Brunt et al. (2004) found that due to the Precambrian basement of the area, there is a possibility that occurrence of alkaline granites may lead to a high fluoride concentration in the groundwater due to weathering. With this in mind and the fact that the minerals fluorite and apatite found around the study site (Carter and Bennett, 1973) fluoride was expected to be found in elevated levels in the groundwater.

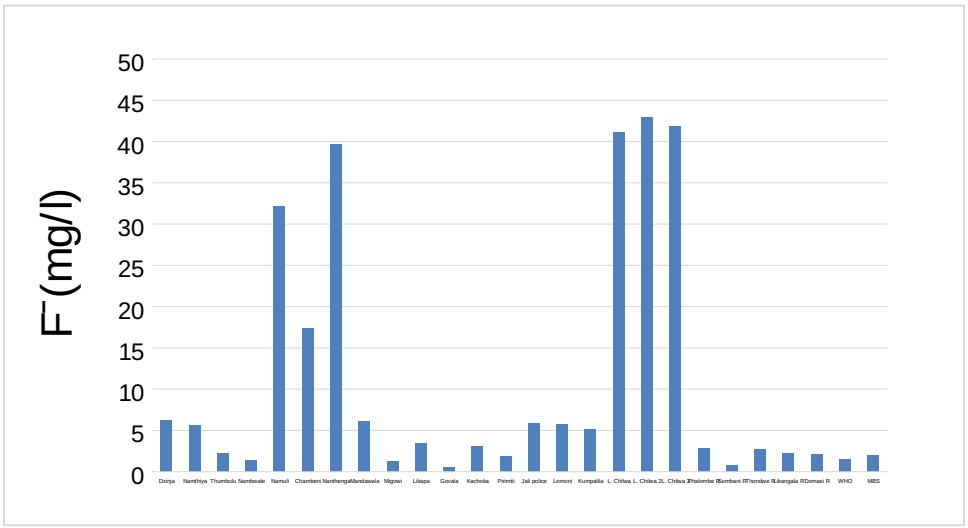
Chloride is considered an important inorganic ion, which deteriorate the quality of drinking water (McCarthy, 2004). High concentrations of Cl^- in drinking water causes a salty taste and has a laxative effect to people not accustomed to it (Bhardwaj and Singh, 2010). Generally, Cl^- is not a significant constituent of silicate rocks. The presence of Cl- in groundwater and surface water is usually attributed to atmospheric sources, decomposition of organic matter and trace impurities in rocks and minerals (Freeze and Cherry, 1979). All the lake water samples exceeded the MPL of Cl^- for drinking water which is specified at 250 mg/L as per WHO (2008) and MBS (2005) (Figure 6b). All groundwater and stream water samples are below the MPL for Cl^- as specified by WHO (2008).

All groundwater, stream water and lake water samples have NO_3^- concentration below the WHO (20

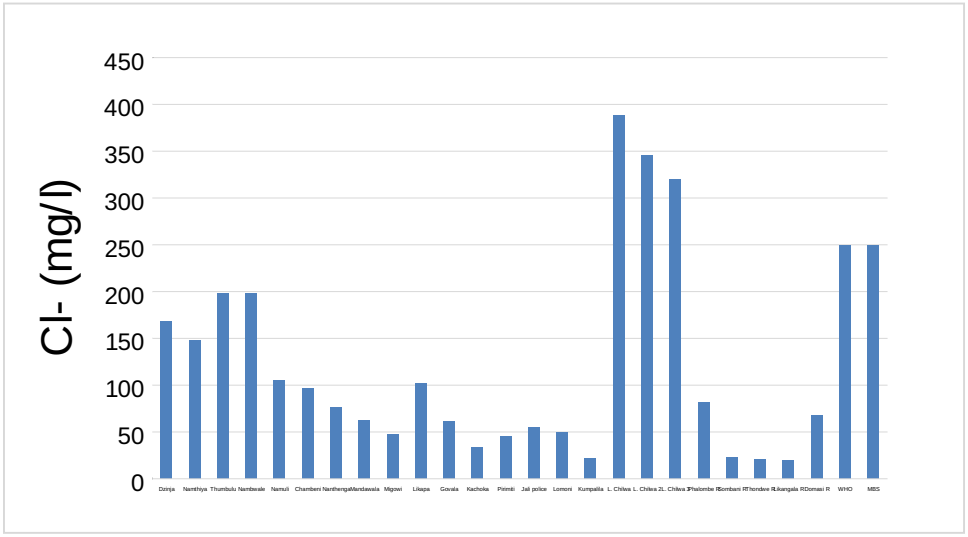
The concentration of SO_4^{2-} is below the MPL of 400 mg/L specified by the WHO (2008) and by MBS (2005) in all the groundwater, lake water and stream water samples. Like Cl^-, SO_4^{2-} is not a major constituent of silicate rocks. The presence of SO_4^{2-} in the aquifer may be explained by the oxidation of pyrite found in the rocks of the area. Higher concentration of SO_4^{2-} in drinking water is associated with respiratory problems (Subba-Rao, 1993).

Bicarbonate (HCO_3^-) is the dominant anion in the study area. Almost all groundwater samples have HCO_3^- concentration exceeding the prescribed limit of 300 mg/L in the drinking water (WHO, 2008) (Figure 6d). All the stream water samples and lake water samples have HCO_3^- concentrations below the MPL of the WHO (2008) standard.

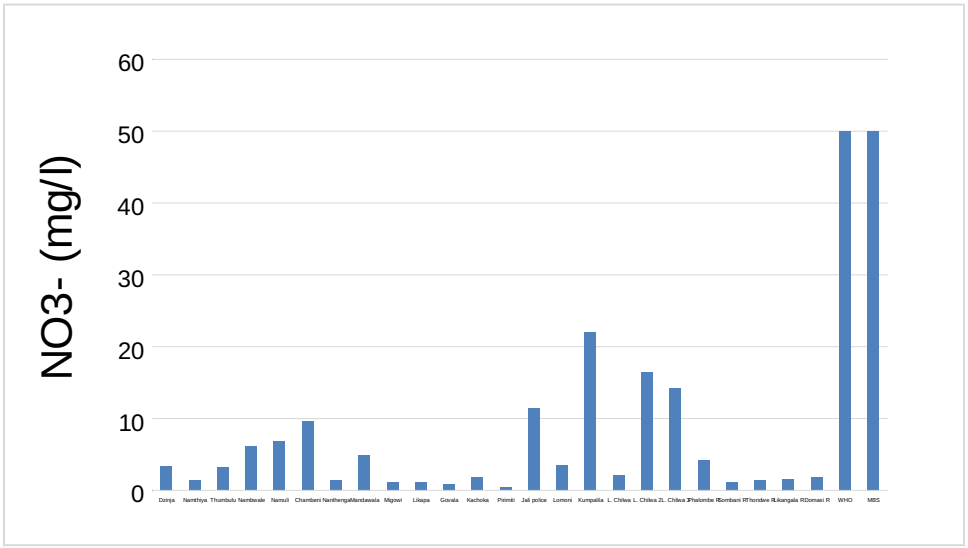
a)



b)


Cl- (mg/l)
450
400
350
300
250
200
150
100
50
0
Dzinja
Namthiya
Thumbulu
Nambwale
Namuli
Chambeni
Nanthenga
Mandawala
Migowi
Likapa
Govala
Kachoka
Pirimbi
Jali police
Lomoni
Kumpalila
L. Chilwa
L. Chilwa 2
L. Chilwa 3
Thalombe R
Bombani RT
Thondwe R
Lukangala R
Domasi R
WHO
MBS

c)


NO3- (mg/l)
60
50
40
30
20
10
0
Dzinja
Namthiya
Thumbulu
Nambwale
Namuli
Chambeni
Nanthenga
Mandawala
Migowi
Likapa
Govala
Kachoka
Pirimbi
Jali police
Lomoni
Kumpalila
L. Chilwa
L. Chilwa 2
L. Chilwa 3
Thalombe R
Bombani RT
Thondwe R
Lukangala R
Domasi R
WHO
MBS

d)

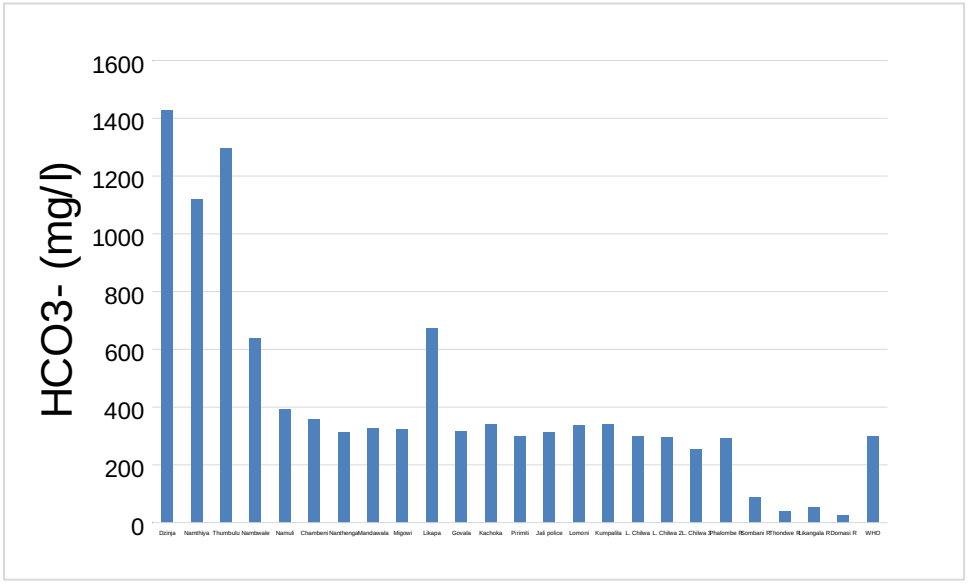


Figure 7: Plots of concentrations of (a) F- (b) Cl-, (c) NO3-, and (d) HCO3- for groundwater and surface water in the Lake Chilwa Basin. Also shown on the plots are bars representing World Health Organization (WHO) maximum permissible concentrations in drinking water (WHO, 2008).

5.2 Ionic evolution of groundwater and surface waters

The piper diagram (Figure 8) shows the relative proportions of cations and anions of three distinct water types shown in grouping. The water types have facies of: (A) Na+K-HCO3, (B) Na+K-Cl, and (C) Ca-Mg-Na+K-HCO3-Cl. Water type A consists of all stream water samples and show a range of 70 to nearly 90% Na+K and the anions are predominantly HCO_3 > 80%. Watertype B consists of lake water and have Na + K between 90 and 100% and anion facies dominated by Cl of 60 to 70%. Watertype C consists of groundwater and is a mixed cation and mixed anion facies and has Ca^{2+}, Mg^{2+}, Na^{+} + K^{+} in the cation facies and mainly HCO_3^{-} and Cl^{-} in the anion faces. The cation faces have the following composition: 40 to 80% Ca, 10 to 35% Mg and 30 to 50% Na + K, whereas, the composition of the anion facies is 60 to nearly 90% HCO_3 and 10 to 40% Cl.

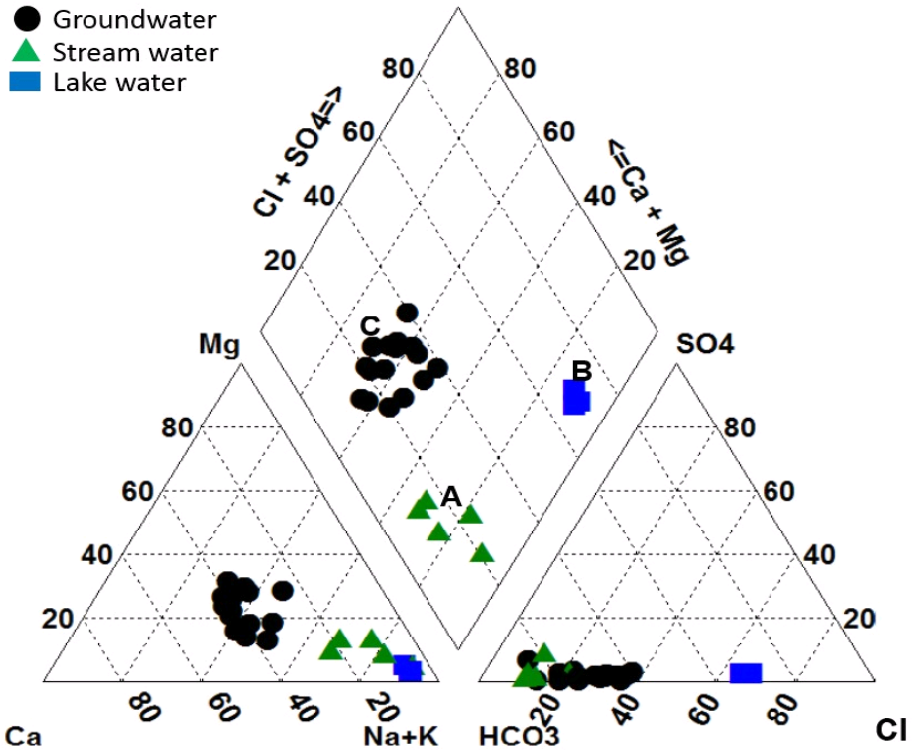


Figure 8: Piper plot showing ionic proportions for groundwater and surface water in the Lake Chilwa Basin.

CHAPTER 6

6.0 Conclusions

Water-rock interaction involving weathering of silicates control the major ions such as calcium, sodium and magnesium in groundwater, whereas, evaporation is the dominant factor leading to poor water quality in the water from Lake Chilwa. The pH are slightly acidic, but mostly alkaline in nature. The major processes controlling the water quality in the Lake Chilwa Basin varies in relation to the type of water reservoir.

Bicarbonate (HCO_3^-) is the dominant anion in the study area. Almost all groundwater samples have HCO_3^- concentration exceeding the prescribed limit of 300 mg/L in drinking water (WHO, 2008). The occurrence of Ca2+ and HCO_3^- in groundwater causes the salty condition. The most common salt of bicarbonate is calcium bicarbonate ($Ca(HCO_3)_2$). In particular, $Ca(HCO_3)_2$ contributes to TDS, a common parameter for assessing water quality. Lake Chilwa waters are mostly classified as sodium chloride whereas stream waters are sodium bicarbonate. Elevated Na+ concentrations may be due to evaporation and probably cation exchange where Ca2+ is adsorbed on clay minerals in exchange for Na+.

Notable characteristics of the water include high EC and high concentrations of TDS, HCO_3^-, Cl^-, F^- and Ca^{2+} in groundwater and lake water. Failure of these parameters (e.g., TDS, HCO_3^-, Cl^-, F^- and Ca^{2+}) to comply with the WHO or MBS guidelines standards for drinking water signify that the some of the groundwater and lake water are of poor quality and unacceptable for human consumption without treatment.

Therefore, in general, the groundwater geochemistry of the Lake Chilwa Basin is principally controlled by water-rock interaction involving dissolution and precipitation of minerals, whereas, that of surface water, especially Lake Chilwa is controlled by evaporation and cation exchange.

REFERENCES

- Atekwana, E.A. & Krishnamurthy, R.V., (1998). *"Seasonal variations of*

dissolved inorganic carbon and δ13C of surface waters: application of a modified gas evolu

- Atekwana, E.A. & Richardson, D.S., (2004). "*Geochemical and isotopic evidence of a groundwater source in the Corral Canyon meadow complex, central Nevada, USA. Hydrological Processes,"* 18(15), pp.2801-2815.
- Atekwana, E.A. & Seeger, E.J., (2015). "*Carbonate and carbon isotopic evolution of groundwater contaminated by produced water brine with hydrocarbons. Applied Geochemistry*," 63, pp.105-115.
- Bath, A.H., (1980). "*Hydrochemistry in groundwater development*: *report on an advisory visit to Malawi, British Geological Survey Report,"* WD/OS/80/20
- Carter, GS. & Bennett, JD., (1973). *The geology and mineral resources of Malawi.* Geological Survey Department Bulletin, Zomba, Malawi 6, 1-62.
- Chapman, D., 1992. "*Water quality assessment; A Guide to the use of Biota sediments and water in Environmental Monitoring"*. University Press, Cambridge.
- Chavula, G., & Mulwafu, W. (2007). "*Hazardous water: an assessment of water quality and accessibility in the Likangala Catchment area in Malawi*". Malawi Journal of Science and Technology, 8(1), 30-41.
- Chidya, R. C. G., Sajidu, S. M. I., Mwatseteza, J. F., & Masamba, W. R. L. (2011). "*Evaluation and assessment of water quality in Likangala River and its catchment area*". Physics and Chemistry of the Earth, Parts A/B/C, 36(14-15), 865-871.
- Chilton, P. J., & Smith-Carington, A. K. (1984). "*Characteristics of the weathered basement aquifer in Malawi in relation to rural water supplies*" (pp. 57-65). IAHS Press.
- Chimphamba, J., Ngongondo, C. and Mleta, P., 2009. "*Groundwater chemistry of basement aquifers: A case study of Malawi*". The Basement Aquifers of Southern Africa, p.39.
- Clark, I. D. (1997). "*Tracing the hydrological cycle*". Environmental isotopes in hydrogeology, 35-61.
- Compton, J. S. (1988). "*Degree of supersaturation and precipitation of organogenic dolomite*". Geology, 16(4), 318-321.
- Craig, H. (1961). "*Isotopic variations in meteoric waters"*. Science, 133(3465),

1702-1703.

- Deutsch, W.J. and Siegel, R., (1997). "*Groundwater geochemistry: fundamentals and applications to contamination*". CRC press.
- Drever, J.I., (1997). "*The Geochemistry of Natural Waters: Surface and Groundwater Environments*". Prentice Hall. Eaglewood Cliffs, New Jersy, USA.
- Ebrahimi, P. and Vilcáez, J., (2018). "*Effect of brine salinity and guar gum on the transport of barium through dolomite rocks: Implications for unconventional oil and gas wastewater disposal"*. Journal of environmental management, 214, pp.370-378.
- Ebrahimi, P. and Vilcáez, J., (2018). "*Petroleum produced water disposal: Mobility and transport of barium in sandstone and dolomite rocks"*. Science of The Total Environment, 634, pp.1054-1063.
- Ebrahimi, P. and Vilcáez, J., (2018). *Effect of brine salinity and guar gum on the transport of barium through dolomite rocks: Implications for unconventional oil and gas wastewater disposal.* Journal of environmental management, 214, pp.370-378.
- Edmunds, M., Smedley, P., (2005). "*Essentials of medical geology*". Elseveiser Inc. Chapter 12, Oxford: BGS, NERC.
- Edmunds, W.M., Savage, D., (1991). "*Geochemical characteristics of groundwater in granites and related crystalline rocks*". In Downing, R.A., Wilkinson, W.B. (Eds) Applied groundwater Hydrology, a British Perspective, 199-216. Clarendon Press, Oxford, U.K.
- Freeze, R.A., Cherry, J.A., (1979). "*Groundwater*". Prentice Hall, Englewood Cliffs.
- GARRELS, R.M., (1967). "*Genesis of some ground waters from igneous rocks*". Researches in geochemistry, 2, pp.405-420.
- Garson, MS., (1960). "*The geology of Lake Chilwa area"*. Geological Survey Department Bulletin, Zomba, Malawi 12.
- Gat, J.R. and Tzur, Y., (1968). "*Modification of the isotopic composition of rainwater by processes which occur before groundwater recharge*". Weizmann Inst. of Science, Rehovoth, Israel.
- Gibbs, R.J., (1970). "*Mechanisms controlling world water chemistry*". Science,

170(3962), pp.1088-1090.

- Jalali, M., (2006). "*Chemical characteristics of groundwater in parts of mountainous region, Alvand, Hamadan, Iran".* Environmental Geology, 51(3), pp.433-446.
- Kramer JR., (1968). "*Mineral-water equilibria in silicate weathering*". In: Kantor J (ed) Rep XXIII Int+Geol Congr, Prague, Czechoslovakia, 6:149-160.
- Lancaster, N., (1979). "*The physical environment of Lake Chilwa*". In Lake Chilwa (pp. 17-40). Springer, Dordrecht.
- Macuiane, M.A., Kaunda, E.K. and Jamu, D., (2011). "*Seasonal dynamics of physico-chemical characteristics and biological responses of Lake Chilwa, southern Africa*". Journal of Great Lakes Research, 37, pp.75-82.
- Malawi Bureau of Standards (MBS, 2005b) Malawi standard; drinking water-specifications. Malawi Standards Board. MS 214:2005. ICS 13.030.40 (first revision).
- Mapoma, H.W. and Xie, X., (2014). "*Basement and alluvial aquifers of Malawi: An overview of groundwater quality and policies*". African Journal of Environmental Science and Technology, 8(3), pp.190-202.
- Marfia, A.M., Krishnamurthy, R.V., Atekwana, E.A. and Panton, W.F., (2004). " *Isotopic and geochemical evolution of ground and surface waters in a karst dominated geological setting: a case study from Belize, Central America*". Applied Geochemistry, 19(6), pp.937-946.
- Markl, G. and Bucher, K., (1997). "*Reduction of Cu^{2+} in mine waters by hydrolysis of ferrous sheet silicates*". European Journal of Mineralogy, pp.1227-1236.
- Mast, M.A., Drever, J.I. and Baron, J., (1990). "*Chemical weathering in the Loch Vale watershed, Rocky Mountain National Park, Colorado"*. Water Resources Research, 26(12), pp.2971-2978.
- Mathess G., (1982). "*The properties of groundwater"*. Wiley, New York.
- McCarthy, T.S. and Ellery, W.N., (1994). *"The effect of vegetation on soil and ground water chemistry and hydrology of islands in the seasonal swamps of the Okavango Fan, Botswana*". Journal of Hydrology, 154(1-4), pp.169-193.
- McFarlane, M.J. and Bowden, D.J., (1992). "*Mobilization of aluminium in the*

wathering profiles of the African surface in Malawi". Earth Surface Processes and Landform

- Meybeck, M., (1987). "*Global chemical weathering of surficial rocks estimated from river dissolved loads"*. American journal of science, 287(5), pp.401-428.
- Missi, C., (2018). "*Physical, chemical and isotopic characteristics of groundwater and surface water in the lake Chilwa basin, Malawi".* Pp. 24-31.
- Mkandawire, T., (2008). "*Quality of groundwater from shallow wells of selected villages in Blantyre District, Malawi*". Physics and Chemistry of the Earth, Parts A/B/C, 33(8-13), pp.807-811.
- Monjerezi, M., Vogt, R.D., Aagaard, P. and Saka, J.D., (2011). "*Hydro-geochemical processes in an area with saline groundwater in lower Shire River valley, Malawi: an integrated application of hierarchical cluster and principal component analyses*". Applied Geochemistry, 26(8), pp.1399-1413.
- Njaya, FJ., (2001). "*Review of management measures for Lake Chilwa, Malawi: Final report 2001*". United Nations University fisheries training programme, Iceland.
- Petrides, B. and Cartwright, I., (2006). "*The hydrogeology and hydrogeochemistry of the Barwon Downs Graben aquifer, southwestern Victoria, Australia*". Hydrogeology Journal, 14(5), pp.809-826.
- Rajmohan, N. and Elango, L., (2004). "*Identification and evolution of hydrogeochemical processes in the groundwater environment in an area of the Palar and Cheyyar River Basins, Southern India*". Environmental Geology, 46(1), pp.47-61.
- Sajidu, S.M., Masumbu, F.F., Fabiano, E. and Ngongondo, C., (2007). "*Drinking water quality and identification of fluoritic areas in Machinga, Malawi*". Malawi Journal of Science and Technology, 8(1), pp.42-56.
- Saka, J.K., (2006). "*A chemical study of surface and groundwater in the Lake Chilwa Basin, Malawi"*. Groundwater Pollution in Africa, p.229.
- Stallard, RF., Edmond, JM., (1987). "*Geochemistry of the Amazon 3. Weathering chemistry and limits to dissolved inputs*". J Geophys Res 92: 8293-8302.
- Subba Rao, N., (1998). "*Groundwater quality in crystalline terrain of Guntur district, Andhra Pradesh*". Visakha Sci J, 2(1), pp.51-54.

- Subramani, T., Elango, L. and Damodarasamy, S.R., (2005). "*Groundwater quality and its s*
- Swanzie, A., Stubbs, M., (1972). "*Malawi in maps. Hodder & Stoughton Ltd.Smith-Carington, AK., Chilton, PJ., 1983*". Groundwater resources of Malawi. Departments of Lands, Valuation and Water; Republic of Malawi, Lilongwe.
- Todd, D., (1980). "*Groundwater Hydrology, 2nd edition*". Wiley, Newyork.
- Von Hellens, A., (2013). "*Groundwater quality of Malawi–fluoride and nitrate of the Zomba-Phalombe plain"*. First Cycle, G2E. Dept. of Soil and Environment. Uppsala, Sweden: Swedish University of Agricultural Sciences.
- Wanda, E.M., Gulula, L.C. and Phiri, A., (2013). "*Hydrochemical assessment of groundwater used for irrigation in Rumphi and Karonga districts, Northern Malawi*". Physics and Chemistry of the Earth, Parts A/B/C, 66, pp.51-59.
- World Health Organization, (1996). "*Guidelines for drinking-water quality*". Vol. 2, Health criteria and other supporting information.