

**MAPPING THE EXTENT OF WATER SALINITY IN THE SHORELINE
AQUIFERS: LAKE CHILWA BASIN, MALAWI**

**MASTER OF SCIENCE IN WATER RESOURCES MODELLING AND
GOVERNANCE**

TRYNESS BANDA

UNIVERSITY OF MALAWI

September, 2022



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GOVERNANCE**

**By
TRYNESS BANDA**

Submitted in partial fulfilment for the degree of Master of Science Water Resources
Modelling and Governance

University of Malawi

September, 2022

DECLARATION

I declare that except where references are made, this thesis is my original work and has not been presented for any other award at this or any other university.

Full name

Signature

Date

CERTIFICATE OF APPROVAL

The undersigned certifies that this thesis represents the student's own work and effort and has been submitted with our approval.

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DEDICATION

To my husband

To my mother

You are a blessing

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ABSTRACT

There is a dynamic interface between fresh groundwater and saline ocean water in coastal regions worldwide, known as the fresh-saltwater interface, where salt and freshwater mix caused by natural and anthropogenic activities. The interface migrates inland in a saltwater intrusion process, which further results in salinization and can have significant economic and ecological impacts. This study has employed geophysical and geochemical techniques to map the extent of salinization of the shoreline aquifers of Kachulu. The geophysical data acquisition and processing of 2D ERT (Electrical resistivity Tomography) was performed using ABEM SAS 4000 and RES2DINV software using a Wenner electrode configuration array. The geophysical survey successfully delineated aquifers with various resistivity values related to recharge and migration processes, including saltwater intrusion in the basin. Evidence from the geochemical study of boreholes and the lake water samples corroborated the ERT result. Elevated EC, turbidity, *pH*, TDS levels and other chemical parameters measured from the sampled boreholes showed that the salt impairs the inland aquifers through various sources. This study successfully mapped the areas of freshwater aquifers and the extent of the salinity in the aquifers of Kachulu, contributing to sustainable future decisions, planning, and development in the study area.

TABLE OF CONTENTS

ABSTRACT.....	vi
LIST OF TABLES	xi
LIST OF FIGURES	xii
LIST OF ABBREVIATIONS	xiv
GLOSSARY OF TERMS.....	xv
CHAPTER ONE	1
INTRODUCTION.....	1
1.1 Background.....	1
1.2 Statement of the Problem	7
1.3 Main Objective	7
1.3.1 Specific Objectives	8
1.4 Significance of the study	8
1.5 Problems and Limitations	9
1.6 Organisation of the thesis	9
CHAPTER TWO	10
LITERATURE REVIEW	10
2.1 Overview of groundwater salinization	10
2.2 Salinization sources	11
2.2.1 Halite dissolution.....	11

2.2.2 Saltwater intrusion	13
2.2.3 Evaporation at or near the land surface	13
2.2.4 Connate saline groundwater	14
2.2.5 Agriculture sources	15
2.2.6 Oil and gas brines	16
2.2.7 Road salts.....	17
2.3 Methods of identifying the salinity and sources of salinization	18
2.3.1 Electrical Resistivity method.....	18
2.3.2 Geochemical methods.....	30
2.3.3 A combination of Geophysical and Geochemical methods.....	33
2.3.4 Common indicators of seawater intrusions	35
2.4 Chemical interactions of groundwater and surface water in streams, lakes and wetlands.....	43
2.5 Summary of the Literature Review	46
CHAPTER THREE	48
METHODOLOGY	48
3.1 Study area	48
3.1.1 Location, Rainfall and Population size	48
3.1.2 Geology	50
3.1.3 Groundwater of lake Chilwa.....	50

3.2 Data collection and analysis	52
3.2.1 Geoelectrical resistivity data collection.....	52
3.2.2 Geoelectrical Resistivity Data Processing and interpretation.....	55
3.2.3 Geochemical data	57
3.2.4 Temperature, pH, EC and TDS	58
3.2.5 Sulphates, Nitrates	58
3.2.6 Fluoride.....	59
3.2.7 Metals (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Fe^{2+}).....	59
3.2.8 Turbidity	59
3.2 Summary of the Methodology.....	60
CHAPTER FOUR.....	61
RESULTS AND DISCUSSIONS	61
4.1 Geophysical data	61
4.2 Hydrogeochemical data	66
4.2.1 pH	67
4.2.2 TDS and EC.....	71
4.2.3 Turbidity	75
4.2.4 Cations (Na^+ , Ca^{2+} , Mg^{2+} and K^+)	76
4.2.5 Anions (SO_4^{2-} NO_3^- Cl^- F^- , HCO_3^- , CO_3^{2-} , PO_4^{2-}).....	78
4.3 Summary of Results and Discussion.....	80

CHAPTER FIVE	82
CONCLUSIONS	82
CHAPTER SIX	84
RECOMMENDATIONS.....	84
REFERENCE	86

LIST OF TABLES

Table 1: The resistivity of some rocks, minerals, and chemicals (Keller and Frischknecht, 1966)	21
Table 2: Interpretation of subsurface materials in the study area (Hezreek et al., 2018)	26
Table 3: Resistivity and conductivity value of selected soils and water (Hazreek et al., 2018)	57
Table 4: Interpretation of subsurface materials of the study area	62
Table 6 Summary statistics of the physical and chemical compositions for groundwater samples. All values are in mg/L except pH, temperature (°C), and electrical conductivity (EC) (µS/cm). Minis is the minimum value, Max is the maximum value, and SD is the standard deviation	69
Table 7: Results of the physical and chemical analyses of the groundwater and Lake Chilwa samples, Quality Standards for the World Health Organization (WHO) Drinking Water Guidelines (WHO, 2008) and Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005)	70

LIST OF FIGURES

Figure 1. Illustration of the freshwater-saltwater interface. On islands, the freshwater lens is surrounded by saltwater; Figure 1b: Illustration of the freshwater-saltwater circulation after groundwater extraction Klassen et al. 2014(a) and Lyles, 2000(b) ..	2
Figure 2. The evolution and mixing of pristine water to saline water (Panno et al., 2006). ..	40
Figure 3. A plot of chloride vs electrical conductivity illustrating Saltwater intrusion, normal groundwater conditions and mixing between the two (Washington State Department of Ecology, 2005) ..	41
Figure 4: A Piper plot showing five water families; (1) $\text{Na}^{2+}\text{-HCO}_3^-$ (2) $\text{Na}^{2+}\text{-Cl}^-$ (3) $\text{Ca}^{2+}\text{-Cl}^-$ (4) $\text{Ca}^{2+}\text{-HCO}_3^-$, and (5) $\text{Na}^+\text{-SO}_4^{2-}$ (Steinich et al., 1998).....	42
Figure 5: TDS variation with depth relative to sea level for water samples on Saturna Island, British Columbia (Allen and Liteanu, 2008) ..	43
Figure 6: Map of Malawi showing the location of the study area and the areas of freshwater. The map shows lake chilwa and groundwater sampling locations. Shapefiles provided by Geological Survey Department, Malawi ..	49
Figure 7: The study flow chart.....	52
Figure 8: ABEM Terrameter 1000 ..	54
Figure 9: Schematic layout for conducting long profiles (the roll along with method) ..	55
Figure 10: combined-long and short protocol (ABEM, 2007) ..	55

Figure 11: (a and b) shows the Earth Imager Resistivity Depth inverse model for the Electrical Resistivity Tomography (ERT) for profile one and two (Note: Lake was located at 0 m of the ERT).....	63
Figure 12: Map of Malawi showing the distribution of pH in the groundwater samples. Shapefiles provided by Geological Survey Department, Malawi.....	68
Figure 13: Plot of total dissolved solids (TDS) concentrations and EC for Groundwater and Lake Water. The plot is also a line representing the Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005).....	73
Figure 14: Colour of water at Nyangu Borehole	75
Figure 15: Plot of Turbidity. The plot is also a line representing the Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005).....	76
Figure 16: Plots of concentrations of cations (a) Na ⁺ and (b) K ⁺ for Groundwater and Lake Water. The plot is also a line representing the Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005).....	77
Figure 17: Plots of concentrations of Anions for groundwater and Lake Water. Also shown on the plots are lines representing the World Health Organization (WHO) maximum permissible concentration.	79

LIST OF ABBREVIATIONS

ERT	Electrical Resistivity Tomography
EC	Electrical Conductivity
GOM	Government of Malawi
GIS	Geographical Informational Systems
GPS	Geographical Positioning System
MBS	Malawi Bureau of Standards
SWI	Salt Water Intrusion
TDS	Total Dissolved Solutes
VES	Vertical Electrical Soundings
WHO	World Health Organization

GLOSSARY OF TERMS

Saltwater intrusion	is the movement of saline water into freshwater aquifers, which can lead to groundwater quality degradation, including drinking water sources and other consequences
Geophysical survey	is archaeological methods that use ground-based physical sensing. Techniques to produce a detailed image or map of an area
Resistivity	is the electrical resistance of a conductor of unit cross-sectional area and unit length

CHAPTER ONE

INTRODUCTION

1.1 Background

There is a dynamic interface between fresh groundwater and saline ocean water in coastal regions worldwide (Goebel et al., 2019), referred to as the fresh-saltwater interface (Barlow, 2013). This boundary between salt and fresh water is not distinct; the zone of dispersion, transition zone, or saltwater interface is brackish with salt and freshwater mixing (Nwankwoala, 2011). It may be sharp and characterized by an abrupt transition from fresh to saltwater. However, more commonly, it is transitional due to mixing and diffusion processes (Barlow, 2013).

Mostly, the fresh/saltwater interface position depends on the magnitude of freshwater discharge, which responds to climatic variation by moving seaward if the hydraulic gradient increases or moving landward if the hydraulic gradient decreases (Bear et al., 1999). Bear et al. (1999) further explain that the dense saltwater circulates inland, creating a saline zone or "wedge" below the less dense overlying freshwater aquifer (Figure 1a). Under natural conditions, fresh groundwater flows toward the ocean, and its flow is predominantly driven by topography but is influenced by the aquifer's hydraulic conductivity (Figure 1b; Lyles, 2000).

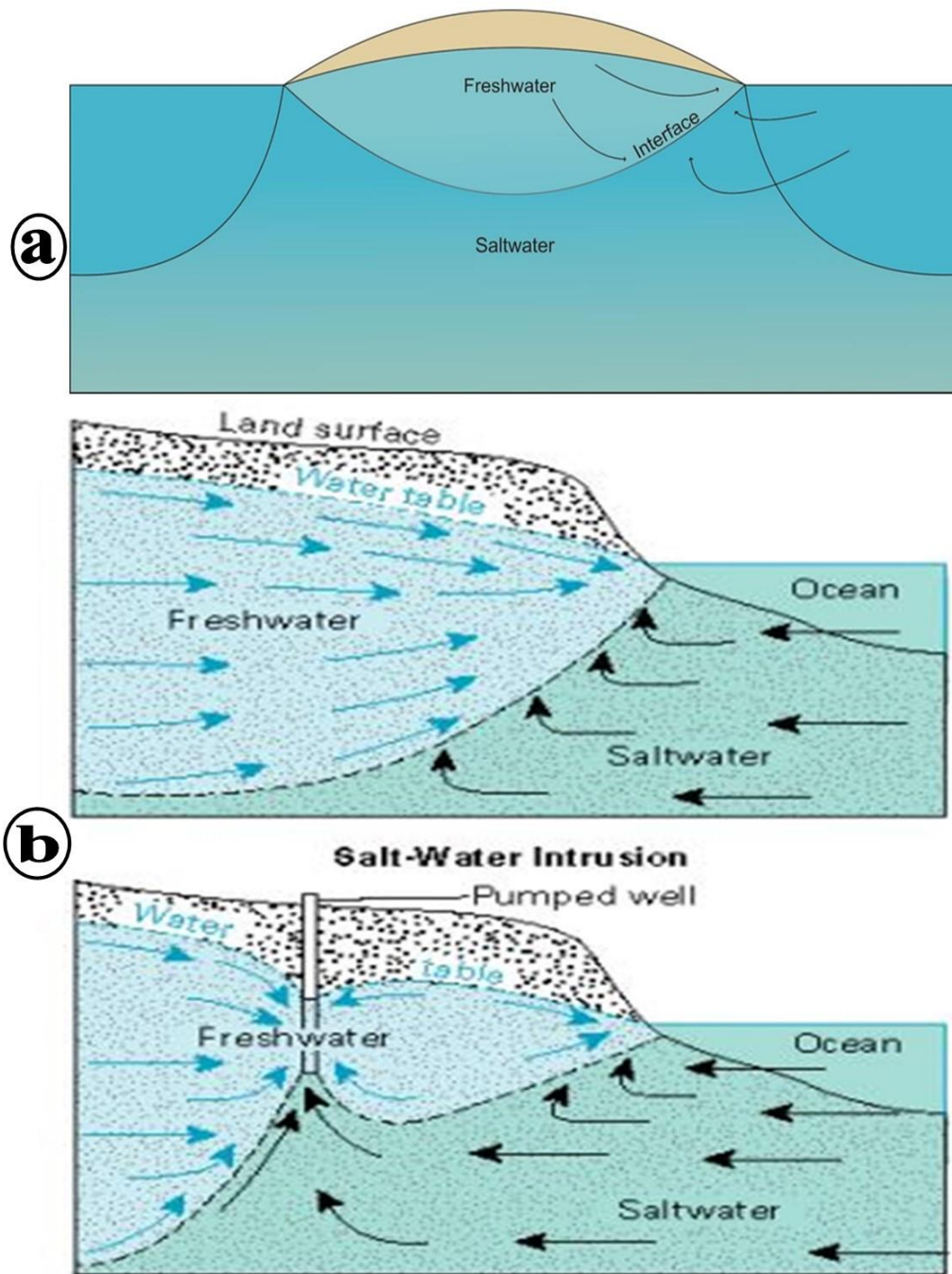


Figure 1. Illustration of the freshwater-saltwater interface. On islands, the freshwater lens is surrounded by saltwater; Figure 1b: Illustration of the freshwater-saltwater circulation after groundwater extraction Klassen et al. 2014(a) and Lyles, 2000(b)

Klassen et al. (2014) indicate that the natural and anthropogenic changes in hydrologic systems lead to the interface migrating inland, in a process called a saltwater intrusion which results in salinization and can have significant economic and ecological impacts. The anthropogenic changes occur due to groundwater extraction by the shoreline residents, who depend mainly on groundwater as the primary source of freshwater for daily survival, industrial and agricultural purposes. Salinization of fresh groundwater tapped in wells and boreholes renders the water unsuitable for domestic supplies and other uses. Once it happens, the process is irreversible, the wells will be abandoned, and the aquifer cannot readily be used (Black, 1977).

Subsequently, people resort to unprotected shallow hand-dug holes in dry riverbeds or surface water (Bath, 1980). Besides the fact that these water sources sometimes run dry, numerous water-borne diseases attend to water consumption from these sources (Asare, et al., 2013). Abandonment of the boreholes leads to scarcity of water for the people and increased costs for water. For areas in developing countries like Malawi, the provision of alternative water sources could take many years due to inadequate financial resources. The unavailability of the water source could mean suffering on the part of the communities and other water-related health problems arising from using water sources of poorer quality.

Consequently, maintaining the appropriate balance between pumping rates and aquifer recharging capacity is paramount to controlling saltwater intrusions. Maintaining the proper balance works only where groundwater monitoring is practiced; otherwise, in its absence, the intrusion could take place (Mato, 2015).

Therefore, groundwater management of coastal groundwater resources is a critical component of achieving global freshwater security, with 40% of the worldwide population living within 100 km of the coast (CIESIN, 2012). A crucial step in managing coastal groundwater resources is mapping and monitoring salinity distribution in the subsurface. Still, it is impossible without knowledge of the spatial distribution of fresh and saline groundwater and the processes that determine the evolution of salinity. Mapping of the salinity distribution is usually accomplished through geochemical methods, which offer a good view of geochemical processes affecting groundwater quality, which is essential in locating and managing usable water supplies (Herczeg et al., 1991; Bouchaou et al., 2008). But there has been increasing recognition of a need to supplement this method in areas with complicated hydrogeological conditions or where limited borehole coverage results in large uncertainty in understanding the extent of saltwater intrusion (Goebel et al., 2019).

This study will address a challenge of the need to map freshwater/saltwater interfaces in Kachulu area where modelling suggests the imminent threat of saltwater intrusion, but no sampling data are available. The study will employ geophysical and hydrogeochemical measurements to achieve the objective. The combination aims at enhancing the details of the subsurface, both soil and water, with the understanding that whatever affects the soil has consequential effects on the water. Electrical Resistivity (ER) surveying is a geophysical technique that produces ER cross-sections of shallow earth structures in 10s of meters of depth. The method is used to detect the water table, fresh-salt water boundary and subsurface geological boundary, and it has been used in hydrogeological, mining, and environmental investigations since the 1920s (Telford et al., 1990).

It has been used to characterize aquifers, and these are underground layers of porous rock where water can be withdrawn. The method is unique because it detects pore water conductivity (Adepelumi et al., 2008; Khalil, 2006). However, the method cannot assess groundwater quality directly in terms of its ion content. Thus, geochemical measurements were also carried out to identify the chemical content of groundwater.

The number of societies facing water shortages increases as the groundwater table level decreases due to excessive usage. The level of surface and groundwater resource pollution increases due to several anthropogenic activities (Asante et al., 2017). The situation is worse for many people in developing countries who primarily rely on groundwater resources as a vital and valuable water resource (Taufiq et al., 2018). For this reason, there have been many studies on water quality in various parts of the world. Because it is a vital source of drinking water and irrigation, groundwater quality should be monitored and protected from pollutants (Hadian et al., 2017).

Also, water quality in coastal areas faces several environmental challenges because of the high population density in these regions (Small & Nicholls, 2003). One issue that affects groundwater quality in coastal areas is saltwater intrusion (Lal & Bithin, 2019; Roy & Bithin, 2018). Groundwater salinity is commonly described by chloride content or total dissolved solids content (TDS). High salinity content in groundwater limits its use for domestic, agricultural and industrial applications (Monjerezi, 2012). Similarly, the low levels of K^+ in Groundwater could be the consequence of its tendency to be retained in clay minerals and contribute to secondary minerals formation (Zhu & Fujimura, 2007).

The British Geological Survey (BGS) (NERC, 2004) indicates that groundwater in some parts of Malawi is characterized by high salinity due to evaporative concentration or dissolution of evaporative minerals in sedimentary rocks. Groundwater with the high salinity in southern Malawi is a major cause of groundwater quality degradation (Davis, 1969; Monjerezi et al., 2011). For instance, the lake Chilwa basin in southern Malawi has saline groundwater, and surface waters and water use are impaired by high concentrations of solutes (Food and Agricultural Organization (FAO), 2005). Understanding the occurrence of saline groundwater resources in different settings is important. Both for the scientific community and the many practitioners dealing with the challenges of groundwater management, the major challenge facing hydro-geochemical investigations of saline groundwater is the determination of the source of salt and mechanism(s) that redistribute the salt to other locations where it becomes a problem (Gunn and Richardson, 1979; Tickell, 1997).

Expanding groundwater supplies countrywide and improving drinking water quality remains a national priority (Government of Malawi (GOM), 1995). Thus, this study aims to map out the extent of the water salinity in the aquifers of Kachulu area. The extent of the water salinity will give an insight into the locations and depths at which borehole wells can be drilled to contact non-intruded/uncontaminated freshwater zone.

1.2 Statement of the Problem

High salinity is one of the main problems affecting the groundwater in Malawi (NERC, 2004; Bath, 1980). According to Food and Agricultural Organization (FAO, 2005), the groundwater and surface water of the lake Chilwa basin (where Kachulu lies) is saline. Studies have been done on analyzing the salinity of the lake and other surrounding basins; however, no studies have been conducted in Kachulu area in an attempt to map out the extent of water the salinity. The unavailability of studies entails that people will continue to drink impaired water and may suffer from other water-related health problems from using water sources of inferior quality (Mato, 2015).

For instance, drinking water of much higher fluoride concentrations results in consumers being subject to dental and skeletal fluorosis (Smith & Chilton, 1983). Drinking water of excess Na^+ water causes severe health problems like hypertension (Mose et al., 2017). The extent of salinization of the aquifers in Kachulu area has to be addressed soon, or else salinity will become a limitation for sustainable development. Delineating the extent of the water salinity is paramount as it will inform decision-makers to find better ways of enabling Kachulu residents to access potable water. Therefore, this forms the focus of analysis in this master thesis.

1.3 Main Objective

The main objective of this study is to map the extent of water salinity in the aquifers of Kachulu area near lake Chilwa.

1.3.1 Specific Objectives

- To conduct a geophysical survey in Kachulu area, lake Chilwa
- To carry out a geochemical analysis for the existing boreholes and the lake water
- To investigate the extent of salinity in the aquifers of Kachulu area

1.4 Significance of the study

The results of this study are useful to bridge the information gap needed in addressing groundwater issues and provide a foundation for groundwater monitoring as, up to now, the extent of the saline groundwater is still not fully understood. Groundwater monitoring is important as it provides groundwater quality information, such as identifying specific chemical species and associated concentrations that impair groundwater quality. Such information can help decision-makers better understand the water quality and their potential effects on public health and the ecosystem and address water quality impairment issues.

This study will provide locations of freshwater aquifers, which will give an insight into where boreholes should be drilled and at what depth, thus alleviating the challenge the engineers face in implementing borehole drilling projects. The study will also provide data on the sources of salinization.

The data from salinization sources is essential as it will help decision-makers understand the best methods and parameters to address a particular salinity problem (Richter & Kreitler, 1993).

1.5 Problems and Limitations

During data collection, unstable and negative resistivity was experienced, and some of the electrodes had no contact with the ground. The negative resistivity was experienced because of poor electrode connection/grounding and possibly low current measurements. This was addressed by adding water to every electrode to ensure a good connection between the electrode and the ground.

1.6 Organisation of the thesis

This report contains five chapters. The present chapter mainly introduces the problem, objectives, problem statement and justification. The preceding chapter two provides an overview of known sources of salinization and geophysical and hydrogeochemical techniques employed to elucidate salinity sources. It also reviews work from scholars who have conducted similar studies in the study area and other areas. Methods applied to examine the problem are presented in chapter three, followed by results and discussion in chapter four. The report is concluded in chapter five and the recommendations are presented in chapter six.

CHAPTER TWO

LITERATURE REVIEW

This review examines different salinization sources, the methods of identifying salinity in an area, and the results. This review will also note the groundwater in Malawi to give an insight into the groundwater quality.

2.1 Overview of groundwater salinization

Salinization is when non-saline soils become saline to affect agriculture production, environmental health and economic welfare (Rengasamy, 2006). There are various classifications of water resources based on salinity levels (Freeze and Cherry, 1979). The classifications vary in number and names of classes, the parameters to which class limits are linked, and class limits' values (e.g. EC, TDS or chloride content). This study used the classification of Freeze and Cherry (1979) because it is one of the most used worldwide (Weert et al., 2009). The classification put water into four categories as fresh ($\text{TDS} < 1,000 \text{ mg/L}$), brackish ($1,000 < \text{TDS} \leq 10,000 \text{ mg/L}$), saline ($10,000 < \text{TDS} \leq 100,000 \text{ mg/L}$), and briny ($\text{TDS} > 100,000 \text{ mg/L}$) (Freeze and Cherry, 1979).

2.2 Salinization sources

The major groundwater salinization sources described in the following sections include halite dissolution, saltwater intrusion, evaporation at or near the land surface, connate water, agriculture salinization, oil and gas brine and road salts.

2.2.1 Halite dissolution

Anderson and Browns (1992) described the dissolution of salt rock in unsaturated water for halite as indirectly proportional to the time scale of the relevant transport mechanisms. Johnson (1997) summarized the water supply, a deposit of salt, a drainage point that will accept the resultant brine, and hydrostatic pressure to cause water flow through the system as the requirements for halite dissolution. If these requirements are met, the mixing of brine and freshwater does occur. Many pieces of literature, such as Herczeg et al. (1991), Nesbitt and Cramer (1993), Land (1997), Vengosh et al. (2002), indicate that in sedimentary basins, the dissolution of evaporite minerals is a common cause for salinization.

Many sedimentary basins consist of rock salt deposits (halite) at great depths, although salt diapirism leads to shallow deposits (Richter & Kleitler, 1993). Halite deposits may be linked with other salts depending on the depositional history. These salts include (e.g., carnallite or sylvite), sulphates (e.g., polyhalite, anhydrite, gypsum, or carbonates (e.g., dolomite, or limestone). The salts (halite or other evaporite deposits) may dissolve in regional groundwater or local recharge (Bennet & Hanor, 1987). According to Hitchon et al. (1969) and Richter and Kreitler (1986), the resultant brine may discharge at the land surface or become part of a fresh groundwater system.

In addition, further discharge of halite-solution brine and evaporation of the saltwater at the land surface leads to the rise of salt flats, covered by gypsum or halite crusts (Richter & Kreitler, 1986). In confined aquifer systems, the dissolution of soluble salts such as gypsum and halite minerals within the aquifer leads to a slow increase in salinity and the chemical modification toward an occurrence of chloride and sodium ions. In semi-arid and arid climates where the evaporation rate is above precipitation rates by up to one order of magnitude, salt may be concentrated by evapotranspiration in the subsurface. These salts are flushed into the groundwater by large seasonal recharge pulses (Drever & Smith, 1978). Furthermore, Richter and Kreitler (1993) indicates that an increase in TDS and other chemical constituents shows halite solution as the salinity source in different sources' nonexistence. On the other hand, many chemical components and constituent ratios have to be used as potential tracers to differentiate halite solution from other sources, such as oil-field brines. The parameters most often used include the major ions Ca^{2+} , Mg^{2+} , Na^+ , Cl^- , SO_4^{2-} , and HCO_3^- . Most Scholars have recommended the following ratios to identity halite source of salinity versus other sources, including K^+/Na^+ , $(\text{Ca}^{2+} + \text{Mg}^{2+})/(\text{Na}^+ + \text{K}^+)$, $\text{Na}^{2+}/\text{Cl}^-$, $\text{Ca}^{2+}/\text{Cl}^-$, $\text{Mg}^{2+}/\text{Cl}^-$, $\text{SO}_4^{2-}/\text{Cl}^-$, K^+/Cl^- , $(\text{Ca}^{2+} + \text{Mg}^{2+})/\text{SO}_4^{2-}$, $\text{SO}_4^{2-}/(\text{Na}^+ + \text{K}^+)$, and $\text{SO}_4^{2-}/\text{TDS}$ (Richter and Kreitler, 1993; Kloppmann et al., 2001; Mace et al., 2006). Piper diagrams are also used to explain salinity occurrences. Water lying near the right-hand side of the piper diamond is considered saline because it is rich in Na^+ , K^+ , and Cl^- .

2.2.2 Saltwater intrusion

According to Lyles (2000), saltwater intrusion occurs when saltwater moves into a freshwater aquifer, and it is a major common process that impairs groundwater quality in shoreline aquifers (Wicks et al., 1995). Saltwater intrusion can be aggravated by pumping freshwater at high rates, and pumping can reduce the natural gradient to the lake by moving the fresh-saltwater interface inland. The reduction in natural gradient results mainly from anthropogenic activities such as excessive groundwater abstraction and land-use changes that reduce recharge to the fresh groundwater system (Jones et al., 1999).

Furthermore, other mechanisms that lead to salinization due to pumping include up coning from depth (Washington State Department of Ecology, 2005) and confined intrusion by reversing the hydraulic gradient near the well or well field (Fetter, 2001). Saltwater enters wells through discrete fractures in fractured rock (Allen et al., 2002). Changes in land use may lead to longer period adjustments of natural discharge (unrelated to pumping), reducing recharge rates for land drainage systems (Werner et al., 2013). This decrease in discharge leads to the movement of the position of the freshwater-saltwater interface. Groundwater recharge is required to change under changing climate conditions (Green et al., 2011). A recharge reduction could lead to a landward movement in the freshwater-saltwater interface. Lake -level rise is another potential driver of change to the position of the interface. The rise in lake level can reduce the hydraulic gradient, predominantly in coastal aquifers constrained by topography (Michael et al., 2013).

2.2.3 Evaporation at or near the land surface

Evaporation is the most cause of salinity in closed basins, and it is an essential process resulting in saline soils and groundwater (Gallanthine, 1989).

In areas where evapotranspiration exceeds the precipitation, for instance, in Malawi, during the dry season (from May to October), the saltwater starts as recharge along surrounding highlands, with high dissolved solutes through weathering and dissolution of available soluble mineral compounds (like calcite and halite) along the path flows, leading to an overall increase in TDS content (Yechieli & Wood, 2002).

According to Richter and Kleitler (1993), closed-basin saltwater may be carbonate, sulphate, or chloride-dominated. The variations in chemical constituents are from the differences in inflow characteristics and precipitation reactions (Berner & Berner, 2012). Conversely, increased evaporative concentration mainly results in a trend towards chloride dominance until halite saturation is reached (Richter & Kleitler, 1993).

2.2.4 Connate saline groundwater

Monjerezi (2012); Frape and Fritz (1982); Hanor (1994) state that the origin of natural saline groundwater in deep crystalline and sedimentary environments can be residual (connate) water (e.g., Connate (Latin for "born with")). Monjerezi (2012) further indicated that according to Hanor (1994); Kharaka and Hanor (2005), chemical alteration and physical migration after deposition of the groundwater aquifer may also result in the connate saline source. The residual saltwater can result from the burial or infiltration of sub-aerially evaporated marine or continental waters (Carpenter et al., 1974; Vengosh, 2001).

On the other hand, Nelson and Thompson (1954) indicated that residual brines might be derived from seawater freezing and isolated continental surface waters in polar areas. These fluids from such crystalline and sedimentary environments are characterized as Na^+ - Cl^- , Na^+ - Ca^{2+} - Cl^- , and Ca^{2+} - Na^+ - Cl^- brines (Frape et al., 1984; Wilson and Long, 2006).

Monjerezi (2012) further explained that the residual saline water is not frequently found within the shallow subsurface because of precipitation's regular flushing of formation water over time. The natural salinity in groundwater increases with an increase in depth beneath the land surface as chemical responds with aquifer material, resident time, and mixing of dissimilar waters increase.

Highly concentrated fluids in crystalline rocks have also been recognized to dissolve and alter Cl-bearing mineral phases, leakage of fluid inclusions, hydrothermally driven systems, and magnetic fluids (Edmunds et al., 1984). Lattice incorporation, as well as fluid inclusions trapped in numerous phases during crystallization, are the major sources of Chlorine in crystalline rocks (Edmunds et al., 1984; Frape et al., 1984).

2.2.5 Agriculture sources

According to Jakeman et al. (2016), agricultural sources associated with increased salinity include irrigation, animal waste, and commercial chemicals such as fertilizers, pesticides, and herbicides. Agriculture management techniques can lead to the development of saline seep. There is a balance between the amount of salt entering the soil and the amount of salt removed under natural conditions. The balance maintains the amount of salt in the soil needed for irrigation. Change from natural vegetation to agricultural crops and application of irrigation water add salt to the system.

Irrigation without proper drainage and the use of low-quality irrigation water causes groundwater salinization. Irrigation can deteriorate groundwater quality through saline water's inflow, responding to heavy metals and irrigation–return flow.

Irrigation-return flow is defined as the water that has been diverted for irrigation purposes and was not consumed by the evaporation and transpiration process, hence finding its way back into the surface or groundwater supplies (Jakeman et al., 2016). Irrigation-return flow is concentrated in chemical constituents from several sources such as minerals and a solution of agriculture residues such as animal waste, fertilizers, herbicides, and pesticides (Baslter & Anderson, 1979).

Furthermore, Miller (1980) indicates that the pollution of water by animal waste has increased due to an increase in the animals being raised and modern method used in the livestock industry that results in higher animal populations. The primary sources of pollution are beef cattle and poultry. Nitrate is an important parameter differentiating agriculturally induced contamination from other salinization sources. In agricultural areas, nitrate concentrations are often above background values. Salinization with other sources like saltwater intrusions or oil field pollution is associated with increased chloride, sodium, calcium and magnesium concentrations and small $\text{NO}_3^-/\text{Cl}^-$ ratios.

2.2.6 Oil and gas brines

In this mechanism, oil and gas brine mix with fresh water. In this mechanism, the formation brines unassociated with oil and gas are separated from fresh groundwater by a transition zone of less saline to very saline water that decreases the degree of natural or induced salinization). The mechanism brings concentrated brine into direct contact with freshwater. Thus, the salinization of fresh groundwater by oil-and gas-filled brine is usually very abrupt and is characterized by increased dissolved solids within a relatively short period and short distances (Jakeman et al., 2016).

The contamination of groundwater and surface water occurs when the brines' disposal is done to mix brine and freshwater (Miller, 1980). The mechanism that allows the mixing of oil and gas brine with fresh groundwater is (1) the Surface disposal; the discharge of oil-field waters into coastal waterways, bayous, estuaries, creeks and lakes pollutes the surface waters. Pollution occurs when these surface water bodies are interconnected with groundwater. (2) Injection wells are another mechanism for mixing oil and gas brine with fresh water. It is done for enhanced recovery or brine disposal. The improved recovery occurs in producing formation. (3) lastly, plugged and abandoned boreholes are another mixing mechanism.

Furthermore, exploring oil and gas has created many boreholes that penetrate shallow, freshwater aquifers and deep-water aquifers. Such holes may be plugged and abandoned in a condition that may allow communication between the different water types. Brine flow into freshwater along abandoned boreholes can occur where brine units or freshwater units are not sealed. The hydraulic heads in brine units are higher than the hydraulic head of the freshwater unit. Henceforth the salinity concentration ranges of individual constituents and the type of chemical constituents vary more in oil and gas brines than in halite solution brine and saltwater intrusion. There is a strong correlation between sodium and chloride concentrations in natural brines. The oil-field brines have the highest Cl^-/Br^- ratios found in natural salts waters. The ratios are greater than 10×10^{-4} in oil-field brines and less than 10×10^{-4} in halite brines (Whittemore & Pollock, 1979).

2.2.7 Road salts

Salts are used as an effective road deicing agent, with good results regarding their primary purpose of providing safe travel during winter months.

There are numerous benefits of street salting, such as improved fuel efficiency and reduced costs associated with accidents. They also come with adverse environmental effects such as contamination of surface runoff of surface waters like lakes. The degree of contamination potential is equal to the number of years the salt is applied to a stretch of road and the amount of salt used to that stretch each year (Miller, 1980).

The Chloride ion parameter is widely used to identify street-salt contamination. It is a good tracer because it is the most conservative in dissolved in groundwater, the most abundant ion in street-salt solution, and it is analyzed on a routine basis. Additionally, bromide is also a good tracer of salinity because of its conservative nature once dissolved in groundwater. It is expressed as Cl^-/Br^- weight ratios and can be used to differentiate salinity derived from road salt (halite) as opposed to oil-and gas-field brines, deep formation waters, and seawater as halite solution produces some of the lowest Cl^-/Br^- ratios measured in naturally saline waters (Miller, 1980).

2.3 Methods of identifying the salinity and sources of salinization

2.3.1 Electrical Resistivity method

The geo-electrical resistivity method is a widely used geophysical exploration technique for groundwater exploration. It gives an insight into hydrogeological investigations related to aquifer delineation, lithological boundaries, and geological structures that provide subsurface information (Bose et al., 1973).

Hazreek et al. (2018) further indicate that the application of the electrical resistivity method is a well-known non-destructive technique applicable to measure the Electrical Resistivity Value of the subsurface materials assisted with the computer modelling software.

Most importantly, it is cost-effective, less time-consuming, and easy to monitor to obtain a subsurface resistivity profile. The technique is used to establish the extent and sources of groundwater salinity because electrical resistance is susceptible to the salinity of pore-water in the subsurface and is therefore useful in identifying fresh and saltwater (e.g., Chongo et al., 2011). It involves injecting current into the ground and measuring the earth's response to the current to measure resistivity. The current enters the ground through current electrodes. The response consists of recording the potential difference by another pair of potential electrodes, which measures the subsurface material's impedance (Asare, 2013).

In recent years geophysical (e.g., electrical and electromagnetic methods) imaging of the subsurface has shown to be highly effective for large-scale exploration and characterization of the extent of saltwater intrusion in shoreline environments (Goebel et al., 2019). These methods could detect the extent and sources of groundwater salinity (Liao et al., 2018) and the boundary of fresh and saltwater from the electrical current difference (Shim et al., 2004). These methods provide a measure of subsurface electrical resistivity, which is highly sensitive to changes in pore fluid salinity, and thus are ideally suited to this application.

Also, the salinity increases with depth where both fresh water and saline water occur. The increase in salinity produces a decrease in electrical resistivity of water, and thus, resistivity varies with depth within groundwater wells in shoreline aquifers (Nwankwoala, 2011). The resistivity of groundwater varies from 10 to 100 ohm•m depending on the concentration of dissolved salts. Note that lake water's low resistivity (about 0.2 ohm•m) is due to the relatively high salt content.

However, extremely low formation resistivity in this lake water environment may be due to clays and brackish water (TerraHydro, 1997). Subsequently, this makes the resistivity method ideal for mapping the saline and freshwater interface in the coastal/ shoreline area (Loke, 2000).

On the other hand, Loke (2000) states that it is vital to understand the relationship between some common rocks and resistivity before dealing with 2D and 3D resistivity surveys because resistivity surveys give a picture of the subsurface resistivity distribution subsequently, to convert the resistivity picture into a geological image, one needs to know some of the typical resistivity values for different types of subsurface materials and the geology of the area surveyed. Table 1 gives the resistivity values of common rocks, soil materials, and chemicals, including several industrial contaminants' resistivity values (Keller & Frischknecht, 1966).

Table 1: The resistivity of some rocks, minerals, and chemicals (Keller and Frischknecht, 1966)

Material	Resistivity ($\Omega \cdot m$)	Conductivity (Siemen/m)
Igneous and Metamorphic Rocks		
Granite	$5 \times 10^3 - 10^6$	$10^{-6} - 2 \times 10^{-4}$
Basalt	$10^3 - 10^6$	$10^{-6} - 10^{-3}$
Slate	$6 \times 10^2 - 4 \times 10^7$	$2.5 \times 10^{-8} - 1.7 \times 10^{-3}$
Marble	$10^2 - 2.5 \times 10^8$	$4 \times 10^{-9} - 10^{-2}$
Quartzite	$10^2 - 2 \times 10^8$	$5 \times 10^{-9} - 10^{-2}$
Sedimentary Rocks		
Sandstone	$8 - 4 \times 10^3$	$2.5 \times 10^{-4} - 0.125$
Shale	$20 - 2 \times 10^3$	$5 \times 10^{-3} - 0.05$
Limestone	$50 - 4 \times 10^2$	$2.5 \times 10^{-3} - 0.02$
Soils and waters		
Clay	1 - 100	0.01 - 1
Alluvium	10 - 800	$1.25 \times 10^{-3} - 0.1$
Groundwater (fresh)	10 - 100	0.01 - 0.1
Sea water	0.2	5
Chemicals		
Iron	9.074×10^{-8}	1.102×10^7
0.01 M Potassium chloride	0.708	1.413
0.01 M Sodium chloride	0.843	1.185
0.01 M acetic acid Xylene	6.13	0.163
Xylene	6.998×10^{16}	1.429×10^{-17}

The resistivity of these rocks depends much on the degree of fracturing and the percentage of the fractures filled with groundwater. Igneous and metamorphic rocks typically have high resistivity values, while sedimentary rocks, which usually are more porous and have a higher water content, typically have lower resistivity values.

Wet soils and fresh groundwater have even lower resistivity values, and clayey soil has a lower resistivity value than sandy soil. Subsequently, this makes the resistivity method ideal for mapping the saline and freshwater interface in the coastal/ shoreline area (Loke, 2000).

Loke (2000) further indicated that metals such as iron have extremely low resistivity values. Chemicals with strong electrolytes, such as potassium chloride and sodium chloride, can significantly reduce ground water's resistivity to less than one ohm•m, even at relatively low concentrations. A strong electrolyte is a solution/solute that completely, or almost completely, ionizes in a solution. These chemicals are good conductors of electricity. The effect of weak electrolytes, such as acetic acid, is comparatively smaller. Hydrocarbons, such as xylene, typically have very high resistivity values.

Several scholars employed the geophysical method in the investigation of the salinization of an area. For instance, Leite *et al.* (1978) used a tripotential technique with the Wenner configuration of resistivity surveys to study coastal aquifers in Bahia, Brazil. Using the wenner array electrical resistivity survey, Oteri (1983) has delineated saline water intrusion in the Dungeness shingle aquifer, Dungeness, England. Just like Leite *et al.* (1978) and Oteri (1983), this study also adopted a wenner electrode configuration array because, according to Baharuddin *et al.* (2013), the configuration is good at providing a clear image of groundwater and saltwater. Additionally, Chongo *et al.* (2015); Zarroca *et al.* (2011); Goebel *et al.* (2017) and others have demonstrated the effectiveness of ERT for mapping saltwater intrusion onshore. These methods effectively delineate the extent and sources of groundwater salinity and effectively locate high-yielding aquifers with freshwater (Asare *et al.*, 2013).

Several other scholars also conducted groundwater investigations using a single method, like Oteri (1981), who investigated saline contamination of a chalk aquifer by mine drainage water at Tilmanstone, England, using a geo-electrical survey of Schlumberger configuration. Similarly, El-Waheidi *et al.* (1992) also conducted a geo-electrical resistivity survey in the central part of the Azraq basin (Jordan) to identify the saltwater/freshwater interface using ABEM Terrameter SAS 300-B resistivity meter by Schlumberger configuration.

Correspondingly, Nowroozi *et al.* (1999) are other scholars who studied the aquifers of Virginia's eastern shore on saltwater intrusion by electrical resistivity survey using Schlumberger configuration. Radhakrishnan *et al.* (1999) have also identified the potential groundwater zones in the coastal aquifers in Tuticorin, Tamil Nadu, by conducting 60 vertical electrical soundings using Schlumberger configuration geophysical resistivity method. Lenin *et al.* (2008) studied the vulnerability assessment of seawater intrusion and the effect of artificial recharge in the Pondicherry coastal aquifer using GIS. GIS can be an essential tool for developing solutions for water resources problems, assessing water quality, and managing water resources on a local or regional scale.

Again, Benkabbour *et al.* (2004) have determined the depth of the base of the saturated zone in the aquifer and have helped in imaging the lateral and vertical distribution of groundwater salinity of the Plio-quaternary consolidated coastal aquifer of the Mamora plain, Morocco, using Direct Current resistivity method. Wilson *et al.* (2006) have used direct current earth resistivity methods to characterize the saline interface's nature at Te Horo on the Kapiti Coast in New Zealand.

Song Sung-Ho *et al.* (2007) have delineated the spatial extent of seawater incursion in a watershed experimental in the coastal area of Byunsan, Korea, using vertical electrical soundings. Vouillamoz *et al.* (2007) have conducted an integrated approach of Magnetic Resonance Soundings (MRS) and Vertical Electrical Soundings (VES) to characterize a non-consolidated coastal aquifer in Myanmar.

Equally, Adepelumi *et al.* (2008) conducted a vertical electrical resistivity (VES) sounding survey utilizing surface Schlumberger electrode arrays in the Lekki Peninsula coastal zones in Lagos, Nigeria. The VES resistivity curves obtained showed a dominant trend of decreasing resistivity with depth (thus increasing salinity). The rock matrix, salinity and water saturation are the major factors controlling the resistivity of the formation. Moreover, this investigation shows that the surface DC resistivity method can accurately map saline water intrusion into the aquifers. Abdul Nassir *et al.* (2001) have delineated and mapped the intrusion boundary between fresh water and saline water in Yan, Kedah, and northwest Malaysia by geoelectrical imaging surveys. Shaaban (2001) also employed Vertical electrical soundings (VES) in a coastal area of northwestern Egypt used to evaluate shallow brackish to fresh water-bearing limestone aquifer of the Pleistocene age and deep saline water-bearing sandy limestone of the Miocene age.

Bhattacharya and Patra (1966) carried out Electrical Resistivity Soundings using the Schlumberger configuration around Digha in the coastal region of West Bengal, India, to investigate the existence of saltwater pockets and the possibility of saltwater intrusion.

Patra (1967) conducted electrical resistivity soundings to identify the saline water intrusion around the Jaldha coast, West Bengal.

Similarly, Srinivasarao (2007) Groundwater quality suitable zones identification applications of GIS, Chittoor area, Andhra Pradesh, India. Gondwe (1983) also attempted to detect saline water intrusion in the aquifers within the coastal belt of the Mtwara region in southeast Tanzania using the geophysical method of electrical resistivity. Phukon et al. (2004) applied the multicriteria evaluation technique in the GIS environment for groundwater resources mapping in Guwahati city areas.

Likewise, Hazreek et al. (2018) mapped out seawater intrusion using Electrical Resistivity Imaging (ERI) in the Malaysian Coastal area using an electrical resistivity set of equipment consisting of ABEM Terrameter SAS 4000, ABEM Electrode Selector 464, 4 multicore cables and 61 stainless steel electrodes. The line survey length was 160 m with 2 m of equal electrode spacing interval, which mapped the subsurface profile up to 30 meters in depth. Werner-Schlumberger configuration was used since it has the most vital signal strength and can detect vertical changes and horizontal structures (Loke, 2015). Henceforth the study also used a Wenner electrode configuration. Furthermore, it is good at detecting sand clay boundaries and provides a clear image of groundwater and saltwater intrusion (Tajul Baharuddin et al., 2013). The results of electrical resistivity surveys offered a piece of important information on the subsurface geology in the study area. The results showed saltwater's distribution, freshwater, and salt and freshwater mixing up to 30 m.

Hazreek et al. (2018) further indicate that the interpretation of the electrical resistivity value (ERV) results were based on four ERV ranges, as shown in Table 2. The resistivity value below 5 Ωm was classified as seawater and marked as dark blue in the ERT.

Then, ERV of 5 – 15 Ωm was categorized as brackish water and marked as blue in the ERT, while the ERV of 50 – 100 Ωm was interpreted as freshwater and marked as turquoise to green colour in the ERT. Hazreek et al. (2018) considered the high resistivity value to identify the distribution of hard materials underground in the study area. A resistivity value larger than 400 Ωm was interpreted as a hardened layer (rock). It was marked as yellow-red colour in the ERT. Reduction of ERV ($< 5 \Omega\text{m}$) found in all high tide of ERT, indicating the seawater's intrusion process towards the groundwater aquifer. During the high tide, the low ERV distribution was almost similar, thus verifying the results and interpretation of ERT obtained. In conclusion, the study revealed seawater migration towards the inland area during the high tide due to the pushing effect and increasing seawater levels.

Table 2: Interpretation of subsurface materials in the study area (Hezreek et al., 2018)

Resistivity Value	Material	Mark on inverse model
$< 5 \Omega\text{m}$	Seawater	Dark blue colour
5 – 15 Ωm	Brackish	Blue colour
50 – 100 Ωm	Freshwater	Turquoise – green colour
$> 400 \Omega\text{m}$	Hard layer (rock)	Yellow – red colour

Similarly, Adeoti (2010) measured five electrical imaging lines and twelve VES using the Schlumberger configuration in Oniru of Lagos State to investigate saline water intrusion into freshwater aquifers. Interpretations were made to these results using both qualitative and quantitative deductions from 1D and 2D geoelectric models.

The interpreted results indicate saltwater plumes occurring in a different part of the study area. The 1D and 2D results correlate to a very high degree showing saltwater intrusion between 13 and 64 m in the study area. Two major freshwater aquifers (shallow < 6 m and deep > 60m) were delineated, with most of them unprotected. The results showed the importance of electrical resistivity and induced polarization to map coastal areas' saline water intrusion problems.

Several scholars, including Oteri (1981); El-Waheidi *et al.* (1992); Radhakrishnan *et al.* (1999); Nowroozi *et al.* (1999), used Schlumberger configuration, which is not ideal because the method may be susceptible to near-surface, lateral variations in resistivity. These near-surface lateral variations could be misinterpreted in terms of depth variations in resistivity. Generally, the interpretation is limited to horizontal layered structures, and vertical data is not captured, unlike the Wenner configuration. Also, Benkabbour *et al.* (2004), Abdul Nassir *et al.* (2001), Hazreek *et al.* (2018), Gondwe (1983), Kouzana *et al.* (2010), Bhattacharya and Patra (1966), Missi (2006), Mato (2015), Monjerezi (2012) and others conducted groundwater investigation using a single method such as the geophysical method, geochemical methods, strontium isotopes and stable isotopes of water methods and hydrogeological method.

It is necessary to use several methods in investigating groundwater to have a good insight and thorough understanding of the salinization of an area.

Jehyun Shin *et al.* (2011) characterized the coastal aquifers using geophysical well-logging and borehole temperature monitoring on the eastern coast of Jeju Island, Korea. Electrical conductivity's vertical conductivity represented patterns typical of a freshwater-saltwater interface depending on seawater intrusion and aquifer properties. The borehole temperature monitoring using a thermal line sensor assisted in characterizing coastal aquifers' variability at a high temporal and spatial resolution. Consequently, geophysical well-logging and borehole temperature monitoring could enhance knowledge of basalt's subsurface structure and interactions of fresh water and saltwater in coastal areas.

Also, Choudhury *et al.* (2001) carried out a geophysical study comprising electrical resistivity and seismic refraction methods in the alluvial coastal belt of Digha in Eastern India to investigate the status of seawater intrusion. Harikrishna *et al.* (2012) did an integrated analysis using remote sensing, hydrogeology, hydrochemistry, and geophysical investigations that successfully revealed the extent of saltwater intrusion Around Kolleru lake. Menyeh (2012) acquired both the geo-electrical resistivity profiling and vertical electrical sounding data using a Schlumberger electrode configuration from small communities. Their outlying areas lie in the Gushiegu and Karaga Districts of Northern Ghana, analysing the aquifer's characteristics and recommending a hydro-geologically suitable location to construct boreholes in communities.

The study successfully revealed that a three subsurface layer's geoelectric sequence is very harmonious to the weathering profile over the fresh bedrock - thick topsoil, the weathered and fractured bedrock. The geoelectric sections do not provide evidence of a descent into the fresh bedrock. Based on the perceived aquifer properties, sites were recommended for drilling water supply boreholes for the communities.

Similarly, Onojasun (2011) conducted a geophysical survey using electrical resistivity methods in the Willetton area, Perth, Western Australia, to delineate the basement aquifer's geoelectrical characteristics and identify the groundwater potential in the area. The study employed Vertical electrical sounding with ABEM SAS 3000 Terrameter and Schlumberger electrode configuration for data collection. The results showed that the study area has relatively homogenous subsurface stratification with four distinct subsurface layers above 37m. The four subsurface layers comprise topsoil mainly of unconsolidated sand containing organic matter, unsaturated sand layer with consolidated and highly resistive, water-saturated sand layer with high water-saturated soil, and the sub-stratum layer consisting of clay material. The study results showed that the aquifer performance is best at about 32m; hence for sustainable water supply, the boreholes should be drilled to about 32 m to hit a prolific aquifer.

The study acclaims scholars such as Harikrishna *et al.* (2012); Onojasun (2011); Menyeh (2012), and others who used a combination of several approaches in the investigation of groundwater. The combination of several methods enabled the scholars to successfully characterize the coastal aquifers by obtaining accurate information on the groundwater salinization of an area.

2.3.2 Geochemical methods

Groundwater sampling and major ion analysis can be used to identify saltwater intrusion into the groundwater. These major ions dissolved in water include Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , HCO_3^- , and SO_4^{2-} and the major ion ratios include Cl^-/Br^- , $\text{Ca}^{2+}/(\text{HCO}_3^- \text{ and } \text{SO}_4^{2-})$, $\text{Ca}^{2+}/\text{Mg}^{2+}$, and Na^+/Cl^- . Determining whether groundwater quality has been or has not been influenced by saltwater will determine groundwater zones. Good results for identifying saltwater intrusion are obtained by analyzing and reviewing some concepts about saltwater intrusion or contamination into groundwater (Sudaryanto & Naili, 2018). Monjerezi (2012) states that each salinity source has a distinctive chemical and isotopic composition. The underlying principle behind all geochemical techniques used for tracing salinity sources assumes that the original saline source's chemical and isotopic composition is preserved during the salinization process. However, the water-rock interactions may modify the saline source's original composition and mask its identity.

Water quality information can be obtained based on the concentration of major ions because, naturally, the chemical composition of water changes. The concentration of major ions in water helps to identify whether the water has been polluted with saltwater or not (Bear et al., 1999). The major ions ratio in water is highly affected by the interaction between freshwater and saltwater (oxidation-reduction, ion exchange) (Gimenez et al., 1997). The most dominant ions in the groundwater that has not been affected by saltwater are CO_3^- and HCO_3^- .

In contrast, in groundwater affected by saltwater or containing dissolved mineral salts in aquifer rocks, the composition will change (Nurwidyyanto & Widodos, 2006).

Saltwater has a high Na^+ (around ten mg/L) content because the constant contact results in the release of cation to replace Ca^{2+} , thereby changing the water type into a $\text{Na}^+\text{-HCO}_3^-$ type. The major ions ratio in water can be found by analyzing the environmental conditions, indicating whether seawater intrusion has occurred (Bear et al., 1999).

Monjerezi (2012) studied groundwater salinity in the lower Shire River valley (Malawi) using Hydro-geochemical and isotope constraints on sources and evolution to understand the origins of saline/brackish groundwater resources prevailing in the lower Shire River valley (Malawi). Major ion data and isotopes were assessed using complementary approaches, proving constructive to others with the same targets. In the Principal Component Analysis (PCA) and Integrated application of hierarchical cluster analysis (HCA), the results from geochemical and isotope indicated salinity at all levels. EMMA gave evidence of a discrete saline end-member implying localized sources of contamination of fresh groundwater with saline groundwater instead of increasing salinity along the flow path.

Monjerezi (2012) further indicated that the possible cause of the contamination was related to fault systems' coincidence with distinct saline/brackish groundwater zones. The association of boron (B), strontium (Sr), Lead (Pb) and barium (Ba) with the most occurring solutes in brackish/saline groundwater was a result of a common source and complexing with inorganic ligands and the influence of low pH associated with salty groundwater. Monjerezi (2012) study only focused on using strontium isotopes and stable isotopes of water, major and minor elements, to investigate salinization processes.

Still, these methods alone cannot offer a complete understanding of the salinity problem as they only reveal the localized nature of the salinity problem. Consequently, combining geophysical methods to analyze salinity variation with depth and the aquifer's stratification is recommended.

Mato (2015) also studied Groundwater quality degradation due to saltwater intrusion in Zanzibar Municipality. The author collected data from 154 boreholes in Zanzibar Municipality. Also collected water samples from the boreholes and analyzed them for salinity parameters, including EC, chlorides, salinity percentage and TDS. Some parameters, like faecal coliforms and nitrogen nitrate, were also identified. The study results showed saltwater intrusion in the coastal aquifers of Zanzibar municipality. Uncontrolled groundwater pumping presents a real water resources management problem that could quickly deplete the only freshwater resource sustaining the island. Therefore, the water resources authorities in Zanzibar should take proactive steps toward curbing the saltwater intrusion threats by controlling the groundwater withdrawal and putting in place a long-term monitoring system.

Similarly, Missi and Atekwana (2020) measured groundwater's physical, isotopic and chemical properties, lake Chilwa and streams in the lake Chilwa Basin, Malawi, to assess water quality and identify the hydrogeochemical processes that control water quality. Groundwater data from 16 boreholes, five stream water samples and three samples from lake Chilwa were acquired using standard methods and investigated for pH, temperature, electrical conductivity, TDS, stable isotopes of hydrogen and oxygen and major ions.

The study results indicated that in most locations, the TDS concentrations, HCO_3^- and Cl^- , were above the recommended limits of the drinking water standards and the World Health Organization (WHO) standards. Henceforth the results of the study showed that poor water quality was due to natural water-rock interactions. Missi (2006) recommended that since stream water quality was 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.

2.3.3 A combination of Geophysical and Geochemical methods

Folorunso et al. (2013) studied saltwater intrusion into Lagos, Nigeria's coastal aquifer, by employing geophysical and geochemical techniques to map and provide evidence that the saltwater from the adjacent Lagos lagoon has intruded the study areas' coastal aquifers.

The delineated geo-electrical layers were juxtaposed with logs from both boreholes located within the campus. This study deduced that excessive groundwater extraction and possibly reducing groundwater gradients that allow saline water to displace fresh water in the investigated aquifer are responsible for the observed saline water intrusion. The ERT resistivity-depth models showed that some of the aquifer units were found to have been impacted by saline water due to incursion from the Lagoon. Generally, the polluted regions were characterized by a low resistivity value, less than 10 Ωm . Evidence from the geochemical study of the borehole and the lagoon water samples corroborated the ERT result; thus, in using the two methods, the study successfully revealed that the coastal aquifer under the university of Lagos campus had been intruded by saltwater from the adjacent Lagoon.

Similarly, Pujari and Soni (2009) conducted Seawater intrusion studies near Kovaya limestone mine, Saurashtra coast, India, by chemical analysis of the major cations, anions, and resistivity imaging survey. Also, Gurunadha *et al.* (2011) conducted geophysical and geochemical investigations to decipher subsurface geologic formation and assess seawater intrusion in the Godavari Delta Basin. Chemical analyses of groundwater samples have indicated the range of salt concentrations and the correlation of geophysical and borehole lithology data in the study area, predicting seawater-contaminated zones and the influence of in situ salinity upstream of the study area.

Edet and Okereke (2002) have attempted to delineate shallow groundwater aquifers in the coastal plain sands of the Calabar area (Southern Nigeria) using surface resistivity and hydrogeological data. Again Balasubramanian *et al.* (1985) have demarcated the potential groundwater zones in the Tambaraparani basin's coastal aquifers, Tamil Nadu using geophysical resistivity geochemical techniques.

Sheriff *et al.* (2006) also conducted geoelectrical and hydrogeochemical studies to delineate seawater intrusion in Wadi Ham, UAE, using a 2D earth resistivity survey. Equally, Kouzana, L. *et al.* (2010) conducted a seawater intrusion study of the Korba aquifer by geophysical and hydrochemical methods. About 38 Vertical Electrical Sounding (VES) were conducted over the coastal area between Korba and Oued Lebna. The interpretation of these electric soundings was done using Winsev software. The relationship of the different electric surveys allowed realizing geoelectric sections indicating the vertical configuration of seawater intrusion. This study demonstrates that saltwater intrusion reached approximately 3km inland.

The high groundwater salinity anomaly observed in Diar E Hajjej, Garaet Sassi and Takelsa-Korba zones was explained by seawater intrusion. Baharuddin *et al.* (2013) also conducted a study to investigate seawater intrusion into the agricultural sustainability at Carey Island, Selangor, Malaysia. Application of geo-electrical method combined with geochemical data for oil palm cultivation.

The study commends scholars like Folorunso *et al.* (2013); Sheriff *et al.* (2006), and others who combined the geophysical and geochemical techniques in the investigation of groundwater. Similarly, Monjerezi (2012) recommended that a combination of geophysics, quantitative hydrogeology (field studies and hydraulic modelling), and geology should be conducted to characterize the salinity problem fully. Based on the Literature, we may say that both geophysical and geochemical methods are applicable in saltwater intrusion mapping. The literature also shows that many authors have used these methods because they are inexpensive and do not need a comprehensive chemical analysis for samples collected at discrete. Henceforth, the study employed geophysical and geochemical methods to delineate the extent of saline water in the Kachulu area. Combining the two methods will ensure that the purpose of the study is achieved.

2.3.4 Common indicators of seawater intrusions

The World Health Organization stipulates that the mixing of 2% salt water (250 ppm) in a freshwater aquifer is above the aesthetic objectives for the upper limit of chloride (water begins to taste salty) (Custodio, 2005). The water becomes unusable for use if the mixing exceeds 4%, and the water becomes unusable except for cooling and flushing if the mixing exceeds 6% (Custodio, 2005; Darnault and Godinez, 2008).

Henceforth the water quality indicators of SWI are essential for water management because they enable monitoring of coastal aquifers that involve measuring baseline water quality parameters (such as EC, TDS, and major ions) (Barlow & Reichard, 2010). Additional, monitoring groundwater quality brings awareness to the early signs of migration of the fresh-saltwater interface and provides information on saltwater incursion (Barlow & Reichard, 2010). Still, the indicators of SWI can be vital during the drilling process to know if saltwater is encountered as the borehole progresses.

In this case, a relatively inexpensive and readily measured indicator is needed not to acquire a comprehensive analysis of samples collected at discrete depths during drilling.

Several techniques have been proposed by different scholars for determining indicators of SWI. The techniques range from basic (e.g., high chloride values indicate saltwater intrusion. (Lyles, 2000; Snow et al., 1990) to complex (e.g., model-based indicators (Kennedy, 2012; Scheidleder, 2003). The review dwells much on the basic and quantitative /graphical approaches.

2.3.4.1 Basic Approaches

Saltwater contains around 35,000 mg/L of dissolved solids, of which 19,000 mg/L is chloride (Lyles, 2000). Consequently, Scheidleder (2003) stated that the leading cause of high chloride (Cl^-) in coastal aquifers is most likely attributed to SWI. Lyles (2000) conducted a statistical analysis of 187 groundwater samples collected from Lopez Island, Washington, USA, to identify wells affected by SWI and suggested that chloride concentrations over 100 mg/L indicate SWI.

Similarly, Kennedy (2012) developed a GIS-based approach for assessing SWI in Nova Scotia; chloride concentrations greater than 50 mg/L were recorded, indicating SWI. The study by Lyles (2000) recommended that further investigation is needed to characterize other salinity sources, not saltwater intrusion, contributing to high chloride levels. Indeed, there are several sources of salinity and SWI alone, through looking at its indicators cannot be the basis of the study and may provide insufficient evidence. Other scholars, such as Snow et al. (1990), also indicate that using single chemical parameters as indicators of SWI can be problematic.

For instance, the high Cl^- , Na^+ , Br^- and SO_4^{2-} values generally correspond with SWI intrusion or connate water source, and Ca^{2+} , Mg^{2+} , K^+ , and Sr^- are not useful when distinguishing between different types of saline water. Chloride-bromide relationships are usually applied to distinguish between marine and non-marine salinity sources (Kharaka et al., 1987). Chloride is preferentially separated over bromide into sodium, potassium, and magnesium halogen salts as precipitation occurs. Henceforth, brines formed by halite dissolution are associated with low Br^-/TDS and Cl^-/Br^- ratios (Rittenhouse, 1967). On the other hand, the brines derived from evaporated seawater can be identified by high Br^-/Cl^- (Carpenter et al., 1974; Kharaka et al., 1987).

2.3.4.2 Quantitative and Graphical Approaches

Kennedy (2012) states that there is a need to consider the whole indicators, such as the high chloride content, to determine seawater intrusion in groundwater. Both quantitative and graphic calculations should be conducted.

The chemical contents of seawater are different from one location and according to Anthony (2006), there are at least 11 different types of ions contained in seawater such as; Strontium/Sr (0.008), Calcium/ Ca^{2+} (0.413), Magnesium/Mg (1,294), Chloride/ Cl^- (19.135), Sodium/ Na^+ (10.76), Sulfate/ SO_4^{2-} (2,712), Potassium/ K^+ (0.387), Bicarbonate/ HCO_3^- (0.142), Bromide/ Br^- (0.067), Boron/B (0.004) and Fluoride/ F^- (0.001).

Marques (2014) indicates that EC is the basic indicator to know whether an aquifer has been contaminated by seawater or not. The groundwater is normal if EC is under 1000 $\mu\text{S}/\text{cm}$. However, Marques (2014) further elaborates that observation should be done comprehensively to determine groundwater's normality. Effendi (2003) states that the EC of Seawater is below 51,000 $\mu\text{S}/\text{cm}$, and the rate of the EC is closely related to the TDS value, which can be estimated by multiplying EC by 0.55-0.7. Bear (1999) stipulated that Cl^- 's high content indicates that intrusion of seawater or connate water has occurred. The amount of Cl^- in groundwater can classify its type as to whether the groundwater has a high salt or pure freshwater (Stuyfzand, 1991). Henceforth, this paper has also adopted the EC indicator in analyzing the type of saltwater intrusion in the Kachulu area.

The Chloride and Bromide ratio can be used as a tracker to see the groundwater state. Some processes can be observed from the Cl^-/Br^- ratio (Alcala & Custodio, 2008). According to Klassen et al. (2014), seawater's Cl^-/Br^- ratio is around 297. The ratio of < 297 shows *hypersaline brine* >1000 indicates *evaporate-dissolution*, and one derived from *anthropogenic sewage* or the effect of agriculture is < 800 . Klassen further suggested that some research explained that when calculating the ratio of Na^+/Cl^- , the result of less than 0.86 means that the seawater has contaminated groundwater.

The ratio of >1 indicates that an anthropogenic source contaminates the groundwater. $\text{Ca}^{2+}/(\text{HCO}_3^- \text{ and } \text{SO}_4^-)$ and $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio can also be used as an indicator, where if it is >1 , it means that seawater intrusion is taking place.

Similarly, Carol et al. (2009) stipulated that the enrichment of Ca^{2+} is an indicator of seawater intrusion into groundwater if the ratio of $\text{Ca}^{2+}/\text{Mg}^{2+}$ is greater than 1, which indicates that seawater intrusion is taking place. Moujabber et al. (2006) also explained the Simpson Ratio, namely $\text{Cl}^-/(\text{HCO}_3^- + \text{CO}_3^-)$, as evidence of saltwater intrusions.

Moujabber et al. (2006) further categorize the ratio into five classes, as follows; first, good quality (< 0.5); second, slightly contaminated ($0.5 - 1.3$); third, moderately contaminated ($1.3 - 2.8$); fourth, highly contaminated ($2.8 - 6.6$); and fifth of extremely contaminated ($6.6 - 15.5$). Shoreline areas' hydrochemical indicator of shallow groundwater may also be noted basing the relationship between $(\text{HCO}_3^- + \text{SO}_4^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+})$ and $\text{Na}^+ - \text{Cl}^-$ that should indicate a ratio of 1:1. Still, the two variables must result in $r = 0.87$. The value of r indicates a close relationship between the two variables. The value shows that there has been an increase in Na^+ and a deficiency of Ca^{2+} and Mg^{2+} . Thus, the groundwater enables ion exchange for the types of $\text{Na}^+/\text{Ca}^{2+}$ and $\text{Na}^+/\text{Mg}^{2+}$ (Carol & Kruse, 2012).

Panno et al. (2006) developed a graphical approach to plot different water quality parameters (Figure 5). Panno et al. (2006) suggest that a Cl^-/Br^- vs Cl^- plot best reflects the evolution of water and mixing trends. Mixing occurs between one end-member, demonstrating pristine groundwater of natural background concentrations, other end-members like seawater, road salt and septic effluent, animal waste landfill leachate and basin brines.

As shown in Figure 2, a water sample with a Cl^-/Br^- ratio ranging from 250–400 and a Cl^- concentration above 400 mg/L represents a composition that resembles saltwater and may indicate saltwater intrusion.

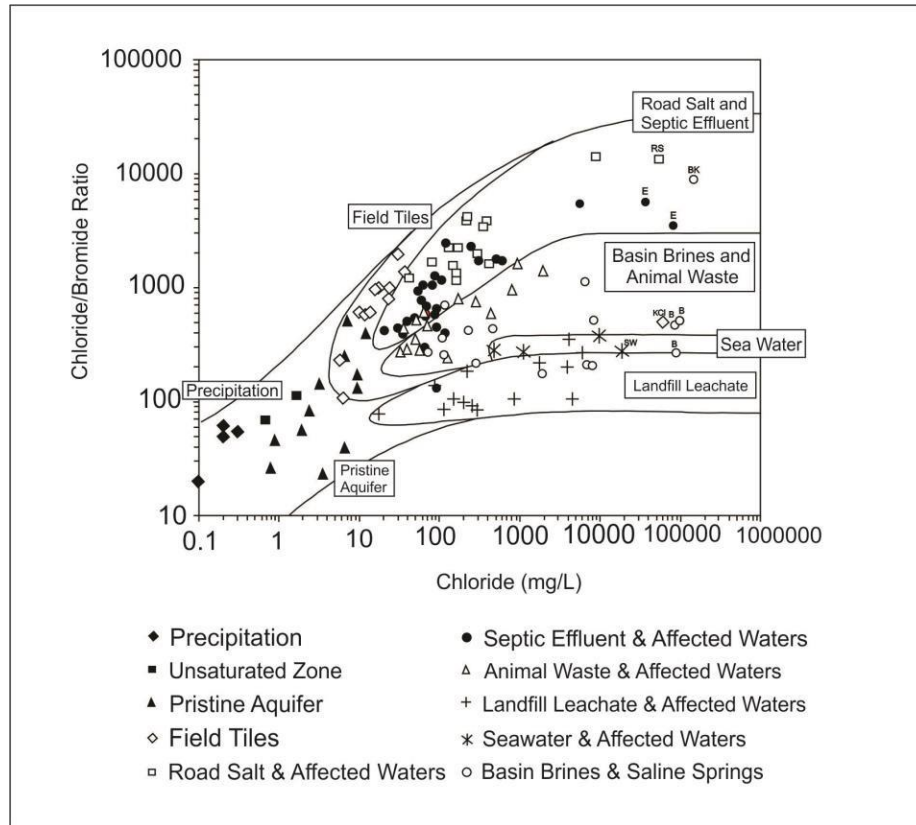


Figure 2. The evolution and mixing of pristine water to saline water (Panno et al., 2006).

An alternative Washington State Department of Ecology (2005) plots a graphical approach for Cl^- vs electrical conductivity (EC). Figure 3 shows three zones on Cl^- vs EC plot: normal, mixed and SWI. EC can be converted to TDS concentration if the chemical composition is known (e.g., Eutech Instruments, 1997). Figure 6 shows that groundwater samples with Cl^- exceeding 200 mg/L and EC exceeding $\sim 1000 \mu\text{S}/\text{cm}$ influenced SWI.

The Graphical approach also indicates that the groundwater samples characterized by Cl^- between 100-200 mg/L and EC between 600-2000 $\mu\text{S}/\text{cm}$ represent a mixing of fresh and saltwater.

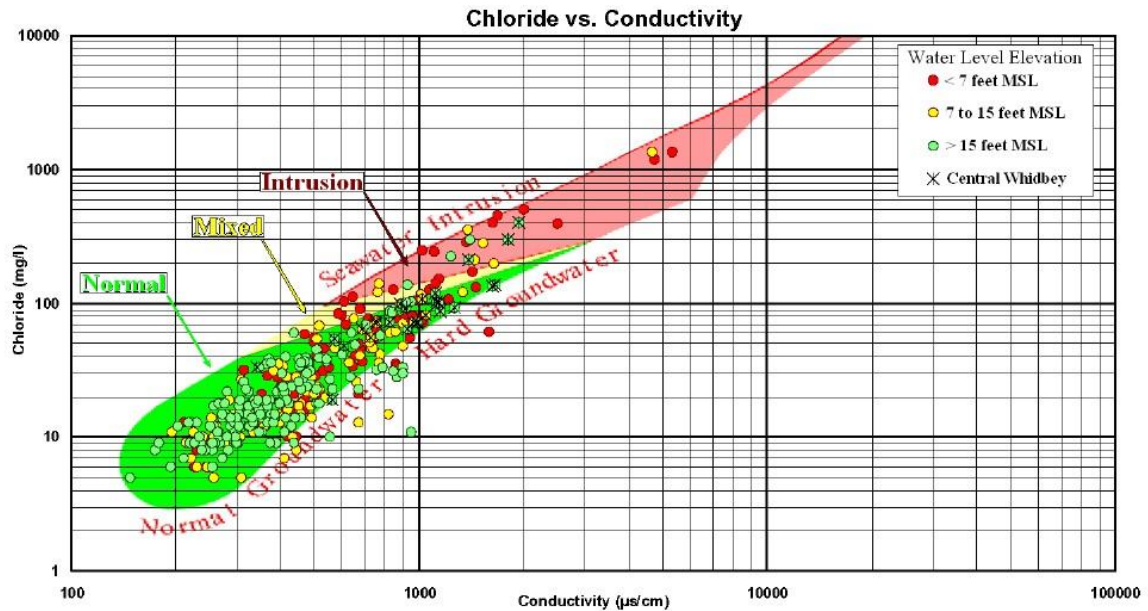


Figure 3. A plot of chloride vs electrical conductivity illustrating Saltwater intrusion, normal groundwater conditions and mixing between the two (Washington State Department of Ecology, 2005)

Steinich et al. (1998) state that traditional Piper plots (Figure 4) can plot the major ions' relative concentrations on ternary diagrams. Samples for seawater and young groundwater are often plotted as end-members, with the other samples illustrating how the groundwater chemistry evolves. For example, symbols can also be scaled according to EC.

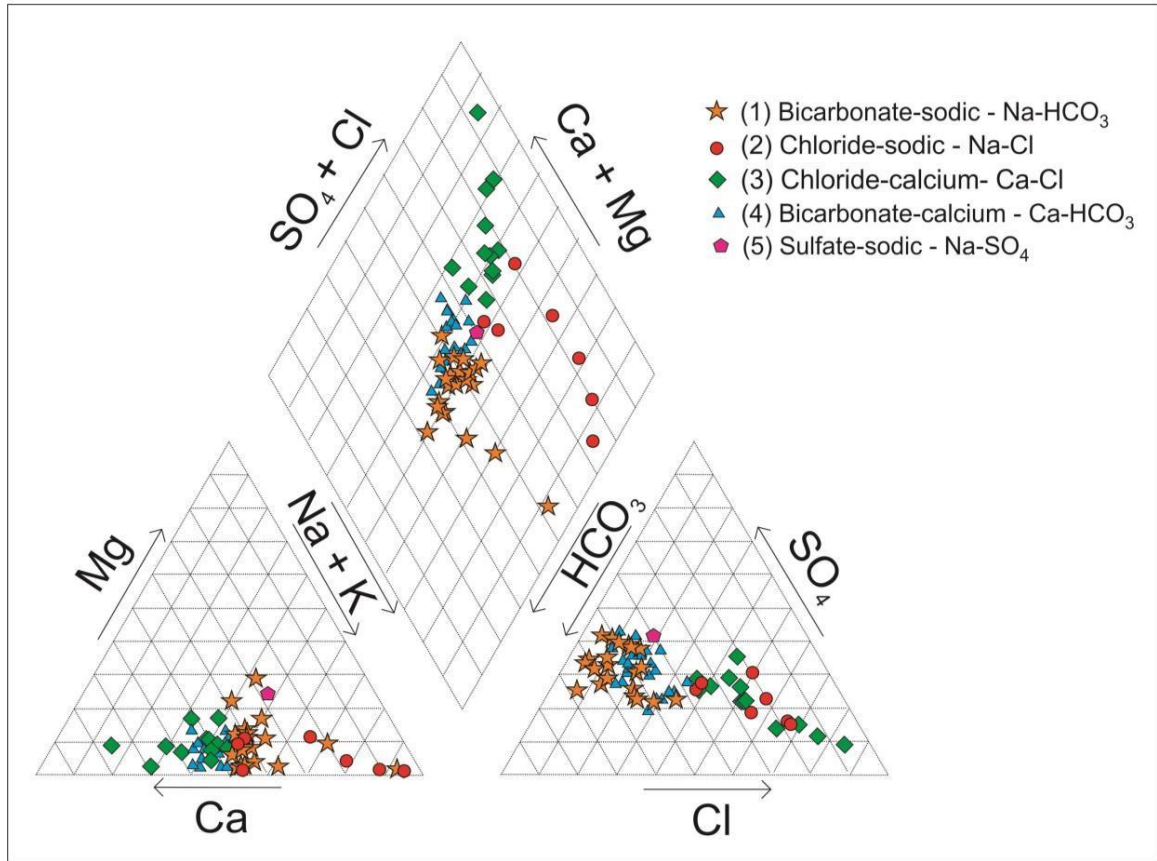


Figure 4: A Piper plot showing five water families; (1) $\text{Na}^{2+}\text{-HCO}_3^-$ (2) $\text{Na}^{2+}\text{-Cl}^-$ (3) $\text{Ca}^{2+}\text{-Cl}^-$ (4) $\text{Ca}^{2+}\text{-HCO}_3^-$, and (5) $\text{Na}^+\text{-SO}_4^{2-}$ (Steinich et al., 1998).

Finally, according to Allen and Liteanu (2008), site-specific approaches can be used for a specific to the situation approach where cation exchange (Ca^{2+} to Na^+) dominates the chemical evolution, includes plotting depth relative to sea level versus TDS, classified according to water type (represented as zones). Waters characterize zone one waters with a high TDS concentration due to direct salinization (mixing fresh groundwater $\text{Ca}^{2+}\text{-HCO}_3^-$ and Seawater $\text{Na}^+\text{-Cl}^-$) in Figure 5. Zone two is characterized by waters with TDS values that do not increase with depth or slightly. These waters show a cation exchange process (Ca^{2+} to Na^+), indicating no increase in salinity. The water types in Zone two differ from $\text{Ca}^{2+}\text{-HCO}_3^-$ to $\text{Na}^+\text{-HCO}_3^-$, with Na^+ rich waters generally found at greater depths.

And then, Zone three represents mixed waters (between Zone two waters and a saline end member) that show a variable cation composition (Ca^{2+} or Na^+) but with increasing Cl^- concentration (Allen and Liteanu, 2008).

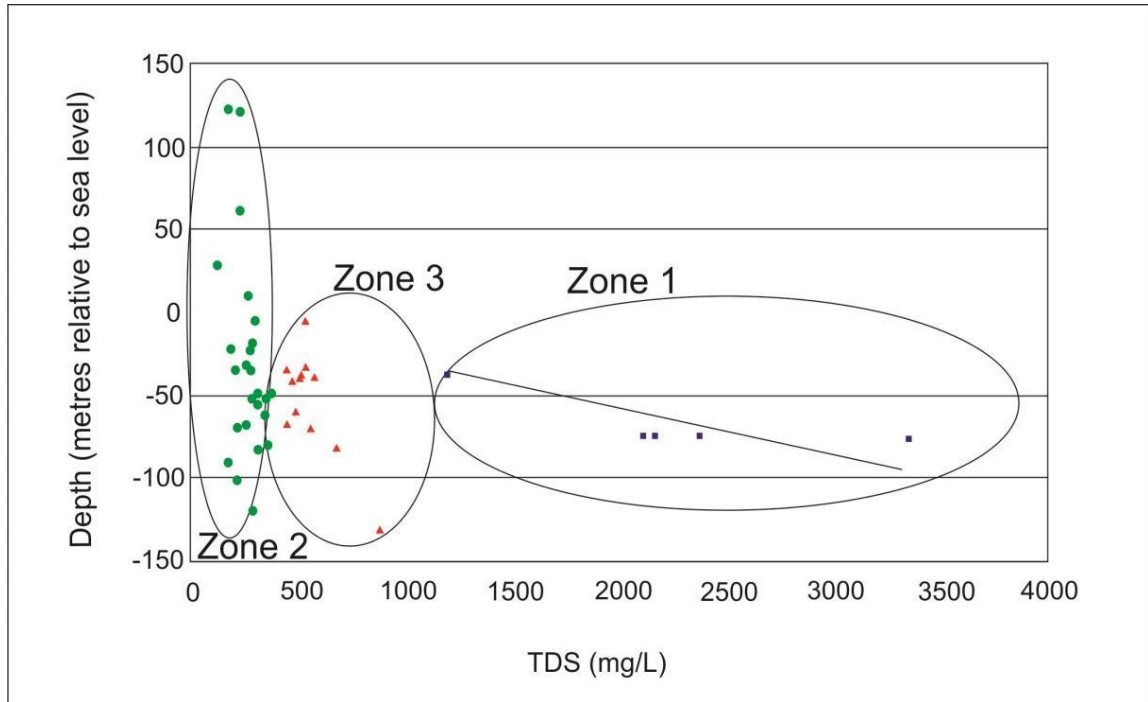


Figure 5: TDS variation with depth relative to sea level for water samples on Saturna Island, British Columbia (Allen and Liteanu, 2008)

2.4 Chemical interactions of groundwater and surface water in streams, lakes and wetlands.

According to the US Geological Survey (2016), groundwater chemistry and surface-water chemistry should be dealt with where surface and subsurface flow systems interact. The water movement between groundwater and surface water provides a major pathway for chemical transfer between terrestrial and aquatic systems.

This chemical movement affects the supply of nutrients such as nitrogen and phosphorus, oxygen, and carbon that fast-track biogeochemical processes on both sides of the interface. This transfer ultimately affects the biological and chemical characteristics of aquatic systems downstream.

The survey continued to indicate that since many streams were contaminated, the need to determine the extent of the chemical reactions in the hyporheic zone is spread widely because of the challenge that the affected stream water will contaminate shallow groundwater. Streams are the best examples of how groundwater and surface water interconnections affect chemical processes. In the hyporheic zone, the Rough channel bottoms cause stream water to enter the streambed and mix with groundwater—this mixing forms sharp changes in the concentration of chemicals in the hyporheic zone. A zone of enhanced biogeochemical activity often develops in shallow groundwater due to the movement of water with oxygen into the subsurface environment, where geochemically active sediment coatings and bacteria are more. This oxygen input to the streambed stimulates a high activity level by aerobic (oxygen-using) microorganisms if dissolved oxygen is readily available. Dissolved oxygen is uncommonly used in hyporheic flow paths at some distance into the streambed, where anaerobic microorganisms dominate the microbial activity. Anaerobic bacteria may use nitrate, sulfate, or other solutes in place of oxygen for metabolism.

The survey results indicated that many solutes are highly reactive in shallow groundwater near streambeds. In the hyporheic zone, the movement of nutrients and other chemical constituents, including contaminants, between groundwater and surface water is affected by biogeochemical processes. For instance, the rate at which organic contaminants biodegrade in the hyporheic zone can be higher than the rates in stream water or groundwater away from the stream. The removal of dissolved metals is also another example in the hyporheic zone. As water passed through the hyporheic zone, dissolved metals were moved by precipitation of metal oxide coatings on the sediments. The lakes and wetlands also have distinctive biogeochemical characteristics concerning their interaction with groundwater. The groundwater chemistry and the direction and magnitude of exchange with surface water significantly affect dissolved chemicals' input to wetlands and lakes.

In general, if wetlands and lakes have little interaction with streams or groundwater, dissolved chemicals' input is mostly from precipitation; thus, the input of chemicals is less. Wetlands and Lakes with a considerable amount of groundwater inflow consist of large inputs of dissolved chemicals. If the input of dissolved nutrients such as phosphorus and nitrogen is more than the output, there is extensive primary production by algae and wetland plants. Oxygen is used in the decomposition process when this vast amount of plant material dies. At times, the loss of oxygen from lake water can be enough to kill fish and other aquatic organisms. The retention of nutrients in wetlands is also affected by the surface-water inflow and outflow magnitude. Retention of chemicals is high when lakes or wetlands have no stream outflow.

The tendency to retain nutrients is less in substantially flushed wetlands through the surface water flow. In general, the increase in surface water inputs and wetlands vary from those that firmly retain nutrients to import and export excessive amounts of nutrients. Furthermore, wetlands commonly have a crucial role in altering the chemical form of dissolved constituents. For example, wetlands with surface water flow tend to retain the chemically oxidized forms and release the chemically reduced forms of metals and nutrients.

2.5 Summary of the Literature Review

Thus, we can deduce that there are seven different sources of water salinization from the literature. It is necessary to know the source of salinization to deal with a particular salinization problem. Furthermore, from the literature, several scholars like Lyes (2000); Kennedy (2012) used a single chemical parameter of chloride to characterize salinity sources. However, other scholars, such as Snow et al. (1990), indicate that using single chemical parameters as indicators of SWI can be problematic. For instance, the high values of Cl^- , Na^+ , Br^- and SO_4^{2-} also correspond with SWI intrusion or connate water source; hence are not useful when distinguishing between different types of saline water. Therefore, this study used several chemical parameters like EC, TDS, Cl^- , F^- , NO_3^- , SO_4^{2-} , Na^+ , K^+ and turbidity to characterize salinity sources in Kachulu area.

Additionally, as evidenced by the literature review, many authors like Leite *et al.* (1978) and Oteri (1983) used the Wenner configuration of resistivity surveys to study coastal, unlike other scholars that include Oteri (1981); El-Waheidi *et al.* (1992); Radhakrishnan *et al.* (1999); Nowroozi *et al.* (1999), who used Schlumberger configuration.

However, according to Baharuddin et al. (2013), the best configuration to employ is Wenner because it is suitable for lateral profiling and provides clear groundwater and saltwater image. Unlike Schlumberger configuration, which is limited to horizontal layered structures, vertical data is not captured. Henceforth it is recommended that the combination of the two methods may give a good insight into the salinization of an area, as evidenced by Frohlich *et al.* (1994). They used Schlumberger geo-electrical depth soundings and horizontal geo-electrical profile using the Wenner configuration to evaluate groundwater pollution surveys in a coastal environment at a sanitary landfill near Provincetown, Cape Cod and the use of Wenner configuration. Like Leite *et al.* (1978); Oteri (1983), this study also adopted a Wenner electrode configuration array to capture vertical data in analyzing the Kachulu area's aquifers.

CHAPTER THREE

METHODOLOGY

3.1 Study area

3.1.1 Location, Rainfall and Population size

The research study was conducted in Kachulu area, Zomba, Malawi. Kachulu is about 30 km from the nearest town, Zomba (UNESCO, 2011), and lies in the lake Chilwa Basin. Lake Chilwa is in the southern region of Malawi in Zomba district, with latitude between 15°00'S and 15°30'S and longitude between 35°30'E and 35°55'E (Figure 6). The area comprises the lake (i.e. open water), typha swamps, marshes and seasonally inundated grassland floodplain. The lake is very shallow, averaging 1-2 metres in depth with a maximum of 5 m (EAD, 2001). The size of the area is about 230,000 ha in area with an average altitude of 627 m above sea level. Chavula (1999) calculated the average rainfall amounting to 1042.9mm per annum for the lake Chilwa catchment. Population pressure around the lake is high, with up to 164 people/ km² and an estimated 77,000 people living in the wetland (UNESCO, 2011). The increase in population greatly impacts the natural resources base, including groundwater. The Chilwa basin plain is surrounded by a few hill formations (including Chisi Island and Mpyupyu Hill). The Lake has no outflow (Sofasi, 2007).

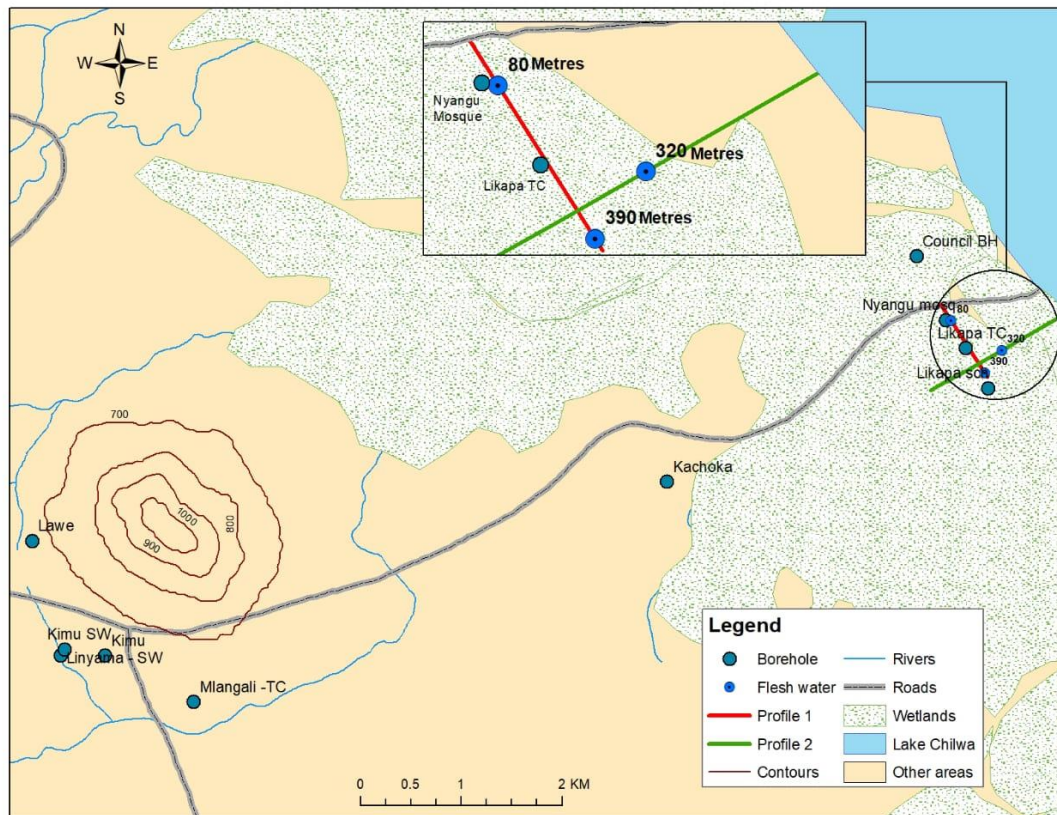


Figure 6: Map of Malawi showing the location of the study area and the areas of freshwater. The map shows lake Chilwa and groundwater sampling locations.

Source: Shapefiles provided by Geological Survey Department, Malawi

3.1.2 Geology

Kachulu area is characterized by ancient metamorphic and igneous rocks of the Malawi basement complex, represented by a group of high-grade metamorphic rocks, primarily charnockitic granulites of quartz and feldspar, and biotite gneisses (Mephram, 1987; Bloomfield, 1965). A series of Precambrian granitic and perthitic rocks are intruded into these gneisses and granites, forming prominent hills. The basement complex rocks are intruded by an alkaline suite ascribed to the Chilwa alkaline province (Mephram, 1987). Mephram (1987) indicates that a complex mix of Quaternary fluvial (alluvial) and lacustrine deposits exist from spatial/temporal influences of open and closed lake Chilwa paleo-environments. The lakebed soil varies from extremely sandy in the north to heavy water-sodden clays in the south. A thick layer of fine silt overlies the whole area of the lake. The areas around the lake Chilwa basin are swampy, dambo areas consisting of fine-grained quaternary alluvial sediments. The sediments are thought to have been deposited in a low-energy environment; thus, the fine-grained particle size gives low yielding. The lowland plains comprise treeless lacustrine flats (Smith-Carington & Chilton, 1983). The soils around lake Chilwa are calcimorphic alluvial soils, locally called “makande soils”. Further “dambos” have been found around the lake (Smith-Carington & Chilton, 1983).

3.1.3 Groundwater of lake Chilwa

According to Bath (1980), there is high salinity in some Malawian groundwater. It arises due to either evaporative concentration or dissolution of evaporate minerals in sedimentary rocks. Evaporative concentration is greatest when the water table is close to the ground surface and exceeds recharge.

Most Sodium and chloride concentrations have been reported for groundwater from the lower Shire valley, resulting from evaporating minerals' evaporation and dissolution. On the other hand, Chilton and Smith-Carrington (1984) also mainly found low-conductivity groundwater in basement aquifers from the Livulezi (central) and Dowa West (south-central) areas. Electrical conductance ranged from $<750 \mu\text{S}/\text{cm}$, but extremes up to $4000 \mu\text{S}/\text{cm}$ (total dissolved solids up to around $2500 \text{ mg}/\text{l}$) were found. Most boreholes close to the river and with shallow water tables have saline groundwater compositions. Affected boreholes are frequently abandoned for water holes in dry riverbeds or surface water.

Missi (2006) indicates that the groundwater in the lake Chilwa Basin is highly saline, leading to water shortages because of poor water quality. According to Saka (2006), the lake is relatively alkaline due to high carbonates and bicarbonates. High salinity is more problematic in these areas as alternative water sources are not readily available (Bath, 1980). The absence of any outflow has led to the high salinity of the lake water (Saka, 2006). The lake's open water is very turbid and saline, supporting only a few specialized plant and animal species (Mephram, 1987). Lake Chilwa has water of about 0-20% of salinity, as evident by the availability of *O. Shiranus Chilwae* species of fish that favours this range of salinity. Several processes occur in the lake, which raises the values of the salinity of the lake, for instance, siltation due to erosion and chemical loading from domestic and industrial discharges (Likongwe, 2002).

Therefore, this study is being conducted to delineate the extent of the area's water salinity in line with previous propositions on the salinity of the lake as documented by various authors Missi and Atekwana (2020); Saka (2006); Mephram (1987) and Likongwe (2012).

3.2 Data collection and analysis

Field trips to Kachulu and desk studies were also conducted to gain insight into the study area's setting and supplement knowledge gaps. This study's general flowchart is given in (Figure 7). Firstly, a desk study aimed to identify the problem in the research area according to previous reports (technical reports and publications were reviewed). The desk study was also undertaken to review all methods (geoelectrical resistivity, hydrogeochemical) to solve the study area's problem.

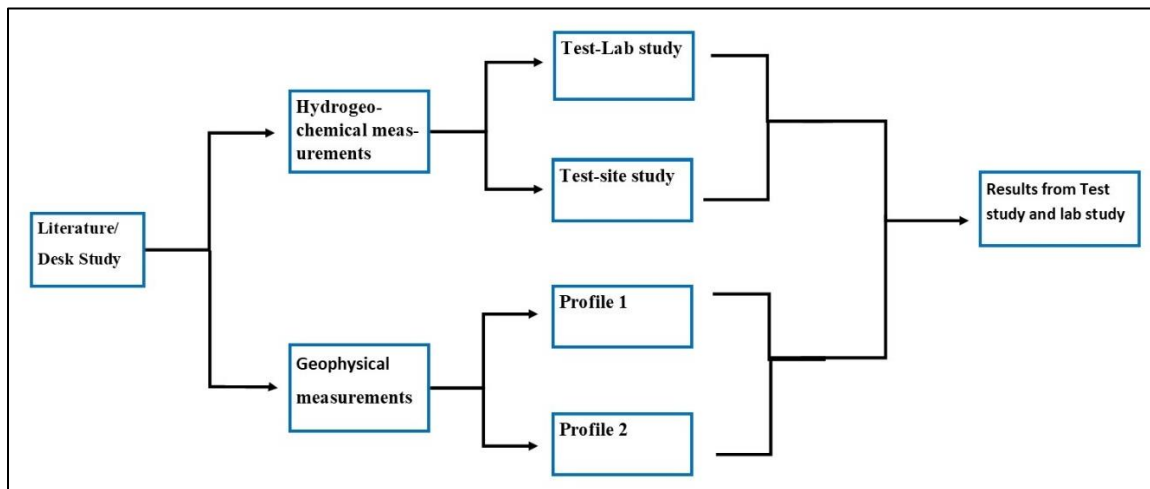


Figure 7: The study flow chart

3.2.1 Geoelectrical resistivity data collection

The data was collected from two Electrical Resistivity tomography (ERT) profiles named profiles one and two.

The profiles were measured using two sets of resistivity meter ABEM Terrameter 1000 ®, ABM Electrode Selector ES464, four multicore cables and a 64-electrode switch box in a LUND configuration multi-electrode data acquisition for the electrical resistivity tomography (ERT) surveys.

The maximum spreading length for profiles was 320m for the 64 electrodes with 5 m spacing with 16 take-out. This spread was aimed at locating deeper aquifers. The survey for all the ERT profiles was carried out using a Wenner electrode configuration array because it detects sand clay boundaries and provides a clear image of groundwater and saltwater (Baharuddin et al., 2013). The ERT profiles were measured close to existing boreholes within the study area. Profile one was measured from the road parallel to the lake (From north-west going south-east), while Profile two was measured from the lake progressively into the mainland Kachulu (from north-east going southwest).

The resistivity meter (Terrameter 1000 ®) (Figure 8) that displays measured resistance or apparent resistivity values on the screen during data acquisition (ABEM, 2007) was connected with an automatic selector system and multicore cable to which electrodes were connected at take-outs with equal intervals. It has four cables denoted as cable one-cable four. Only three cables were laid out and connected to the instrument at the first measurement station, and Cable two and three were connected, excluding cable one. Short and long protocols were used before moving the cable to increase the shallow resolution. Figure (9) shows a systematic layout of the profiles. The spread length of the survey line relied on the target and space available in the field. After running the four by 16 protocol (long protocol), cable one is disconnected and moved to cable four. Then when running the short protocol, cables one and four are turned off.

After getting the results, the equipment is moved to another Centre. Figure (10) below shows the layout of the long protocol and combined protocols' layout.

The sub-surface's resistivity was measured by injecting a certain amount of electric current (10 – 100 mA) into the ground through a pair of stainless-steel electrodes. The grounding of electrodes was correctly installed with good ground contact to avoid the current penetration problem, resulting in a bad data point or error current transmission. During the data acquisition, several electrodes needed to be moistened with water to allow the current underground penetration and propagation due to the hot and dry weather.



Figure 8: ABEM Terrameter 1000

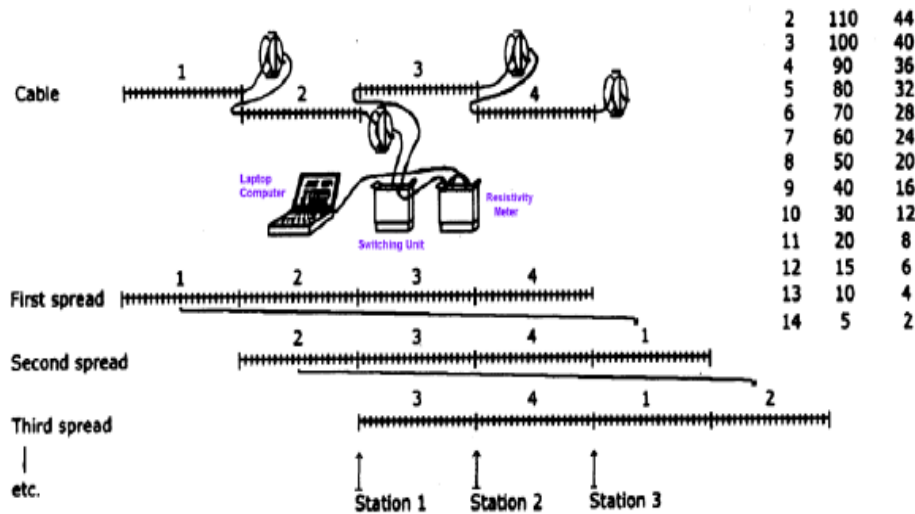


Figure 9: Schematic layout for conducting long profiles (the roll along with method)

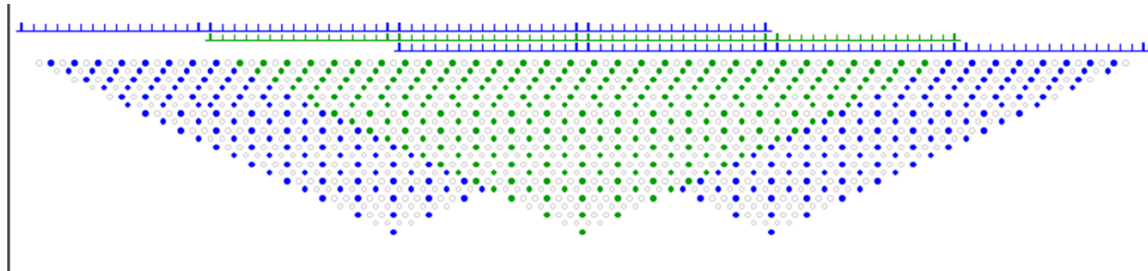


Figure 10: combined-long and short protocol (ABEM, 2007)

3.2.2 Geoelectrical Resistivity Data Processing and interpretation

The data file for all the ERT profiles was imported into Res2DINV software; then, An ATEN USB to serial bridge (COMS) was used to transfer all the ERT profiles' raw data from Terrameter convert it into a standardized format readable by Res2DINV (ABEM, 2007). The protocol WN-4*16 was selected.

The imported data files were then converted to Res 2D Inv format by turning off channels 2 and 3&4 and then edited to remove bad data spots with relatively low or high values. The format data consists of (1) header, (2) data body and (3) end. The complete data were readable by Res2DINV.

The apparent resistivity pseudo-sections were plotted on resistivity profiles using the program RES2DINV (Loke & Barker, 1996) to replicate the stratigraphy and nature of aquifers and potential recharge areas, which could have a bearing on the saltwater intrusion. The scale of resistivity values of the geoelectrical resistivity model was standardized to make the visualization and interpretation process easier. Then the data was analyzed using a RES2DINV inversion algorithm as recommended by (Loke & Barker, 1996) to obtain the Electrical Resistivity Tomography (ERT), thereby obtaining the information about the subsurface lithology and fluid of the study area.

Finally, the inversions were carried out. The inversion routines involve a cell-based inversion technique; it subdivides the subsurface into several rectangular cells. Resistivity is varied to obtain the best fit with the observed data. The experimental and calculated data differences are minimized to obtain an acceptable agreement (Loke & Barker, 1996). This difference is measured by the root-mean-square error (RMS %). However, smoothness-constrained models do not allow for large and unrealistic variations in the output models, as its name suggests. A contour plot has been used to present the true subsurface resistivity for specific areas. This data presentation has been chosen to give data in terms of X and Y location. The product of this presentation is the mapping of certain groundwater cases.

Hazreek et al. (2018) provide the resistivity and conductivity of certain materials (Table 3) below that have been modified after Loke (1999).

Table 3: Resistivity and conductivity value of selected soils and water (Hazreek et al.,2018)

Material	Resistivity (Ohm.m)	Conductivity (S/m)
Clay	1-100	1-0.01
Alluvium	10-800	$1.25 \times 10^{-3} - 1.7 \times 10^{-3}$
Freshwater	10-100	0.01-0.1
Seawater	0.15	6.7

3.2.3 Geochemical data

The groundwater samples were collected from the following ten boreholes within Kachulu and Mpyupyu area from the 9th to 13th October 2017 in Zomba district in the Traditional Authority Mambo. The boreholes from Kachulu include Likapa TC, Council borehole, Nyangu Village, Kachoka CBCC borehole, Likapa primary school, and Mpyupyu has; Mlangali TC, Kimu, Kimu (SW), Linyama (SW), Lawe (Figure 2). The samples were collected, analyzed and the standards were made using the the standard methods for the examination of water and wastewater (APHA, 2005). APHA standard methods are trusted source of accurate, proven methodology for analysing natural waters, water supplies and wastewater, henceforth were used.

The water samples were collected once during the dry season in 1 week, from the 9th to the 13th of October 2017. Four water samples were collected in 500 ml plastic bottles directly from the borehole, and the boreholes were pumped for approximately one minute before the sample was collected. All water samples were filtered through a 0.45 µM nylon filter during collection and before being acidified. The sample bottles were rinsed with the filtered water sample three times before filling up to the edge.

Then later, samples meant for metal analysis were acidified with nitric acid. Metal samples were kept at room temperature in the lab on the bench until the analysis was done, and anion samples were kept in a fridge at 4° C until the analysis was done. Sample analysis was done at the chemistry laboratory of Chancellor College, University of Malawi. The analysis was done to determine the lake water intrusion's actual extent and longitudinal water quality. The results are presented in the range (min-max), mean + standard deviation (SD), and median and have been compared with national (Malawi Bureau of Standards (MBS)) and international (World Health Organization (WHO)) standards.

3.2.4 Temperature, pH, EC and TDS

Several sensitive parameters of water, such as temperature, pH, Electrical conductivity (EC) and Total dissolved solids (TDS), were measured in situ (Table 6). A Hanna Instrument HI991300N waterproof pH/EC/TDS/Temperature meter, which was well-calibrated as described by the manufacturers (Hanna Instruments, MAN991300), was used to measure these parameters as detailed in the standard methods for the examination of water and wastewater (APHA, 2005).

3.2.5 Sulphates, Nitrates

A turbid metric method was employed where a water sample of 100ml was pipetted into a 250ml conical flask. A spoonful of BaCl⁻ mesh was added, followed by 5ml of reconditioning reagent and stirred on a magnetic stirrer for 1 min. PG instruments read the absorbance of 420nm for sulphates and 220nm for nitrates using a T90+UV/Vis Spectrometer (APHA, 2005).

3.2.6 Fluoride

In each test, 100ml of water sample was pipetted into a beaker and 10ml of TISAB was added to a beaker where Fluoride was determined. An ion-selective electrode made by Cole Parmer was used on a seven Multi-Mettler Toledo GmbH 8603 model meter made in Switzerland (APHA, 2005).

3.2.7 Metals (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Fe^{2+})

An acidified 100ml water sample was filtered using Whatman number 42 filter paper until the water sample was clean and ran on AAS Agilent 200 series AA with SPS AA autosampler made by Agilent Technologies Japan LTD in Australia (APHA, 2005).

3.2.8 Turbidity

Turbidity was measured immediately after the sample was drawn using a microprocessor-controlled turbidity meter, H1 93703 (Hanna Instruments limited, Bedfordshire, UK). The instrument was calibrated with standard solution 10 Nephelometric Turbidity Units (NTU), 200 NTU and 999 NTU. The standard solutions were prepared by dissolving 1.000 g hydrazine $(NH_2)_2.H_2SO_4$ in distilled water and diluted to 100 mL in a volumetric and 10.00 g hexamethylenetetramine $(CH_2)_6N_6$, in distilled water and diluted to 100 mL in a volumetric flask. Then 5 mL of $(NH_2)_2.H_2SO_4$ were mixed with 5 mL of $(CH_2)_6N_6$ solution to 4000 NTU stock suspension, which was diluted with distilled water to make 10 (NTU), 200 NTU and 999 NTU standard solutions for instrument calibration.

After calibration, a cell containing distilled water was used as blank to ascertain the measurement accuracy if the reading was zero (APHA, 2005).

3.2 Summary of the Methodology

The data was collected using geophysical and hydrogeochemical methods of groundwater investigation.

The geophysical data was measured in two profiles (profile one and two) using two sets of resistivity meter ABEM Terrameter 1000 ®, ABM Electrode Selector ES464, four multicore cables and a 64-electrode switch box in a LUND configuration. The survey for all the ERT profiles was carried out using a Wenner electrode configuration array. Then the data was analyzed using a RES2DINV inversion algorithm as recommended by (Loke and Barker, 1996) to obtain the Electrical Resistivity Tomography (ERT), thereby obtaining the information about the subsurface lithology and fluid of the study area.

Groundwater samples were collected from ten boreholes and lake Chilwa using standard sampling procedures (APHA, 2005). The data was collected from the 9th to the 13th of October 2017 in Zomba district in the Traditional Authority Mambo. Four water samples were collected in 500 ml plastic bottles directly from the borehole, and the boreholes were pumped for approximately one minute before the sample was collected. All water samples were filtered through a 0.45 µm nylon filter during collection. The sample bottles were rinsed with the filtered water sample three times before filling up to the edge. Samples were analyzed at the chemistry laboratory of Chancellor College, University of Malawi. The analysis determined the water intrusion's actual extent and longitudinal water quality.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

The Chapter aims to present and discuss the results obtained from the study. The geophysical survey results have been presented and discussed using the earth imager resistivity depth inverse model for the Electrical Resistivity Tomography profiles (ERT). The ERT analysis was necessary to determine freshwater areas in Kachulu area. Additionally, the ERT also indicated the extent of salinity in the area. Then, the presentation and description of data obtained from the geochemical survey by analyzing different chemical parameters and ratios. The parameters include the EC, TDS, Cl^- , F^- , NO_3^- , SO_4^{2-} , HCO_3^- , CO_3^{2-} , PO_4^{2-} , Na^+ , K^+ and turbidity. The geochemical study indicated the water quality of the ten sampled boreholes in the study area and gave insight into the possible salinization sources. The final section concludes the findings of the study.

4.1 Geophysical data

Figure 11 (a, b) shows the resistivity inverse model for profiles one and two for the dry season survey. Figure 11(a) shows profile one, while figure 11(b) indicates profile two. Table 5 shows the subsurface materials' interpretation of the study area. The Subsurface profile mapping generated by surface mapping of the electrical method was interpreted based on the tomography outcome, as shown in Figures 11(a, b).

The two-dimensional (2D) Electrical Resistivity Tomography (ERT) profiles obtained from the survey have resistivity values ranging between 0 – 16,384 Ω m. For the interpretation, this value has been divided into four ranges based on established references (e.g., of Hazreek et al., 2018, see Table 2 in Chapter 2.3). The low resistivity value is associated with saltwater intrusion. The resistivity value below 5.0 Ω m significantly impacted the presence of saline water in aquifers (Oyeyemi, 2015).

Table 5 indicates that the resistivity value below 5 Ω m was classified as saltwater and marked as dark blue. Then, ERV of 5 – 15 Ω m was categorized as brackish water and marked as blue colour in the ERT, while the ERV of 50 – 100 Ω m was interpreted as freshwater and marked as turquoise to green colour in the ERT. The high resistivity value is also considered to identify the distribution of hard materials underground in the study area. Resistivity value larger than 400 Ω m was interpreted as a hardened layer (rock) and marked yellow-red colour in the ERT. The two freshwater points marked as turquoise to green colour (with ERV of 50 – 100 Ω m) in the ERT have been mapped as shown in Figure 6.

Table 4: Interpretation of subsurface materials of the study area

Resistivity Value	Material	Mark on inverse model
< 5 Ω m	Seawater (saltwater)	Dark blue colour
5 – 15 Ω m	Brackish	Blue colour
50 – 256 Ω m	Freshwater	Turquoise – green colour
> 400 Ω m	Hard layer (rock)	Yellow – red colour

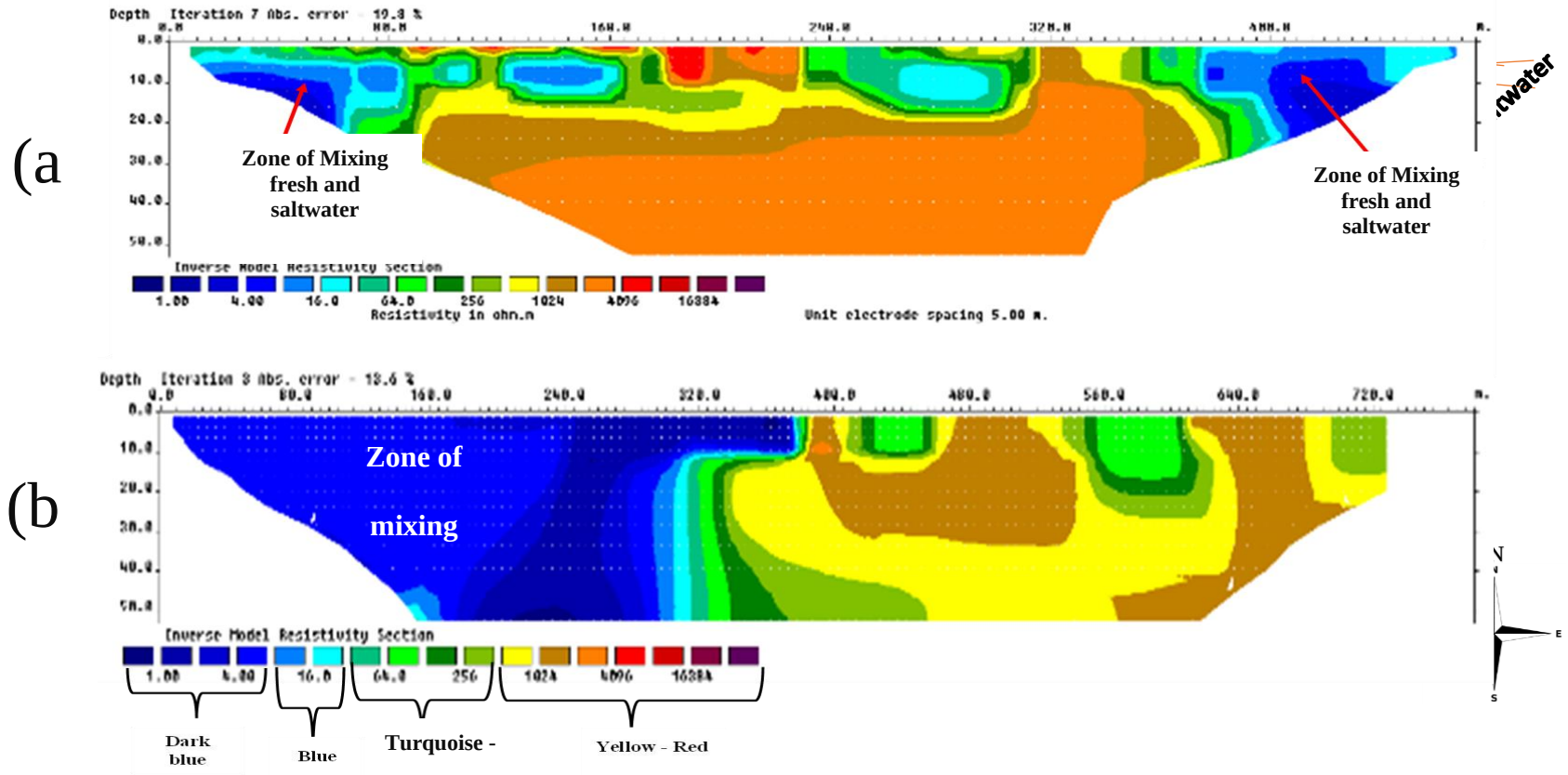


Figure 11: (a and b) shows the Earth Imager Resistivity Depth inverse model for the Electrical Resistivity Tomography (ERT) for profile one and two (Note: Lake was located at 0 m of the ERT)

Geophysical results have been discussed based on electrical resistivity tomography (ERT), as shown in (Figure 11). Electrical resistivity surveys provide essential information on the subsurface geology in the study area, and they indicate variation in subsurface conductivity/resistivity, reflecting the fluid content. The results show lake water's distribution, fresh water and mixing of salt and freshwater up to 50 m in depth. Based on the electrical resistivity value (ERV) results, four ERV ranges have been identified for interpretation, as shown in Table 5.

In both profiles one and two, the reduction of ERV ($< 5 \Omega\text{m}$) ERT was found, indicating the saltwater's intrusion process towards the groundwater aquifer. According to Figure 11(a) above (Profile one), the low ER distribution was almost in a similar trend, thus verifying the results and interpretation of ERT obtained. Profile one at 360m crosses profile two at 520m. At the point of crossing, the resistivity value larger than $400 \Omega\text{m}$ has been detected, indicating the possibility of a hardened layer (rock). It has been marked as yellow-red colour in both the ERT profiles. Saltwater has been mapped at 0-80 m on the survey line at 20 m depth and 435m on the survey line at 35m because the subsurface area has predominantly low resistivity ($< 5 \Omega\text{m}$). Freshwater with a $64 \Omega\text{m}$ resistivity between $50 - 100 \Omega\text{m}$ has been detected at 80m on the survey line at 25m. Consequently, another freshwater zone is registered at 390m on the survey line at 25m with the same resistivity ranges. These freshwater areas are shown in Figure 11 (a) and mapped in figure (6) above.

On the other hand, high resistivity is registered at a distance of 210m and 50m depth ranging from $1024-4096 \Omega\text{m}$.

Resistivity values in this range are the Basalt rocks (Igneous and metamorphic rocks), as indicated by Keller and Frishknecht (1966) in the resistivity of some rocks (See Table 1 in chapter 2). This has been found unsurprisingly because the Kachulu area's geology contains igneous and metamorphic rocks. Igneous and metamorphic rocks are characterized by negligible porosity and permeability in terms of groundwater exploitability. Therefore, this area is not feasible for borehole drilling because of the freshwater absence, as depicted in figure (11) above. Figure 11 (a) also revealed that saltwater and brackish water with a minority of freshwater lenses have the subsurface profile studied. As explained in Chapter One, the domination of saltwater and brackish water in the study area has been found unsurprisingly due to its geological condition.

On profile two (Figure 11b), the saltwater is mapped from 240 -320m on the survey line at 50 m depth and 435m at 35m because the subsurface area has low resistivity of $< 5 \Omega\text{m}$. The low resistivity indicates lake water invasion of the freshwater aquifer to a depth of 0–50 m due to excessive water withdrawal from the nearby boreholes. A borehole (Council borehole) exists at about 80m away from the 435m on profile two. The borehole has brackish water, as explained below by the geochemical study. Brackish water has also been delineated from 1-240m and an extension at 380m on the survey line with low resistivity ranging from 5 – 15 Ωm . The decrease in resistivity structure reflects the conductive nature of the aquifers in Kachulu.

The extension of this low resistivity structure to about 380m on the survey line indicates that there is a possibility that the brackish water percolation may have polluted the shallow aquifer in this area through the porous topsoil. Accordingly, the first and the second aquifer have been contaminated by the saltwater intrusion from the lake.

Freshwater has been registered at 320m of the survey line at 50m with resistivity ranging from 64 Ωm , as shown in Figure 11(b) above. This area is also feasible for borehole drilling. While high resistivity values ranging from 1024 -16884 Ωm (which is $> 400 \Omega\text{m}$) have been observed at a distance of 400-720m, as shown in figure 11(b), indicating unavailability of water but rather the availability of sand soil and rock material under the surface which has high porosity and permeability.

Saltwater intrusion from the ERT resistivity-depth models shows that some aquifer units may have been impacted by saline water due to invasion from the lake. Generally, the polluted regions were characterized by a very low resistivity value, less than 10 Ωm . Other sources of pollution observed from our results include brackish water infiltration from the lake. It is strongly perceived that daily excessive groundwater extraction by the over 20 functioning boreholes in Kachulu area would aggravate the saltwater intrusions.

4.2 Hydrogeochemical data

In the previous section, the geophysical study revealed that some aquifers in Kachulu area had been impaired by salinization; thus, the investigation of water quality in boreholes is paramount because it will help confirm the results obtained by the geophysical method. Henceforth the hydrogeochemical study was conducted to analyze the groundwater quality of the already existing boreholes in the study area. The hydrogeochemical study also aims to identify the possible sources of salinization in the study area, enabling the engineers to determine the best way to alleviate the salinity problem in Kachulu area.

4.2.1 pH

The summary statistics of the results are presented in Table 6, while the physical and chemical parameters results are shown in Table 7. Figure 12 illustrates the distribution of *pH* in the boreholes. *pH* is the measure of the acid balance of a solution- that is, the degree of acidity or alkalinity of a medium. The *pH* scale runs from 0 to 14 (1-6 is acidic, 7 neutral and above 7 to 14 alkaline). In water quality, low *pH* is corrosive to metals, gives a metallic taste and high *pH* gives a bitter taste. A range of 6.5-8.5 was determined as the *pH* to achieve the maximum environmental and aesthetic benefits.

The lake water samples' *pH* was more alkaline, recorded at 9.5 (Table 7). The more alkalinity of the lake means that the lake is saline, and this is because lake Chilwa is a sink without a surface outlet for all sediments from catchment rivers and run-offs (Mumba et al.,1999; Saka, 2006). The *pH* of groundwater ranged from 6.5 to 8.1 and averaged 6.9 (Table 6). One borehole at Likapa primary indicates a *pH* of 7; five boreholes recorded a *pH* below 7, indicating acidity because they are located away from the lake (Figure 12). Four boreholes registered a *pH* above 7, indicating alkaline water (Table 7). Nyangu borehole and Council borehole record water with high *pH* (Alkalinity) because they are located close to the lake, and the saltwater intrusions from the lake may cause the alkalinity (Figure 12).

The higher *pH* recorded at Kimu SW and Linyama boreholes may be attributed to various chemicals and pollutants. For instance, if the soil or bedrock around the groundwater sources includes carbonate and bicarbonate compounds, those materials get dissolved and travel with the water. Alkaline water shows that some boreholes in the study area are saline.

Henceforth the *pH* level confirms the geophysical study results, which concluded that some places in the study area are saline and not fit for other uses due to saltwater intrusions.

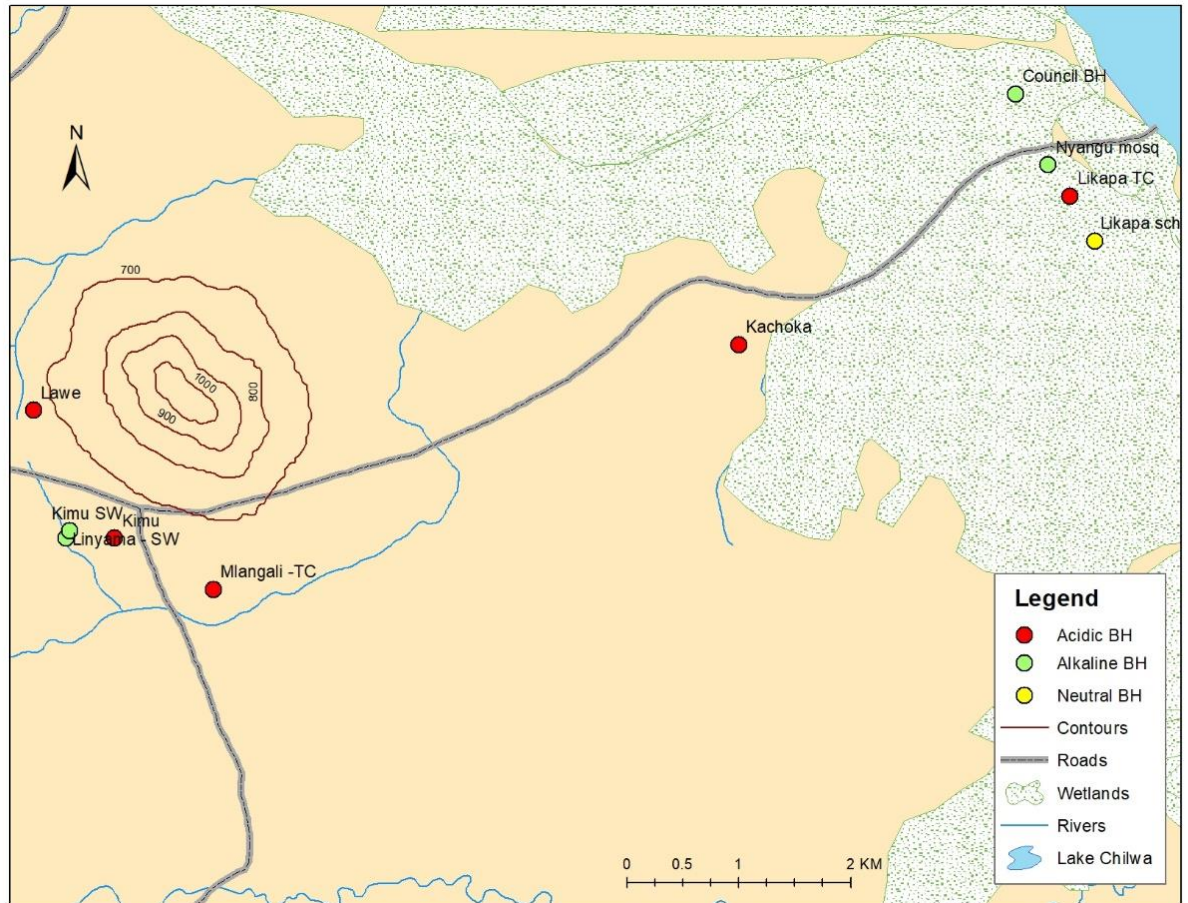


Figure 12: Map of Malawi showing the distribution of *pH* in the groundwater samples. Shapefiles provided by Geological Survey Department, Malawi.

Table 5 Summary statistics of the physical and chemical compositions for groundwater samples. All values are in mg/L except pH, temperature (°C), and electrical conductivity (EC) (µS/cm). Minis is the minimum value, Max is the maximum value, and SD is the standard deviation.

	pH	Ec(µs/cm)	TDS (ppm)	Fe(mg/L)	Mg(mg/L)	Na(mg/L)	Ca (mg/L)	K(mg/L)	F- (mg/L)	NO3- (mg/l)	SO4-2	PO4-2	Cl- (mg/l)	CO3-2	HC O3-	Turbidity (NTU)	Alkalinity	Hardness
mean	6.998	851.2	532	253.7	27.1	54.5	11.2	2.08	0.9	0.89	5.5	4.16	55.3	52.3	110.5	16.6	197.8	102.5
min	6.5	344	168	0.04	0.9	39.8	1.6	0.3	0.5	0.01	1.6	0.04	0.03	2.8	6	0.3	1.1	31.4
max	8.1	2902	1450	942.5	133.5	77.2	22.9	9.6	1.6	2.4	15.97	16.2	119.1	79.9	214.7	40.9	374.4	178.9
SD	0.5	855.8	509.8	396.1	40.6	11.4	7.4	2.92	0.4	0.7	4.8	6.3	43.7	26.8	82.0	17.7	156.4	49.5

Table 6: Results of the physical and chemical analyses of the groundwater and Lake Chilwa samples, Quality Standards for the World Health Organization (WHO) Drinking Water Guidelines (WHO, 2008) and Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005)

WP	pH	Ec(µs/cm)	TDS (mg/L)	Fe(mg/L)	Mg(mg/L)	Na(mg/L)	Ca (mg/L)	K(mg/L)	F-(mg/L)	NO3-(mg/l)	SO4 - ₂	PO4 - ₂	Cl-(mg/l)	CO3 - ₂	HCO3-	Turbidity (NTU)	Alkalinity	Hardness
WHO Guideline	Not stated	Not stated	1000	Not stated	150	Not stated	200	10	1.5	50	400	Not stated	250	Not stated	Not stated	Not stated	Not stated	Not stated
MBS Guideline	Not stated	Not stated	2000	3	150	200	200	10	2	50	800	Not stated	250	Not stated	Not stated	25		800
kachoka	6.8	419	210	0.51	10.4	77.2	15	0.3	1.6	2.4	1.6	0.0	119	75.1	180.3	1.3	330.6	80.0
Nyangu mosque	8.1	2902	1450	942.5	134	63.1	11	9.6	0.5	0.1	16.0	16.2	3.69	2.76	5.9	40.9	5.4	31.4
Likapa TC	6.9	1554	779	506.35	14.9	59.1	1.6	0.4	1.1	0.7	10.1	11.6	0.03	32.7	6.2	38.3	1.1	107.1
Likapa school	7.0	2323	1278	830.7	0.9	48.4	1.9	0.5	0.6	1.0	6.9	8.9	0	27.1	27.0	31.4	2.3	178.9
Council BH	7.8	2507	1251	923	128	56.1	9	9.1	0.5	0.1	14.9	15.2	3.44	2.16	5.0	39.4	4.3	101.1
Kimu	6.5	344	168	0.04	9.73	44.4	5.9	1.5	0.6	0.0	2.1	0.1	68.6	55	93.3	0.4	203.3	54.7
Kimu Sw	7.2	420	210	2.161	14.2	46.4	20	2.1	0.6	0.5	2.5	0.2	71.6	70.9	185.4	8.1	327.2	108.1
Linyama Sw	7.4	426	213	1.228	21.5	54.5	14	0.7	1.3	1.5	2.8	0.1	84.1	79.9	214.7	28.3	374.4	122.7
Lawe	6.7	592	297	0.09	27.1	57.7	23	1.8	0.7	0.8	4.0	0.1	89.1	77.5	168.7	0.3	323.7	168.9
Mlangali TC	6.5	364	183	0.064	11.6	39.9	9.3	1.8	0.6	1.0	3.8	0.2	61.5	49.7	113.2	0.3	212.5	70.8
Lake Chilwa	9.5	3999	2000	0.615	14.5	1673	11	26.5	10.7	28.7	48.9	1.0	2582	626	1240.7	155	2,492.2	88.1

4.2.2 TDS and EC

The average TDS concentration for all groundwater samples was 532mg/L, ranging from 168 to 1450 mg/L, with Kimu borehole registering the lowest and Nyangu borehole registering the highest (Table 6). The lake water recorded high TDS values of 2000mg/L. Figure 13 below shows TDS concentrations for the lake water and the groundwater points against the Malawi Bureau of Standards (MBS) Maximum Permissible Levels of 2000 mg/L. The groundwater samples satisfy the acceptable limit based on the MBS's TDS concentration allowed for drinking water (Figure 13).

Nevertheless, the water consumers in Kachulu area do not accept the water in the boreholes even though the TDS levels are within the acceptable range. For instance, the water at Nyangu borehole is not used for drinking by the people, and the borehole has water of reddish colour (Figure 14) caused by the high levels of iron registered. The elevated TDS values imparted an unpleasant taste; water consumers confirmed this. Apart from imparting an unpleasant taste, water with elevated TDS values may be corrosive and hard as the result of constituents that constitute TDS. For example, iron may cause colour, odour or taste problems; high sulfate levels may be toxic; chloride may impart unpalatable taste; calcium and magnesium may increase hardness levels that limit domestic water use like washing due to its tendency to consume a lot of soap. It may give water a red or blue-green colour if the concentrations of iron and copper are relatively high.

On the same note, as per TDS classification, groundwater and lake water are brackish (TDS >1000 mg/L) (Freeze and Cherry, 1979).

The TDS for the three boreholes (Nyangu, Council, Likapa primary school and the lake water) is more than 1000 mg/L indicating that the water is brackish (Figure 13a). The availability of brackish water in these boreholes suggests that there is a mixing of fresh and saltwater from the lake. The lake water slowly moves from the lake to the inland aquifers because of the introduced gradients. Continue construction of boreholes in the area may aggravate the process enabling Kachulu aquifers to have saline and brackish water.

The availability of brackish water in the boreholes is why people do not use and accept the water. Additionally, the TDS levels are in a trend such that the boreholes close to the lake have more TDS than those away. For instance, Nyangu borehole records higher TDS and is located close to the lake, seconded by Likapa primary school borehole, as shown in figure 6 above. The increased TDS at Nyangu borehole, Council borehole, Likapa Primary school, and the lake water confirms the study's geophysical results that indicate that some of the aquifers in study area Kachulu have saline and brackish water.

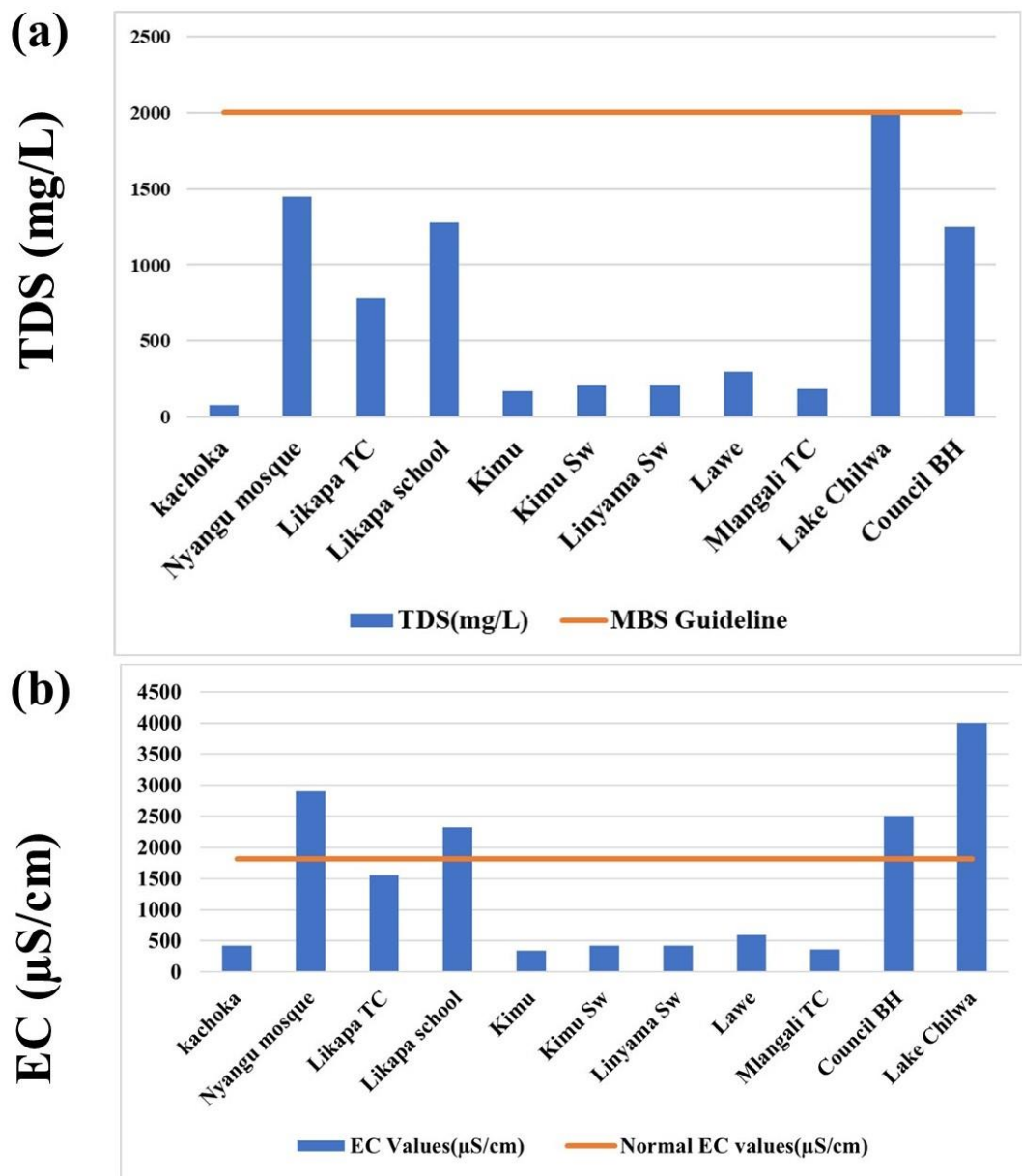


Figure 13: Plot of total dissolved solids (TDS) concentrations and EC for Groundwater and Lake Water. The plot is also a line representing the Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005)

As shown in Figure 13(b), the Lake Chilwa water sample and three groundwater samples (Nyangu Mosque, Likapa primary school and Council BH) have a concentration of EC above the MPL of 1818 $\mu\text{S}/\text{cm}$ specified by the WHO (2008) and MBS (2005).

Table 7 indicates that the EC averaged 851.2 μ S/cm for groundwater and ranged from 344 to 2902 μ S/cm, while the lake water samples recorded the highest EC of 3999 μ S/cm. The increased levels in the lake water may be attributed to the same reason Saka (2006) described that the absence of the lake's outflow has led to the high salinity of the lake water. Most boreholes registered low EC levels; for example, Kachoka CBCC boreholes reported an EC level of 419 μ S/cm. As Mosque (2014) discussed in section 2.3, EC is the basic indicator of knowing whether an aquifer has been contaminated by saltwater. Thus, the groundwater is normal if EC is under 1000 μ S/cm. Boreholes at Nyangu, Likapa Primary school, Council borehole and Likapa TC register a high EC level of 2902 μ S/cm, 2323 μ S/cm and 2507 μ S/cm, 1554 μ S/cm, respectively.

Similarly, lake Chilwa Water has an EC of above 3999 μ S/cm, which is above normal. (Table 7 and Figure 13 (b)). The increase in EC levels indicates the availability of saline in the boreholes and the lake. Henceforth, as Mosque (2014) explained, saltwater intrusion is the source of salinization in these areas. Additionally, these four boreholes are less than 800m away from the Lake; subsequently, the saltwater intrusion in these boreholes may be due to the pumping rate that has introduced gradients, making the saltwater from the Lake gradually encroach the shoreline aquifers. The lake recharges the aquifers, and since its water is saline, the invaded aquifers become more conductive. The ERT survey also reported this trend.

4.2.3 Turbidity



Figure 14: Colour of water at Nyangu Borehole

The lake water sample and five groundwater samples (Nyangu Mosque, Likapa primary school, Likapa TC, Council borehole and Linyama SW) have a concentration of turbidity above the MPL of 25 NTU specified by the MBS (2005) (Figure 15). The lake water records high turbidity values of 155 NTU, seconded by Nyangu borehole, which records turbidity values of 40.9NTU, then Likapa TC, which records 38.3 NTU, Likapa primary school, which records 31.4 NTU, and the Council BH, which records 39.4 NTU and Linyama SW which records 28.1 NTU. High turbidity levels indicate the cloudiness of water caused by total suspended or dissolved solids(salts). Turbidity also affects the colour (Figure 14 above) and water taste.

The high turbidity levels show that the water in these boreholes has water of deteriorated quality and is unfit for consumption (Getso et al., 2018). This confirms the geophysical study, which revealed that the aquifers of Kachulu area have saline and brackish water.

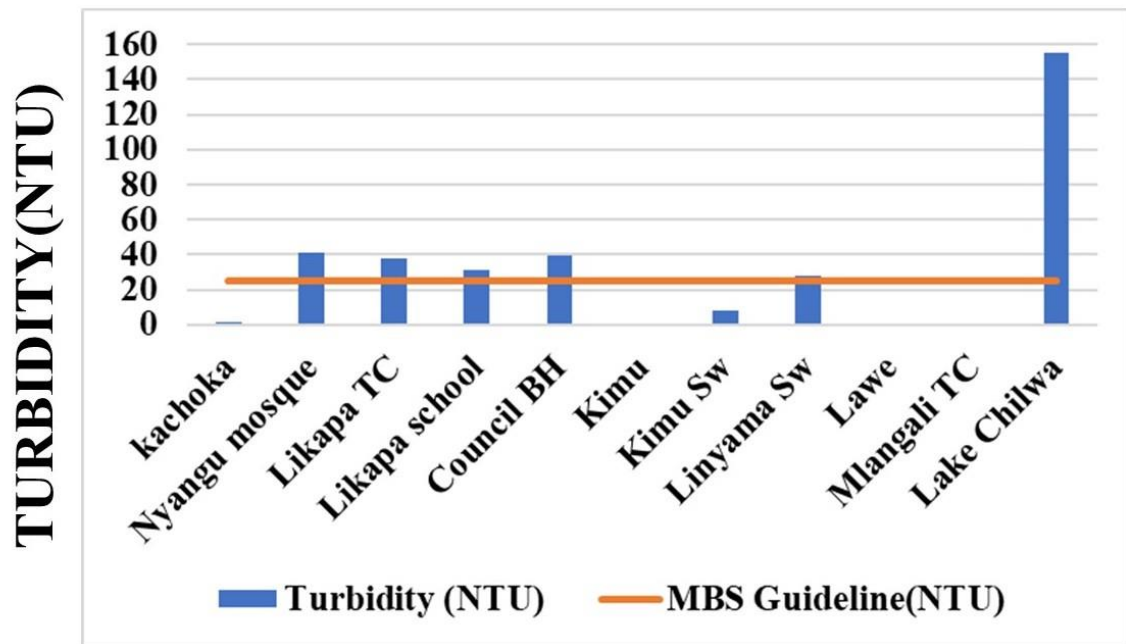


Figure 15: Plot of Turbidity. The plot is also a line representing the Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005)

4.2.4 Cations (Na^+ , Ca^{2+} , Mg^{2+} and K^+)

According to WHO water quality guidelines (2008) and Malawi Standards for water delivered from boreholes and shallow wells (2005), the maximum permissible level (MPL) for Sodium (Na^+) in drinking water is 200 mg/L (Table 7). However, as depicted in table (7), the Na^+ concentrations in all the groundwater samples are below the MPL.

It is also denoted that Na^+ concentrations are higher than other cations (Ca^{2+} , Mg^{2+} and K^+) and anions in most samples (Figure 16).

According to Nurwidyyanto and Widodos (2006), CO_3^- and HCO_3^- is the most dominant ion in groundwater that has not been affected by saltwater. From table 7, Nyangu borehole, Council borehole and Likapa primary school are dominated by the Na^+ and other ions, not CO_3^- and HCO_3^- . This indicates that these boreholes have been affected by saltwater. Also, these boreholes are located less than 800m from the lake. Subsequently, saltwater intrusions may be the source of brackish water in these boreholes.

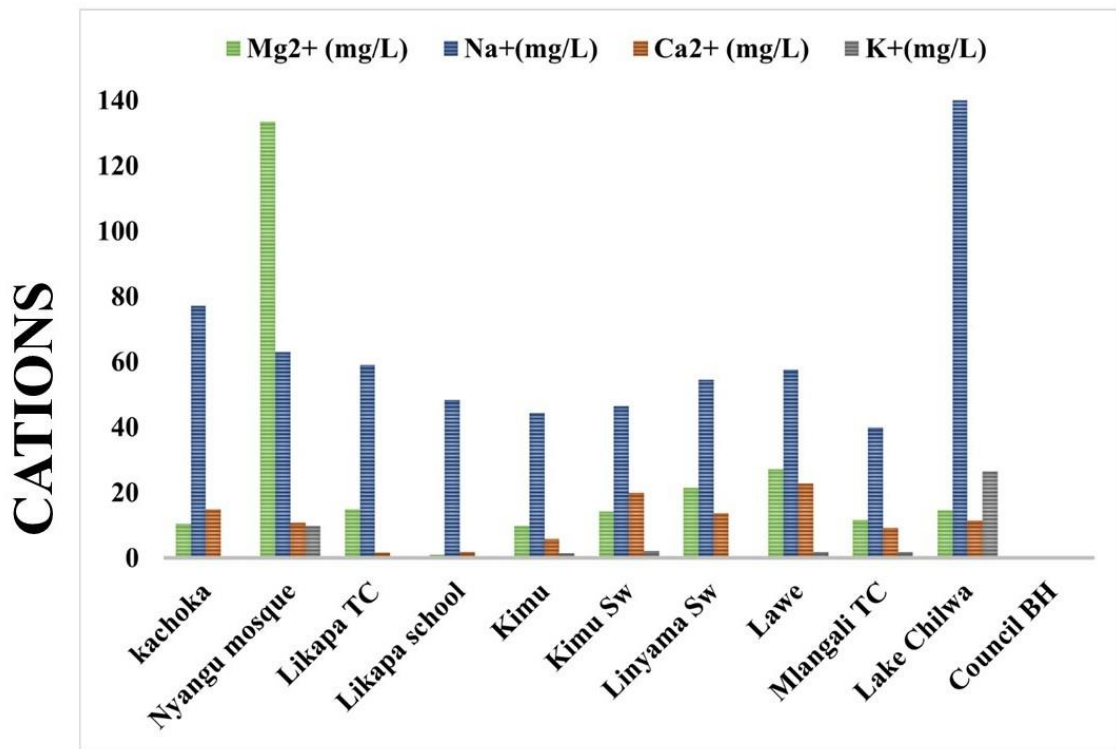


Figure 16: Plots of concentrations of cations (a) Na^+ and (b) K^+ for Groundwater and Lake Water. The plot is also a line representing the Malawi Bureau of Standards (MBS) Maximum Permissible Levels (MBS, 2005)

Na^+ is a vital mineral for the body and maintains the water balance in and around the body's cells. It is vital for proper muscle and nerve function and helps maintain stable blood pressure levels.

Therefore, drinking the water of the recommended quality is recommended to prevent these health disorders. On the other hand, the concentrations of Na^+ in the lake water samples exceed the MPL (Table 7). Excess Na^+ water makes water unsuitable for drinking because it causes severe health problems like hypertension (Mose et al., 2017). Similarly, the concentration of K^+ in groundwater water samples is less than ten mg/L, the MPL as per WHO (2008) and MBS (2005) (Table 7). The low levels of K^+ in Groundwater could be the consequence of its tendency to be retained in clay minerals and contribute to secondary minerals formation (Zhu and Fujimura, 2007).

4.2.5 Anions (SO_4^{2-} , NO_3^- , Cl^- , F^- , HCO_3^- , CO_3^{2-} , PO_4^{2-})

Figure 17 is a plot of all the anions. The figure illustrates that most groundwater samples have been dominated by HCO_3^- ion. This means that the water in these boreholes has not been affected by saltwater (Nurwidyyanto & Widodos, 2006). Table 7 above indicates that one groundwater sample and the lake water sample have F^- concentrations that exceed the permissible limit of 1.5 mg/L as prescribed by WHO (2008) and MBS (2005). This evidence confirms that the groundwater of Kachulu area is saline. The high Fluoride in groundwater concentrations in the lake Chilwa basin results in consumers being subject to dental fluorosis and skeletal fluorosis (Smith and Chilton, 1983). The increase in fluoride in the borehole at Kachoka CBCC may be attributed to the dissolution of rocks because it is located away from the lake, and saltwater intrusion may not be the cause.

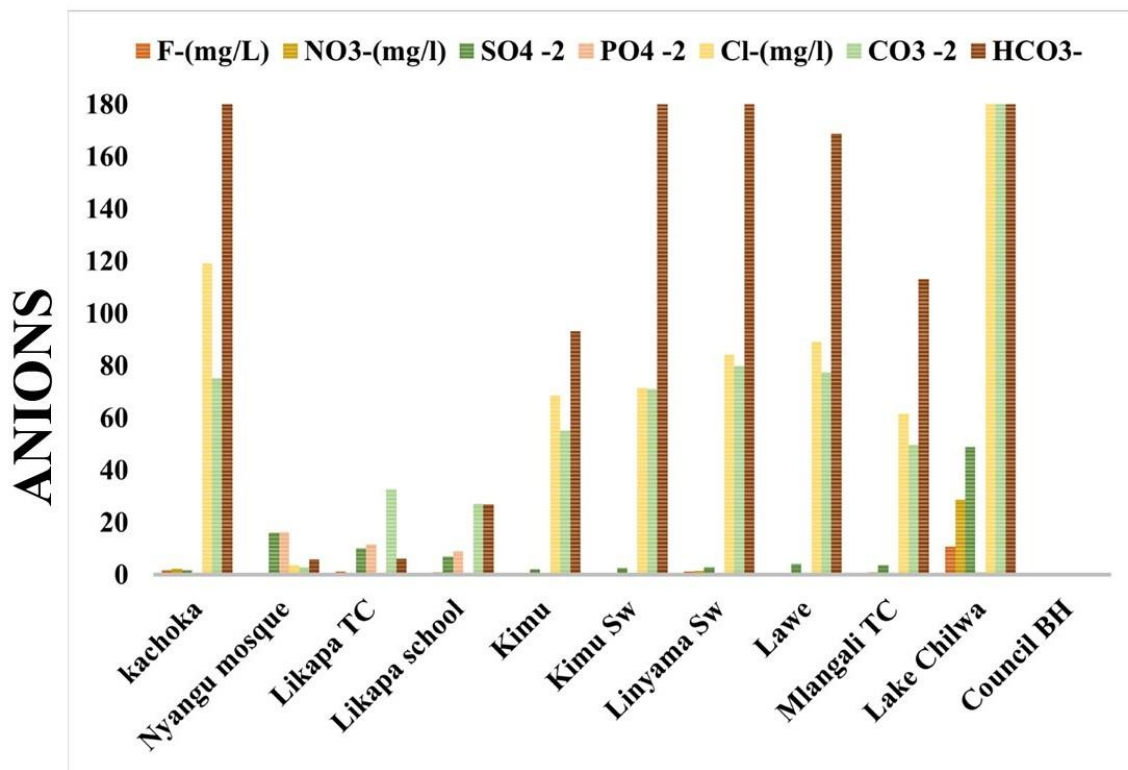


Figure 17: Plots of concentrations of Anions for groundwater and Lake Water. Also shown on the plots are lines representing the World Health Organization (WHO) maximum permissible concentration.

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), while all groundwater samples are below the MPL for Cl^- as defined by WHO (2008), table 7. Chloride is considered an essential inorganic ion, deteriorating drinking water quality when in excess. High concentrations of Cl^- in drinking water cause a salty taste and result in objection to water by consumers. And in groundwater, Chloride sources are attributed to atmospheric sources, decomposition of organic matter and rock dissolution. Snow et al. (1990) indicate that Cl^- 's high values usually correspond with SWI intrusion, connate water source, road salts, and evaporation sources.

All groundwater and lake water samples have NO_3^- concentration below the MPL specified as 50 mg/L per WHO (2008) guidelines for drinking water, table 7. High levels of NO_3^- may be due to decaying organic matter, sewage, and fertilizers used in the area (agriculture source of salinity), as Miller (1980) discussed. This entails that agriculture may not be the source of salinity in the aquifers of the study area. Table 7 denoted that both the lake water and the groundwater samples have SO_4^{2-} concentration below the prescribed limit of 400 mg/L in the drinking water (WHO, 2008). The high values of SO_4^{2-} correspond with saltwater intrusion or connate water source (Snow et al., 1990).

4.3 Summary of Results and Discussion

The geophysical study results demonstrate that some of the groundwater in Kachulu area is impaired by salinity. The low ERV of ($< 5 \Omega\text{m}$) identified in both profiles indicates the intrusion process of the lake water (saltwater) towards the groundwater aquifer due to the induced gradients influenced by high pumping rates from the boreholes in the area. Figure 6 shows the three freshwater points with the ERV range of 50 – 100 Ωm .

The hydrogeochemical study investigated the water quality in ten boreholes in the study area. The results show that most of the boreholes have water of deteriorated quality. The water in the boreholes is brackish due to the mixing of salt and freshwater. Continue groundwater extraction through borehole drilling may aggravate the process and enable salinization. The concentration of EC, F^- , TDS and turbidity analysed in the results and discussion section evidence this. The hydrogeochemical study results also indicated saltwater intrusion as the main source of groundwater salinization.

Furthermore, this study used several Chemical parameters in differentiating different types of saline water; for example, the EC/TDS, the turbidity and the geophysical study explicitly evidence that the saltwater intrusion is the saline source in these boreholes. This was done because using single chemical parameters as indicators of saltwater intrusions can be problematic in determining the salinity source of the ground. Using a single chemical parameter is problematic because the high values of Cl^- , Na^+ and SO_4^{2-} also correspond with saltwater intrusion or connate water source; hence they are not useful when differentiating different types of saline water (Snow et al.,1990). On the other hand, these boreholes have no other sources (analysed in this study) apart from the saltwater intrusion. The source of salinity for these boreholes may be a saltwater intrusion.

The poor water quality reported from the geochemical results in the boreholes confirms the geophysical study, which indicated that most groundwater in the aquifers of Kachulu does not contain freshwater, and only three points have freshwater recommended for borehole drilling.

CHAPTER FIVE

CONCLUSIONS

The geophysical study results demonstrate that some of the groundwater in Kachulu area is impaired by salinity and the extent of salinization, evidenced by the reduction of ERV ($< 5 \Omega\text{m}$) ERT in both profiles. The reduction in ERV ($< 5 \Omega\text{m}$) ERT indicate the intrusion process of the lake water (saltwater) towards the groundwater aquifer due to the induced gradients influenced by high pumping rates from the boreholes in the area. The results in figure 6 clearly illustrate that only three points with the resistivity range of 50 – 100 Ωm have fresh water and are thus recommended for borehole drilling.

The hydrogeochemical study investigated the water quality in ten boreholes in the study area. The results show that most of the boreholes have water of deteriorated quality. The water in the boreholes is brackish due to the mixing of salt and fresh water. Continue groundwater extraction through borehole drilling may aggravate the process and enable salinization. The concentration of EC, F^- , TDS and turbidity analysed in the results and discussion section evidence this. These increased and decreased levels of different parameters lead to many health disorders. The hydrogeochemical study results also indicated saltwater intrusion as the main source of groundwater salinization by analyzing various indicators like the EC and TDS.

The hydrogeochemical poor water quality reported in the boreholes confirms the geophysical study, which indicated that most groundwater in the aquifers of Kachulu does not contain freshwater. The geophysical and geochemical analysis results successfully mapped the extent of water salinity in the aquifers of Kachulu area. This study's results are useful to bridge the information gap needed in addressing groundwater issues by providing data on freshwater aquifers. The study has provided data on the sources of salinization. Data on salinization sources is essential as it will help decision-makers understand the best methods and parameters to address a particular salinity problem, as Richter and Kreitler (1993) indicated. Successively, the study has revealed the extent of saline in the kachulu area and three freshwater points and their depth (shown in figure 6). Freshwater points data will inform engineers in the water development sector about where to drill boreholes without conducting another geophysical survey.

CHAPTER SIX

RECOMMENDATIONS

As evidenced by the study, the groundwater in the area is saline. Therefore, efforts are needed to enable Kachulu area residents to have potable and safe water; the study shows that impaired drinking water leads to different health diseases. There is also a need to move from boreholes drilling and resort to borehole mechanization. This system consists of a borehole, a motorized pump, an overhead tank, and one, two or ten points with spouts where people can fetch water. In Kachulu area, the freshwater may be abstracted away from the contaminated aquifer (such as the borehole at the CBCC) and conveyed into Kachulu area through a pipeline.

The present study only focused on geophysical and hydrogeochemical data to investigate the study area's salinization by mapping its locations and extent (depth). These methods alone cannot provide a complete understanding of the salinity problem. Therefore, the essential insights achieved in the course of this study also offer scope for further work. A combination of strontium isotopes and stable isotopes of water is suggested to characterize the salinity problem fully. Conducting measurements for δD and $\delta^{18}O$ and stable carbon isotopes ($\delta^{13}C$) can be used to create a more robust data set.

Determining the water age using 14-C would allow models to be created that assess the time scale of water evolution and circulation.

Furthermore, the conclusion drawn from the geochemical analysis is the results of water chemical analysis conducted in the dry season in lake Chilwa Basin in Malawi. More frequent sampling (e.g., weekly to monthly) and analysis of the groundwater and surface water in the basin would allow observation of seasonal changes and assess if seasonality plays a role in the geochemical evolution of groundwater and surface water. Scouting additional boreholes in various places of water points on lake Chilwa to increase the sampling density. This study's results could help decision-makers understand the effects of seasonal changes on water resources and apply options for reducing/preventing salinization at the appropriate times. Finally, more studies have been conducted on the salinization of different areas; thus, it is also required to conduct studies on the desalination of salts available in the boreholes /lakes.

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