

**USE OF GEOPHYSICS TO MAP SALINE GROUNDWATER AREAS IN RURAL
WATER SUPPLY – A CASE STUDY OF LUANGWA DISTRICT, LUSAKA
PROVINCE, ZAMBIA**

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(BSc)

**A Dissertation submitted to the University of Zambia in partial fulfilment of the
requirements for the Post – Graduate Diploma in Integrated Water Resources
Management**



THE UNIVERSITY OF ZAMBIA

LUSAKA

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I, Pascal Bukasa Kalenda, declare that this dissertation has never been submitted for any academic award at UNZA or any other University. This dissertation fully represents my work. However, I have adequately acknowledged all sources of material used in this dissertation.

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Abstract

Water is finite and essential to sustaining human life. It plays a vital role in many human activities including industrial production, agriculture, energy, sanitation, and transportation, in addition to sustaining ecosystems that provide valuable services to both environment and human. The objective of this study is to map the saline groundwater area in Luangwa District through the use of geophysics survey which measures variation in the electrical resistivity of the ground. The study aims to promote the use of geophysics survey to site location where to sink boreholes with the view of minimising chances of boreholes that produce saline water. This study undertook an analysis of water samples in 16 out of the 25 suspected saline boreholes in Luangwa district. Out of the 25 boreholes suspected by MWDSEP to have saline water, 16 boreholes were randomly selected for this study. The Ministry of Water Development Sanitation and Environmental Protection database on the boreholes in Luangwa District acted as the sampling frame. Luangwa has 176 boreholes.

Results showed that 14 out of the 16 sampled boreholes had saline water. Result further showed different depths at which low resistivity is prominent within the District, further underscoring the need for undertaking geophysics surveys before sinking boreholes as saline water is of no economic values resulting in loss of investment and increasing the burden on women to walk long distances to fetch fresh water. The study recommends that Government and all stakeholders in the water and sanitation sub-sector should undertake geophysics surveys before sinking boreholes, especially in basins prone to salinity

Dedication

To God Almighty, Giver of all wisdom and knowledge; Auditor Spirit, efficient and master of all Science. I dedicate this work to my parents Eng. Augustin Kalenda and Oscarine Milemba for their consistent moral support, guidance and presence at every milestone of my life, no less this one and to Mr & Mrs Chimbwe and family for their moral support, I further dedicate it to my daughter Joelle Milemba and my son Nathan Shikupilwa for their confidence and consideration; let this dissertation be a model, a path and a mark to which I hope both of you look as a springboard to greater accomplishments and my lovely wife Mbayita Chimbwe for her support and understanding of the stress during my time of study as well as to my brothers and sisters for their morale and encouragement.

To Abigail Mnkosi in remembrance of her late father, my study mate Ngulube Mnkosi. May his star continues to shine brightly through you.

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"Man becomes what he thinks"; say the Theosophists, issues of the great scientific family, it was imperative for us to exhibit the knowledge acquired during our university passage whose end is concretised by the elaboration of this dissertation.

We always learn and learn, to always do better, to always live better with a heart and mind to contribute to improving the well-being of our contemporaries.

My gratitude goes to UNZA, to the IWRM fraternity and particularly to Professor Nyambe for his insight and mentorship; though seemingly succinct to some of our readers, the value of this work owes its merits to Dr Kawawa: these sincere, heartfelt words convey my benevolent gratitude, as he sacrificed to lead me notwithstanding his family and professional responsibilities.

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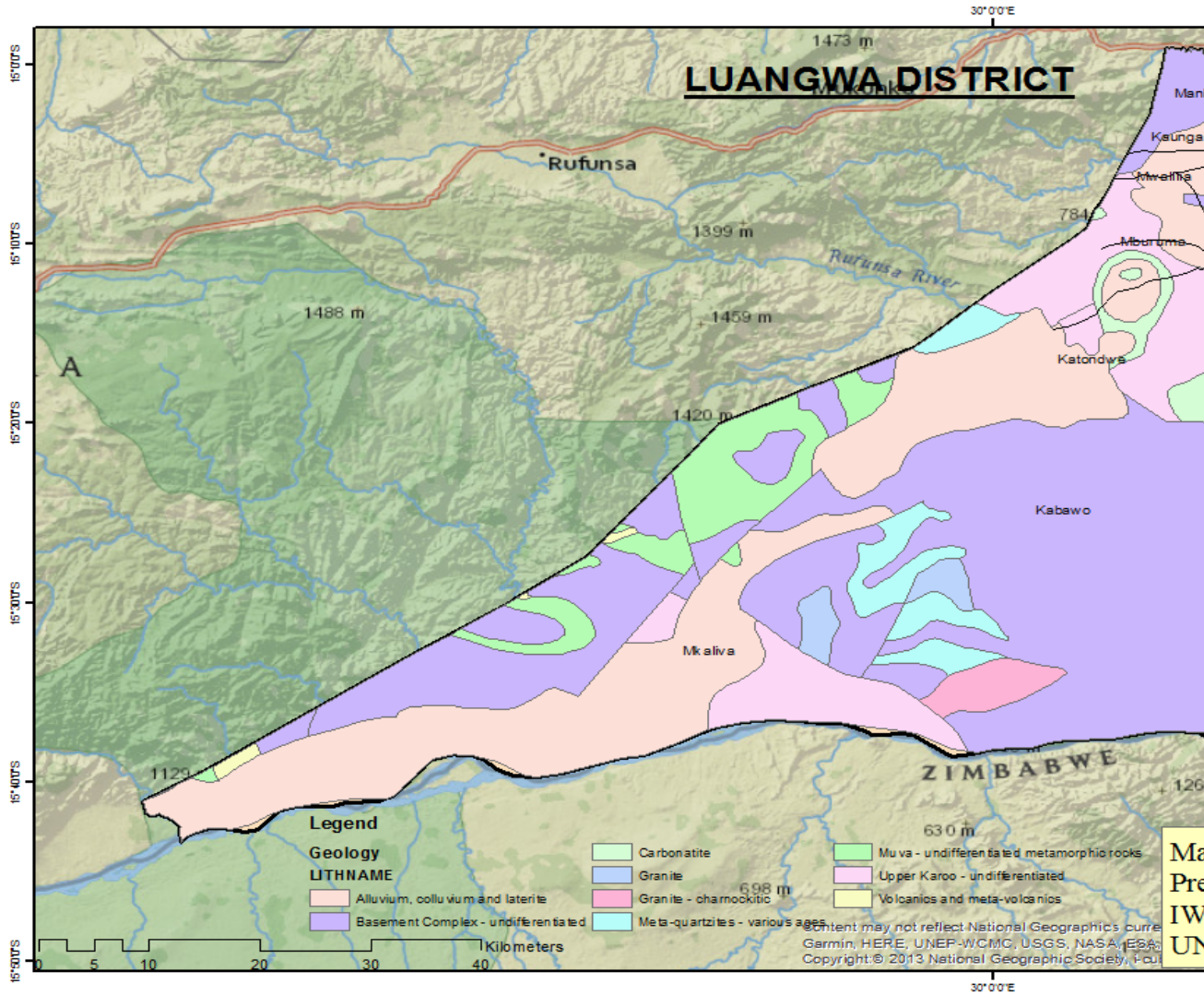


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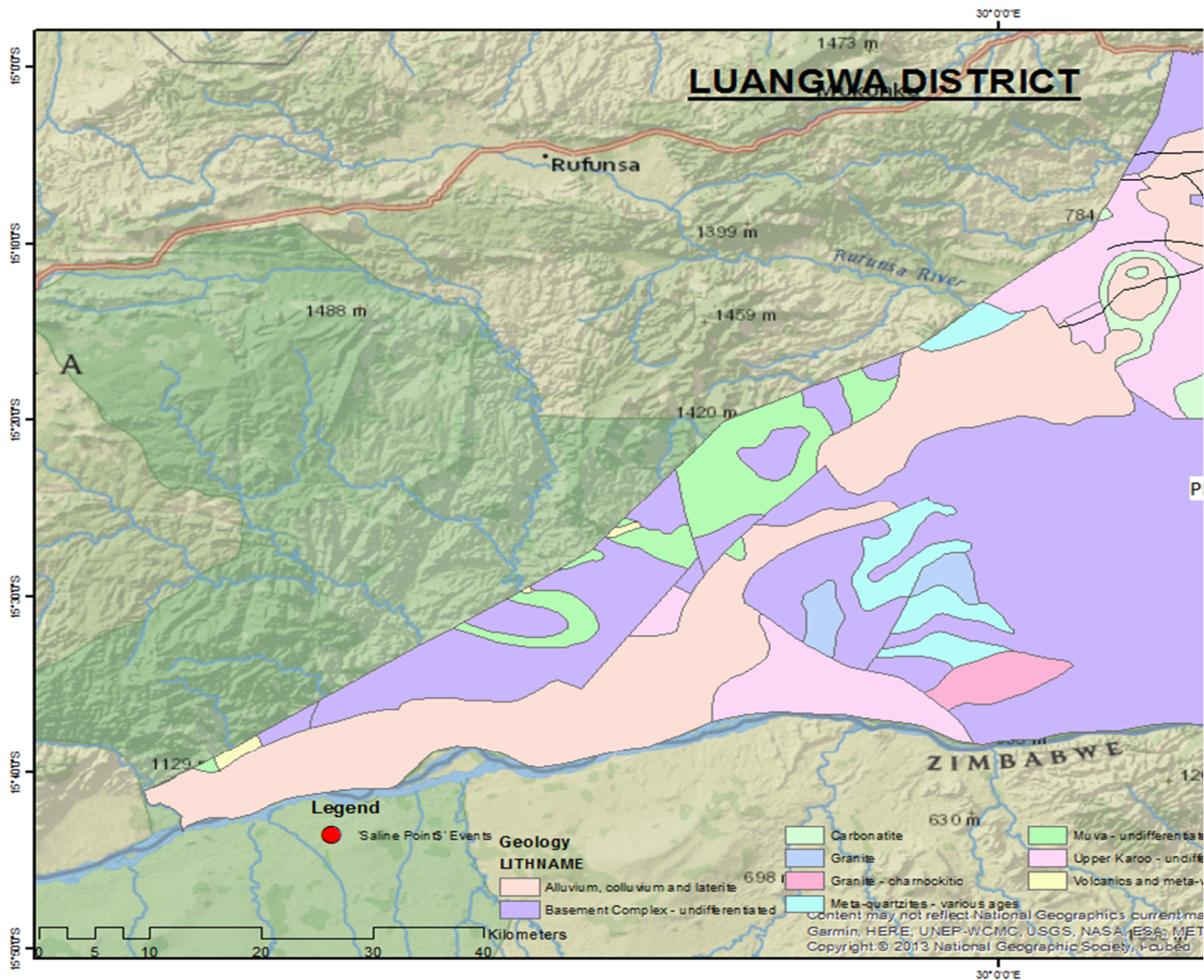


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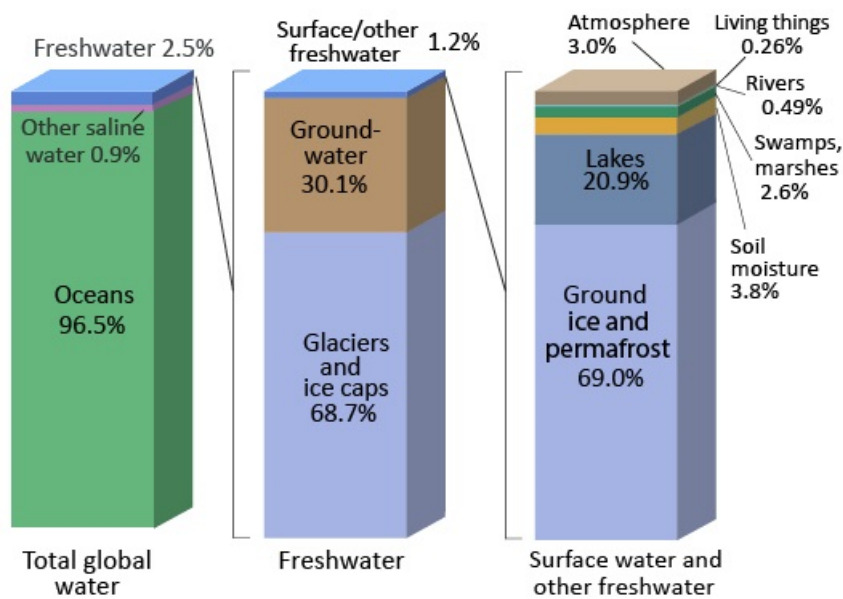
List of Acronyms

CSO	Central statistical office
E	Easting
Ec	Electrical Conductivity
Fe	Iron
GGWR	Global Groundwater Regions
GPS	Global Positioning System
ICRAC	Intergraded Groundwater Resources Assessment Centre
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
LRC	Luangwa River Catchment
LUG	Luangwa
MBGL	Meters below ground level
pH	potential of hydrogen
RES	Resistivity
S	Southing
SADC	Southern African Development Community
SDG	Sustainable Development Goals
TDS	Total Dissolved Solid
TEM	Transient electromagnetic
UNICEF	United Nations International Children's Fund
Unza	University of Zambia
VES	Vertical Electrical Sounding
VTEM	versatile transient electromagnetic
WARMA	Water Resources Management Authority
WGS84	World Geodetic System
ZRC	Zambezi River Catchment
ZABS	Zambia Bureau of Standard

CHAPTER 1: INTRODUCTION

1.1. Background

Water is finite and essential to sustaining human life. It plays a vital role in many human activities including industrial production, agriculture, energy, sanitation, and transportation, in addition to sustaining ecosystems that provide valuable services to both environment and human. Although water seems to be abundant on the planet, 96.5% of the Earth's water is seawater, making it unfit for most human uses. Of the remaining 2.5% fresh water, 98.8% of it is inaccessible, locked either in polar ice caps or deep underground aquifers. Therefore, only 1.2% of all the water on earth is surface and fresh water, which is accessible by human beings (CAP-Net, 2003). See Figure 1 below.



Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, *Water in Crisis: A Guide to the World's Fresh Water Resources*.
NOTE: Numbers are rounded, so percent summations may not add to 100.

Figure 1: Guide to the Freshwater Resources

Water scarcity affects more than 40 per cent of people around the world an alarming Figure that is projected to increase. Although 2.1 billion people have gained access to improved water and sanitation since 1990, dwindling supplies of safe drinking water is a significant problem impacting every continent. In 2011 a total of 41 countries experienced water stress and 10 of which are close to depleting their supply of renewable freshwater and must now

rely on alternative sources. By 2050, it is projected that at least one in four people will be affected by recurring water shortages. (SDG Goal No 6)

According to Weert, Gun and Reckman (2009), fresh groundwater is particularly found in the saturated zone of the subsurface that is most actively involved in the water cycle, the domain of so-called 'meteoric water'. Consequently, fresh groundwater is more likely present in the shallower domains of the sequence of geological layers in which groundwater is stored. Based on this rationale, fresh groundwater is often comparatively young and tends to be actively recharged. In contrast, a large part of all saline groundwater on earth, but probably not all of it is present in a more or less stagnant condition at greater depths and may have been there already for many thousands or even millions of years. Continuous dissolution over geological times of the reservoirs containing this groundwater may have enriched the mineral content in the groundwater. So groundwater salinity tends to increase with increasing depth.

Genetically, most saline groundwater bodies are in one of the following categories:

- Saline groundwater of marine origin
- Saline groundwater of terrestrial origin (natural)
- Saline groundwater of terrestrial origin (anthropogenic)
- Saline groundwater of mixed origin (Weert, Gun and Reckman, 2009)

The contents of dissolved solids in groundwater vary highly from one location to another on earth, both in terms of specific constituents (e.g. halite, anhydrite, carbonates, gypsum, fluoride-salts, and sulphate-salts) and regarding the concentration level. The latter, often called salinity level is a convenient macro-parameter for a first general characterisation of water quality. It is usually expressed as Total Dissolved Solids (TDS) – i.e. milligrams dissolved solids per litre of water, but the use of proxies such as the Chloride Content (mg/l) or the Electrical Conductivity (EC, in $\mu\text{S}/\text{cm}$) is widespread as well.

Africa in general and the sub-Saharan region, in particular, is equally affected by the shortage of fresh water and the available groundwater face quality challenges, for instance, the Kalahari sediments contain essential groundwater resources throughout southern Africa, which however are constrained by very variable water quality (Chongo *et al.*, 2015).

It, therefore, follows that Zambia also has Challenges pertaining to the water quality ranging

from Iron, pH, Arsenic, Alkalinity and Salinity to mention a few.

Given the water scarcity globally and in Zambia, this study will contribute to a body of knowledge on possible geology and topography anomaly profile and precise approaches to mitigate the drilling of a borehole in the saline area, mainly focusing on Luangwa District in Lusaka.

1.2. Statement of Problem

Poor water quality has a negative impact on the physical, social economic and institutional environments. The effects on the physical environment include increased costs of water and sanitation provision to housing infrastructure, environmental degradation arising from sewerage disposal, increased capital investment in water and sanitation infrastructure, depletion of natural water resources and increased cost of environmental impact mitigation. Poor water quality affects increases the cost of water and sanitation provision to housing infrastructure, reduces access to water and sanitation facilities and affects tourism development as well as affects communities participation in economic activities (Lusaka Province Planning 2012).

This study, therefore, seeks to map saline groundwater area in Luangwa District through the use of geophysics survey.

1.3. Purpose of Study

The overall goal of this study is to map the suspected saline groundwater area in Luangwa District through the use of geophysics survey. It aims to promote the use of geophysics survey for siting-locations where to sink boreholes with the view of minimising chances of sinking boreholes that produce saline water. The survey data was processed to produce graphics depth sections, which will ultimately improve how to conduct sitting of boreholes in Luangwa District.

1.4. The objective of the Study

This study has four specific objectives namely:

- I. Map the suspected saline boreholes in Luangwa District
- II. Establish resistivity ranges of geological material in the area
- III. To establish the extent of ground salinity depth in the area
- IV. Assessment of correlation between resistivity and salinity

- V. Recommend borehole construction design, drilling depth for future groundwater development

1.5. Research Questions

This research will attempt to answer the following questions:

- i. Where are the saline water boreholes found within Luangwa District?
- ii. What is the resistivity range in the geological formation of Luangwa District?
- iii. What are the levels of electroconductivity in the saline suspected boreholes in Luangwa district?
- iv. What are the pH, chloride and sulphate levels in the sampled borehole water in Luangwa district?
- v. What is the relationship between resistivity and salinity?
- vi. What are the recommended construction design, drilling depth for boreholes in Luangwa District?

1.6. Justification of the Study

Provision of sufficient and sustainable water in the district is an issue of significant importance as the existing infrastructure is obsolete and lacks the capacity to meet the demand (Luangwa Integrated Development Plan, 2012). In an effort to mitigate this challenge, the Ministries of Local Government and Water Development, Sanitation and Environmental Protection (MWDSEP) have sunk 176 boreholes in the district. This study aims to contribute to the existing body on how to improve access to clean and safe water by undertaking geophysics surveys before drilling boreholes the improved access to safe and clean water invariably leads to enhanced quality of life of the residents as it directly results in a reduction of waterborne diseases such as diarrhoea. The MWDSEP and its Cooperating Partners (UNICEF, Water Aid) will utilise knowledge generated in this study to minimise the sinking of boreholes that produce saline water.

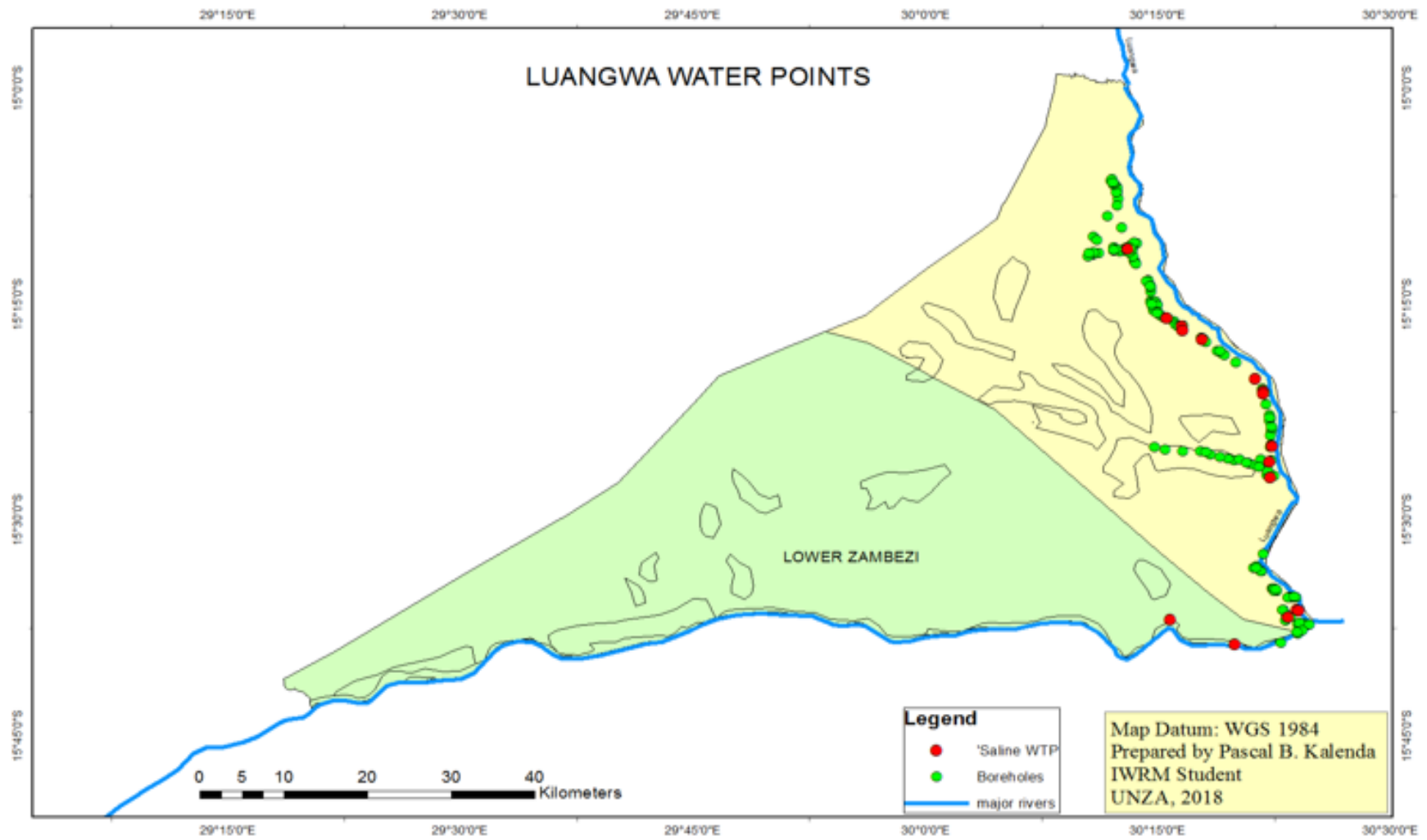


Figure 2 : Luangwa existing water boreholes

1.7. Location and description of Luangwa District

The geographical location of Luangwa district, its geography, soils, vegetation, hydrology and demography are presented here.

1.7.1. Location

Luangwa District which stretches about 3,886 square kilometres and has a population of approximately 24, 330 (Central Statistical Office (CSO) 2012) Luangwa district is predominantly rural with the population mainly dependent on agriculture and fishing, both economic activities being heavily dependent on water. The availability and quality of water, therefore, have a negative impact on the livelihood of the inhabitants. In as much as the government has been trying to improve both availability and quality of water in the district by sinking boreholes, there has been very little, or no known studies were undertaken to guide the exercise except for the Zambia Water Master Plan by JICA conducted in 1995.

Luangwa district is situated 15° 37' 0" S, 30° 23' 0" E (Figure 3) in Lusaka Province of Zambia. The Lower Zambezi national park, which covers most of the Western part of the District, dominates Most of the land area of Luangwa District. The east of the District is the main inhabited area; the Luangwa River bound this area to the East, which is a major tributary of the Zambezi River. The Zambezi River runs along the southern border of the District; the river course marks the border with Zimbabwe and Mozambique.

Within the District, the main inhabited areas are in the Eastern part of the District; the dominant feature in this area is the Luangwa River. The main populated areas are found in the flatter areas. In some cases, villages are transient in that people reside in two locations, within the floodplain area, then when the annual floods come, villages move to sites on higher ground.

Along the main river, alluvial sediments will be encountered. The alluvial sediments will vary in thickness and will become thinner as the slope increases away from the River.

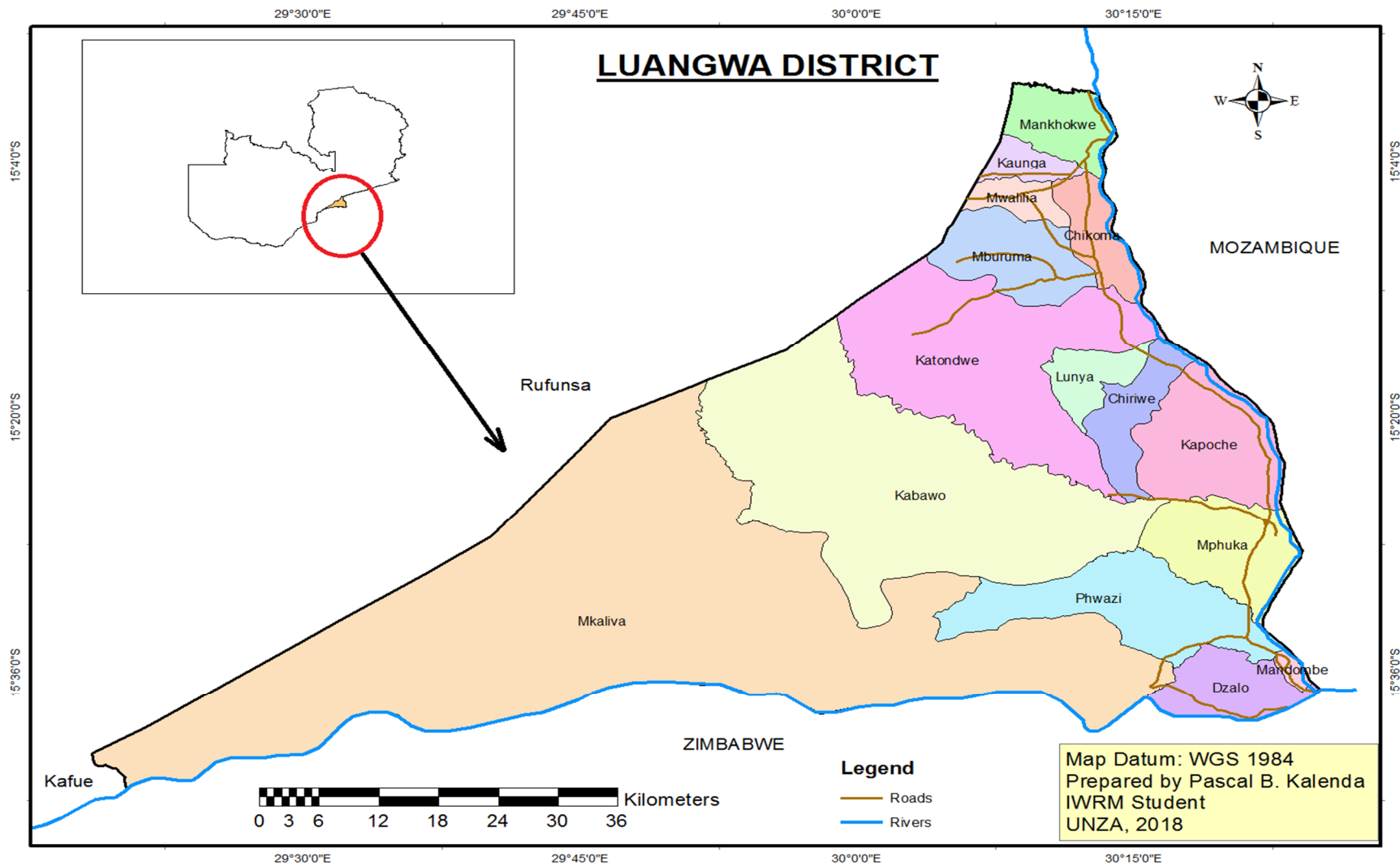


Figure 3: Location of Luangwa District in Lusaka Province, Zambia

1.7.2. Geology, Soils and Vegetation

The alluvial sediments found in Luangwa are composed of Pleistocene to recent deposits of fluvial gravel, sand, silt and clay. Aquifers with good yields can usually be found. Layers of clay and silt should be avoided to obtain good yields. In most areas, the aquifers will yield sufficient water for boreholes with hand pumps or hand dug wells for domestic use.

The other main lithology that will be encountered is Upper Karoo sediments, carbonates and basement rocks. The Upper Karoo is a sequence of sandstones, siltstones and mudstones; good yields will be encountered in the sandstones, the mudstones and the siltstones. Basement rocks that will be encountered include granites and gneissic rock; these rocks have no primary permeability; water resources are only found within secondary features such as fractured and deeply weathered zones. Carbonate rocks are present in the eastern part of the District but are not spatially extensive, see Luangwa lithology map below.

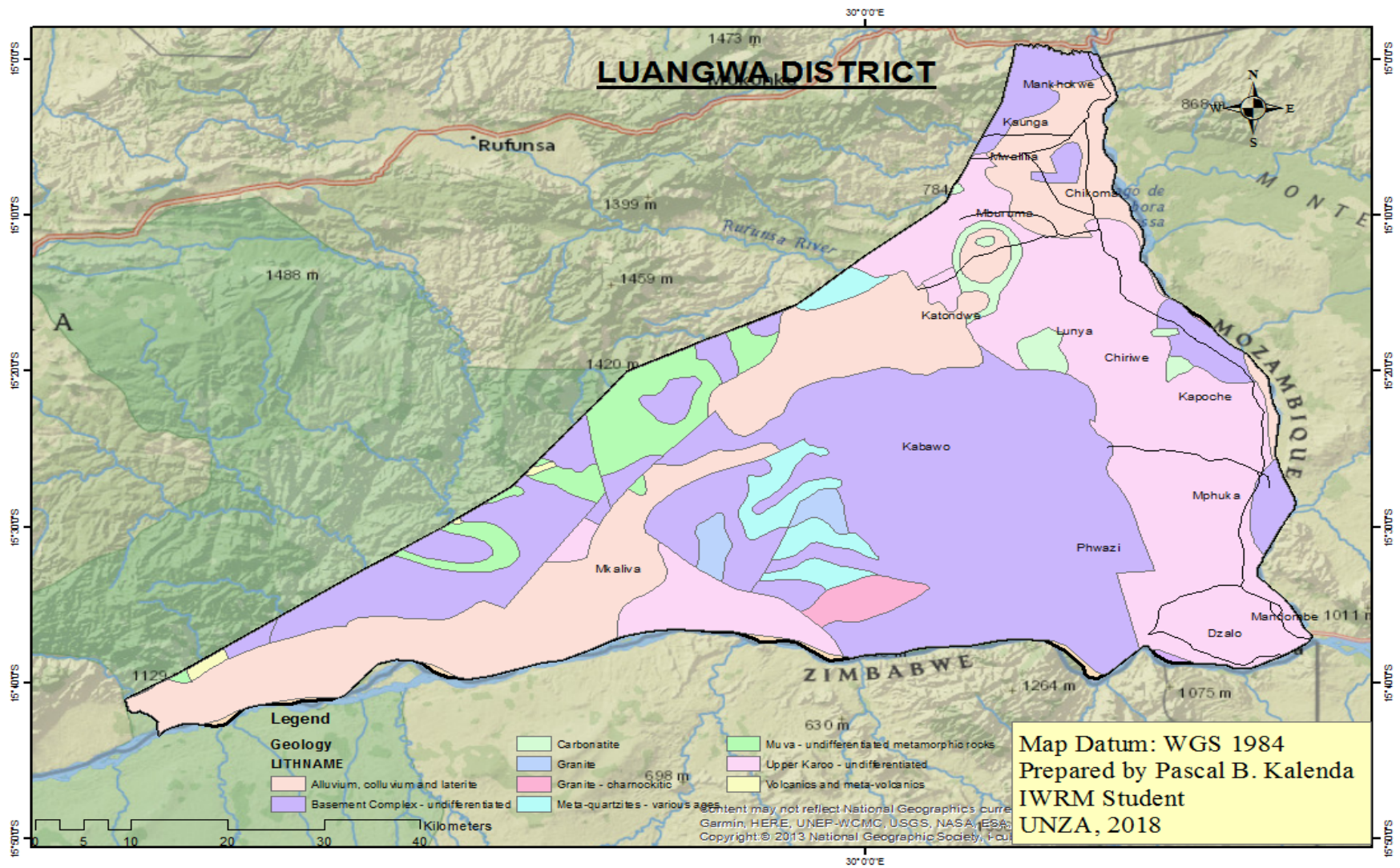


Figure 4: Luangwa Geology

1.7.3. Hydrology

The District has two major rivers, Zambezi and Luangwa Rivers, which meet at the confluence in the south-eastern part of the District. Smaller drainage systems include the Mulambwa, Kaunga, Mulongosi, Rufunsa, Musensenshi, Chakwenga and Chongwe, Dambo areas prone to flooding are found along the Zambezi and Luangwa rivers.

The District abound with two river basins; the Zambezi River Catchment (ZRC) and the Luangwa River Catchment (LRC). The Luangwa River Catchment (LRC) is approximately 145,690.33 Km² within Zambian territory, and it lies between latitudes 9°30" and 15°40" south, and between longitudes 28°00" and 33°45" east, while administratively it lies in five provinces, namely (largest to smallest in terms of areas); Muchinga, Eastern, Central, Lusaka and Copperbelt. The Catchment forms the international boundary with Malawi to the east, and Mozambique and Zimbabwe to the south. The Luangwa basin is the third largest in Zambia after the Zambezi Main River and Kafue Basins, and one of the least disturbed.

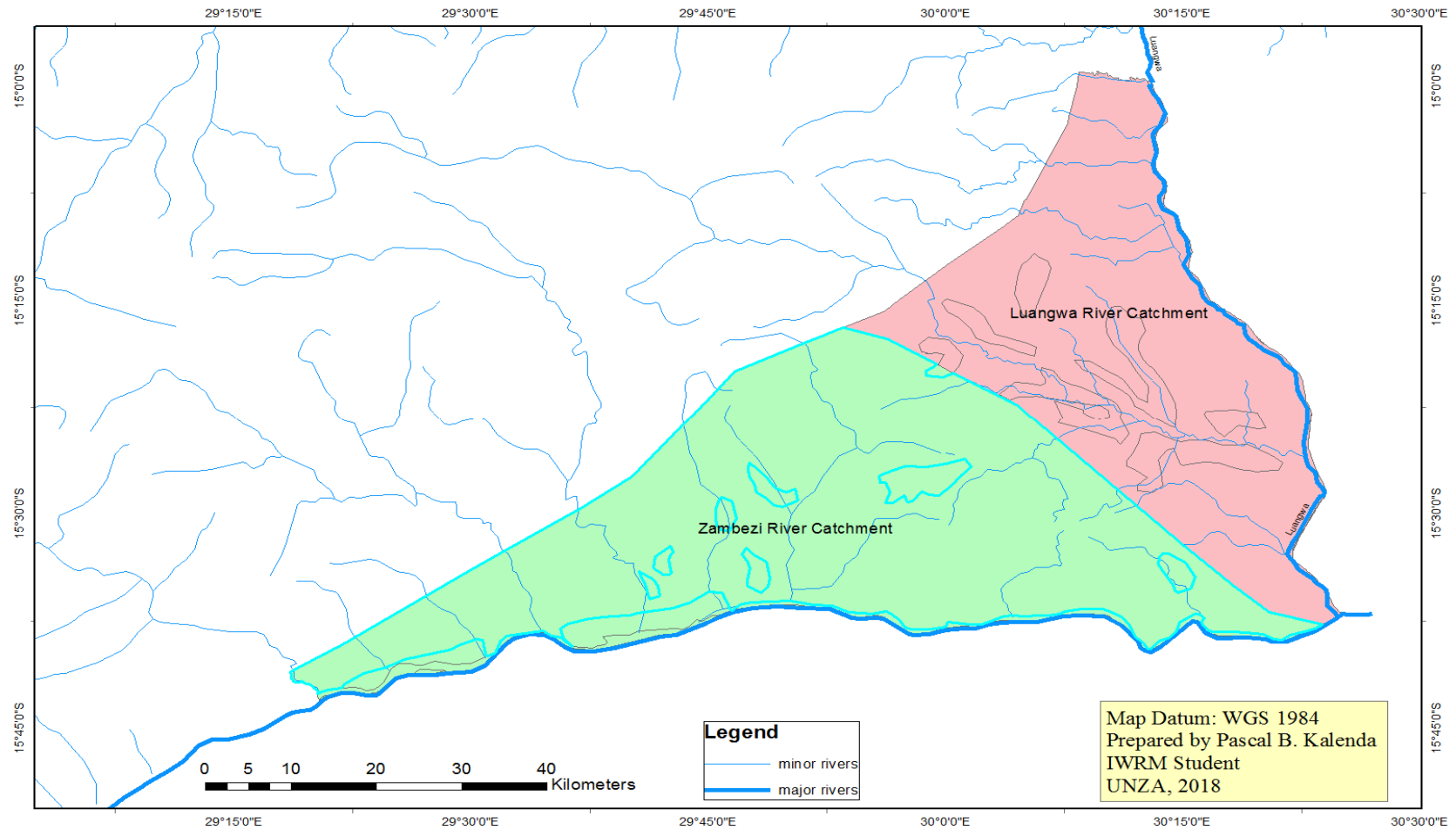


Figure 5: Luangwa District Catchment

1.7.4. Demography and Climate

The district has a total population of 24,304 comprising 11,979 male & 12,235 females (CSO, 2010) and the district is categorised as a low-income district with research showing that over two-thirds of the population earns less than ZMW500 per month. Luangwa is predominantly a farming area with locals engaging in subsistent farming and fishing. Research further shows that agriculture account for the most people employed at 27.7% followed by fisheries at 19% with health and hospitality accounting for the lowest at 1.9% and 1.2% respectively. The crops produced include maize, sorghum, groundnuts, mixed beans and rice. In addition to this, farmers practice horticulture although on a subsistence level. Under livestock production, animals reared include cattle, goats, pigs, chickens, guinea fowls, ducks, sheep and donkeys. The largest ethnic group in Luangwa District is the Nsenga-Luzi, which is one of the Tumbuka groups from Eastern Province with 50.7% of people followed by Chikunda with 27.7% of the people. In addition, there are three major languages (Nsenga, Nyanja and Chikunda) spoken in the district. The traditional ceremonies practised in the district include Mbambala practised by the Nsenga-Luzi people of senior chief Mburuma and, the Dantho by the Chikunda people of Chief Mphuka (Luangwa Integrated Development Plan, 2012).

The District has three main seasons which include the hot, rainy season from late November to April, the cold, dry season from May to August and the hot, dry from September to early November. The mean annual temperature in the valley ranges from 19.1° C in June to 40.0° C in October. (Meteoblue 2018) as shown in Figure 6 below.

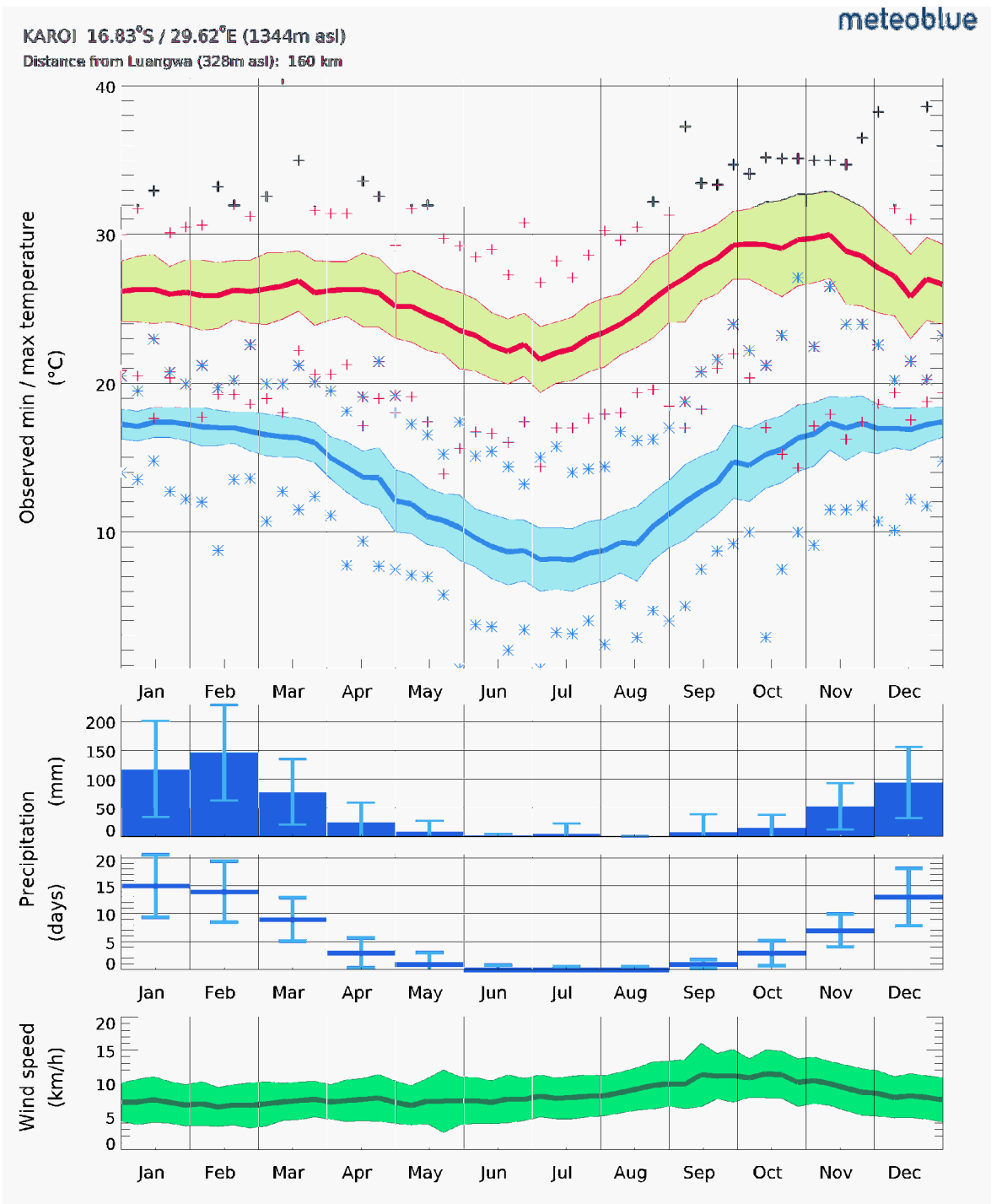


Figure 6: Luangwa Precipitation, Temperature and wind

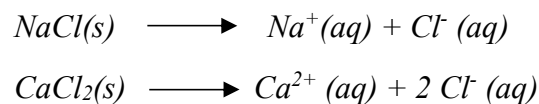
CHAPTER 2: LITERATURE REVIEW

2.1 Theoretical Basis

Precipitation, which is the purest of natural water, is the most dominant source of groundwater recharge, the chemical composition of the precipitation is, therefore, of considerable importance in understanding the chemistry of groundwater. Atmospheric water contains mainly sodium chloride eminent from ocean water transported as a spray, with other constituents in minor amounts, over desert regions; the concentration of salts may be high due to salt-laden dust. A substantial increase in the concentration of dissolved salt may be brought about in the soil zone due to a high evaporation rate. A further increase in the salt concentration may occur as the water infiltrates through the materials in the zone of aeration by dissolution of the soluble minerals, especially carbonates of calcium and magnesium. Solutions of calcium and magnesium are activated in a humid region rich in humus. Firstly, in arid and semi-arid regions, precipitation of calcium and magnesium carbonates in the soil zone is the dominant feature.

In areas where the zone of aeration comprises rocks containing soluble minerals like halite (NaCl), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) anhydrite (CaSO_4), the percolating water may be rich in dissolved constituents, depending on the solubility of the minerals and the duration of contact, even newly formed groundwater will be saline if the percolating water has traversed through a bed of halite, which is highly soluble

Secondly, the Chloride, in the form of the Cl^- ion, is one of the significant inorganic anions, or negative ions, in freshwater or saline water. This is a result of the separation of salt in the following situation sodium chloride or calcium chloride



The sources of chlorine are many, but in this study, we will concentrate chloride and sulphate in groundwater. The taste of salty in drinking water is as a result of the level of concentration of chloride ion.

In this chapter, the focus will be on the geophysics studies that have been done at global, regional and national level highlighting the gaps identified and informing recommendations

aimed at improving the siting of boreholes in saline-prone areas in Zambia particularly Luangwa District. The Chapter will focus on reviewing the published literature in Africa, Southern African Development Community (SADC) region and Zambia salinity in groundwater. The chapter will highlight diverse method used and the gads as for saline groundwater in Luangwa District.

2.2 Definition of keywords

The key terms defined below are Groundwater, Hydrogeology, Geophysics, resistivity, Schlumberger array, Wenner array, dipole-dipole, Electro conductivity, pH, fresh water, aquifer, saline water, iron, chloride, and sulphate

2.2.1 Resistivity

The resistivity has several electrical geophysics methods, direct – current electrical resistivity has found the greatest application to hydrogeology (Zohdy, Eaton and Mabey 1974). The electrical resistivity (or specific resistance) of a medium in the resistance offered by a unit cube of it when a unit current passes normal to the surface of cross-sectional area A. it is given by Ohm's law:

$$\text{Equation 1} \quad \rho = R \frac{A}{L} \text{ ohm } \frac{m^2}{m} = \text{ohm} - m$$

Where ρ = resistivity

R = Resistance offered by the medium of length L and cross-sectional area A

In electrical resistivity survey, a known current I (direct current or low-frequency alternating current) is sent into the ground through a pair of current electrodes A and B , and the potential difference (ΔV) created in the medium between another pair of potential electrodes M and N is measured. The resistance for the formation is given by

$$\text{Equation 2} \quad \rho = K \frac{\Delta V}{I}$$

Where K is termed the geometric factor of the electrode arrangement.

Resistivity Profiling and sounding there are two types of resistivity surveys, namely profiling or lateral traversing and vertical electrical sounding (VES) or depth probing. With profiling,

anisotropism in the horizontal direction is distinguished, while with sounding anisotropism in the vertical direction is distinguished. However, the results of VES and profiling are often affected by both lateral and vertical variation in the electrical properties of the formations. (Karanth 1987)

Studies on resistivity were conducted in the Okavango Delta, Botswana, using the Airborne TEM Survey method and the key findings of the study were that:

- An airborne transient electromagnetic survey of the Okavango Delta has provided a non-intrusive means to map the hydrogeology over the entire delta. Preliminary results indicate significant heterogeneity in resistivity, which when carefully interpreted with borehole data and known geology allow the salinity values and/or lithologies to be defined (Podgorski et al. 2010).

In Zambia, a study on groundwater salinity was undertaken by Chongo *et al.*, (2014) using the Airborne and ground-based TEM(Chongo *et al.*, 2015).

2.2.2 Schlumberger array

Being one of the various types of electrode configuration, in this type also all four electrodes are placed in line, but the distance between the current electrodes (AB) is maintained equal to or more than five times the distance between the potential electrodes and the apparent resistivity is given by:

Equation 3

$$\rho_a = \pi \frac{\left(\frac{L}{2}\right)^2 - \left(\frac{b}{2}\right)^2}{b} \frac{\Delta V}{I}$$

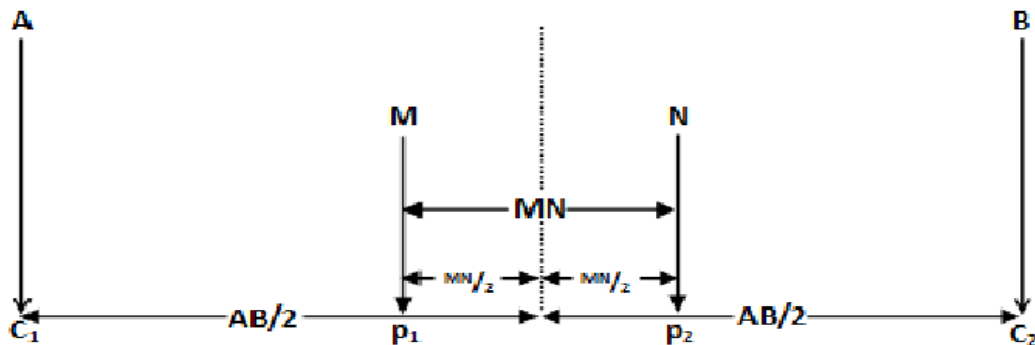


Figure 7: Schlumberger Array Configuration

The depth of the investigation in an isotropic and homogeneous formation is approximately equal to half the distance between the current electrodes (Karanth 1987).

2.2.3 Wenner Array

The wenner configuration is as follows two potential electrodes M and N are placed in line with the current electrodes A and B , all four being situated equidistant from one another and disposed symmetrically with respect to a central point O .

The apparent resistivity of the formation is given by

$$\rho_a = 2\pi a \frac{\Delta V}{I}$$

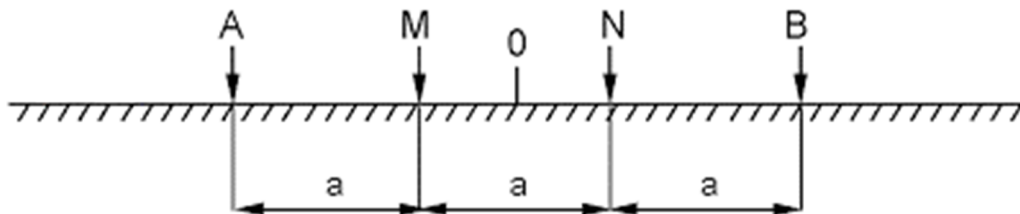


Figure 8: Wenner Array Configuration

The depth of the investigation in an isotropic and homogeneous formation can be approximated to the distance between any two electrodes (Karanth 1987).

2.2.4 Dipole-Dipole Array

In this method developed in Russia, current electrodes and potential electrodes are arranged in pair or dipoles. The electrode pairs can be arranged in several ways, maintaining a much smaller distance between the centres of the dipoles. The dipole-dipole arrays are generally required for deep exploration, as in oil fields, but in recent years they have also been used in groundwater investigation (Karanth 1987).

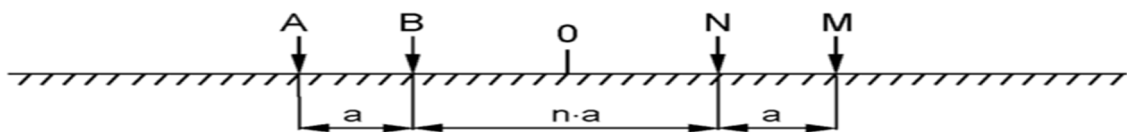


Figure 9: Dipole-dipole Array configuration

In Wenner configuration, it is observed that it is difficult to operate since the depth to spread ratio is 1:3. Therefore, it is difficult or not possible to record values beyond the depth of 100 m. Since the method used is of inverse slope type, the resistivity of each layer can be calculated separately. This method when compared with the exposed well section matched with the resistivity. Therefore, it is easy to calculate and interpret manually without using the curve matching technique. This reduces the error. It is recommended to use the Wenner's inverse slope method for hard rock terrain. In Schlumberger method, the observed value of R is used for calculation. The software has the option for the taking care of the errors for matching with the standard curves. In doing so, the original values of the layers may vary, and the interpretation may differ depending upon the person handling it. The Schlumberger method is easy to operate, because it is less time consuming, and in short spread of current electrodes, spacing greater depth can be achieved. It is not an easy task to interpret the data by the curve matching technique as it is executed manually. Consideration of a number of layers is difficult, because if more layers are demanded, then adjustment through the software during a reduction in the number of curves will have an effect on the thickness of the first layer which will be automatically adjusted. Identifying different curves is also time-consuming (Vasantrao *et al.*, 2017).

The Schlumberger method was selected because it has more advantages compare to wenner method mainly because it is easy to operate and less time-consuming.

2.2.5 Water Quality

The Dublin Principles emphasise that Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment adding that Water has an economic value in all its competing uses and should be recognized as an economic good. It should also be noted that women play a central role in the provision, management and safeguarding of water. Given that Saline water is of no economic value, it means that despite government and its cooperating partners investing in sinking boreholes to provide this resource, women continue to walk a long distance to access clean and safe water as the boreholes sunk within their vicinity has saline water. This robs women of the time to invest in other economic ventures that would better the economic status of their families, further deepening poverty levels. It is therefore important to advocate for Integrated Water Resources Management which is 'a process that promotes the coordinated development and

management of water, land and related resources in order to maximise the resultant economic and social welfare on an equitable manner without compromising the sustainability of vital ecosystems' (UN Water 2000).

The quality of water that we ingest as well as the quality of water in our lakes, streams, rivers, ocean and groundwater is the critical parameter in determining the overall quality of our lives. Water quality is determined by the solutes and gases dissolved in the water, as well as the matter suspended in and floating on the water. Water quality is a consequence of the natural physical and chemical state of the water as well as any alterations that may have occurred as a consequence of human activity. If human activity alters the natural water quality so that it is no longer fit for use for which it had previously been suited, the water is said to be polluted or contaminated. One basic measure of water quality is the total dissolved solids (TDS) which are the total amount of all the solid in milligrams per litre, which remain when the water sample is evaporated to dryness. Table 1 gives a classification scheme for water based on the total dissolved solids.

Table 1 *Classification of water based on total dissolved solids*

<i>Class</i>	<i>TDS (mg/L)</i>
<i>Fresh</i>	0 – 1,000
<i>Brackish</i>	1,000 – 10,000
<i>Saline</i>	10,000 – 100,000
<i>Brine</i>	

The major cations are calcium, magnesium, sodium, potassium; the major anions are chloride, sulphate, carbonate, and bicarbonate (Fetter 2001). Total dissolved solids (TDS) is the measure of all organic and inorganic substances dissolved in a given liquid, revealing the proportion of different solids. With the fact that there are a number of different uses for TDS: in this case, it can measure Salinity levels in borehole water using the formula below.

$$\text{TDS(mg/l)} = \text{Ec} \times \text{KE}$$

Ec= Electro conductivity

KE = correlation factor (0.67)

Table 2 *Zambian Drinking Water Guidelines*

Water Quality test

Well			WHO Limit	Zambian Limit
Lab No.				
Date				
pH				
Conductivity	[μ S/cm]			
Total Hardness	[mg/l] CaCO ₃			500
Calcium Hardness	[mg/l] CaCO ₃			500
Carbonate	[mg/l] CaCO ₃			
Bi-Carbonate	[mg/l] CaCO ₃			
Alkalinity	[mg/l] CaCO ₃			500
Fluoride	[mg/l]		1.50	1.50
Calcium	[mg/l]			200.0
Magnesium	[mg/l]		200.0	150.0
Chloride	[mg/l]		250	600
Sulphate	[mg/l]		250.0	400.0
Nitrite	(NO ₂ -N mg/l)		3.00	
Nitrate	(NO ₃ -N mg/l)		50.0	10?
Iron (ii)	[mg/l]		0.30	1.00
Iron (iii)	[mg/l]		0.30	1.00
Manganese	[mg/l]		0.50	
Silica	[mg/l]			
Potassium	[mg/l]			
Sodium	[mg/l]		R 200	
Lithium	[mg/l]			
Arsenic	[mg/l]		0.010	0.050
Cadmium	[mg/l]		0.003	0.010
Strontium	[mg/l]			
Lead	[mg/l]		0.01	0.05
Dis. Oxygen	[mg/l]			
Free CO ₂	[mg/l]			
Total Coliforms	[#/100 ml]			
Feacal Coliforms	[#/100 ml]			

In examining water quality, the following factors are considered:

2.2.6 Electroconductivity

Electro Conductivity or specific electrical conductance (conductivity) and specific electrical resistance (resistivity) denote the characteristics of a medium to the passage of electricity. Resistivity is the reciprocal of conductivity. In water – quality determinations, conductivity, defined as the conductance of a cube of the one-centimetre side of a substance, is reported in mhos/cm.

2.2.7 Potential of hydrogen (pH)

The pH value of a solution is the negative logarithm of the concentration of hydrogen ions in moles per litre. In pure water the dissociated molar concentrations of H^+ (hydrogen) and OH^- (hydroxyl) ion are equal, each being moles per litre, equivalent to a pH of 7. If the H^+ ions exceed the OH^- ions, as in acid solutions, the pH value is less than 7, while the pH is more than 7 if the OH^- ions exceed the H^+ ions, as in the solutions. A change of pH from 7 to 6 indicates that there is a tenfold increase in the hydrogen ion concentration. In a similar fashion, a change of pH from 7 to 8 indicates a tenfold increase in the hydroxyl ions (Karanth 1987).

2.2.8 Iron

Iron is one of the major constituents of rocks, next in abundance only to oxygen, silicon and aluminium. The important iron-bearing minerals include pyroxenes, amphiboles and micas among silicates, pyrite and chalcopyrite among sulphides, and magnetite and haematite among oxides. Oxide, carbonates and hydroxide iron is present in sandstones as the cementing matrix, in shales, and in small quantities in limestones. In igneous and metamorphic rock, iron is present mostly in the form of complex silicate minerals.

In groundwater, iron may occur when coming into contacts with iron objects like Well casing, pipes; while the iron occurring in groundwater is in the form of ferric hydroxide, in a concentration less than 0.5 ppm. The higher the occurrence of iron the lower the pH (Karanth 1987).

2.2.9 Chloride

Chloride is the anion (negatively charged ion) Cl^- . It is formed when the element chlorine (a halogen) gains an electron or when a compound such as a hydrogen chloride is dissolved in water or other polar solvents. Chloride salts such as sodium chloride are often very soluble in water.

Chloride bearing rock minerals such as sodalite and chlorapatite which are minor constituents of igneous and metamorphic rock, and liquid inclusions which comprise a very insignificant fraction of rock volume are minor sources of chloride in groundwater. In inland basins, initial fresh water may give rise to highly saline waters. Chloride salts, being highly soluble and free from chemical reactions with minerals of reservoir rocks (Karanth 1987).

2.2.10 Sulphate

Sulphate content of atmospheric precipitation is only about 2ppm, but a wide range in sulphate content in groundwater is made possible through reduction, precipitation, solution and concentration, as the water traverses through rocks. The sources of sulphate in rocks are sulphur minerals, sulphides of heavy metals, which are of common occurrence in the sedimentary rocks. Apart from these natural sources, sulphates can be introduced through the application of sulphatic soil conditioners. Calcium, magnesium and sodium, sulphate can be present in high concentration in groundwater. The locally abnormal concentration of sulphate may characterise groundwater traversing through zones of oxidation of sulphide – ore bodies, pyritebodies, pyrite-bearing shales, lignite, coal and gypsiferous beds (Karanth 1987).

2.2.11 Saline Water origins

They are four main origins of salinity which is described in details in table 3 below

Table 3 Genetic categories of saline groundwater

<i>Main class of origin</i>	<i>Genetic category or salinisation mechanism</i>	<i>Typical environment at the time of origin</i>
A0 Marine origin	A1. Connate saline water	Coastal zone (off-shore)
	A2. Intruded by marine transgression	Coastal zone (off-shore)
	A3. Intruded by recent incidental flooding by the sea	Coastal zone (on-shore)
	A4. Laterally intruded seawater	Coastal zone (on-shore)
	A5. Intruded seawater sprays (aerosols)	Coastal zone (on-shore)
	A6. Mixture of A2 (marine transgression) and A3 (recent incidental flooding by sea)	Coastal zone (on and off-shore)
	A7. A6. Mixture of A1 (connate water), A2 (marine transgression) and A3 (recent incidental flooding by sea)	Coastal zone (on and off-shore)
B0 Terrestrial origin - natural	B1. Produced by evaporation (concentration)	Shallow water-table zones in arid climates
	B2. Produced by dissolution of subsurface salts	Zones of salt tectonics or regional halite or other dissolvable formations
	B3. Produced by salt filtering membrane effects	At depth in thick sedimentary basins containing semi- permeable layers
	B4. Emanated juvenile water and other products of igneous activity	Regions of igneous activity
	B5. Mixture of B1 (evaporation) and B2 (dissolution)	Shallow water-table zones in arid climates and aquifers containing dissolvable formations
C0 Terrestrial origin - anthropogenic	C1. Produced by irrigation (input of concentrated residual water)	Arid and semi-arid zones; shallow depths
	C2. Anthropogenically polluted groundwater	Anywhere on earth, particularly in modern consumptive societies
D0 Mixed origin	D0 Saline groundwater produced by mixing an A-, B- or C-class mineralized groundwater with fresh water or with another type of saline groundwater.	Anywhere on earth; hydraulic gradients facilitate the mixing processes

2.2.11.1 Saline groundwater of terrestrial origin – natural

(B1) Groundwater enriched in mineral content by evaporation at or near land surface.

This origin of saline groundwater is linked to shallow water table conditions and develops when climatic conditions favour evaporation (or evapotranspiration through phreatophytes) while flushing of accumulated salts is absent or only weak (Yeichieli and Wood, 2002).

Such conditions prevail on the so-called chotts, sebkhas, Salinas, salars or playas (names of saline lakes in closed basins in various languages and geographical areas in arid and semi-arid regions). It is assumed that the high lake salinity spreads in the underlying groundwater to some depths and some distances. Often a salt crust is formed at the lake bottom during dry periods.

(B2) Groundwater enriched in mineral content by dissolution of naturally occurring soluble minerals underground.

Groundwater may become saline by dissolving salts from evaporating formations (halites) or carbonates layers when flowing through or along such subsurface bodies. Even when flowing through 'ordinary' aquifers (of which only a limited fraction consists of easily dissolvable materials) groundwater may become brackish to saline in a downward direction, if time and other conditions favour dissolution of salts from the aquifer matrix (not uncommon in arid regions).

(B3) Saline groundwater produced as a result of membrane effects

Layers of clay or shale may be compacted that much in deep sedimentary basins that they become effective salt filtering membranes. Groundwater is percolating through such layers, but the dissolved larger ions are not permitted to pass, which leads to building up high groundwater salinity (even brines) near the inflow side of the membrane. This fractionation process often causes brines constituting of calcium and chlorides (Hem and Geological 1985). The process is called salt filtering, ultra-filtration or hyper-filtration.

(B4) Saline groundwater of geothermal origin

In addition to the meteoric and connate waters that form the point of departure of the previous genetic types of saline water, one may encounter highly mineralised water that is produced as a side product of igneous activity. Since it has not been part of the hydrological cycle yet, it is called 'juvenile water'. This process is rare but may be observed in regions of prominent igneous activity.

Highly pressurised and high-temperature groundwater that is present (mostly at greater depths) within areas with high igneous activity has a high dissolving capacity. This groundwater may be enriched in dissolved salts resulting in so-called thermo-mineral waters. In addition, cases of seawater flowing into these volcanic and igneous systems are

known. Hydrothermal groundwater systems may transport this highly salinised groundwater to shallower depths and even create localised hot and salty springs at the surface.

2.2.11.2 Saline groundwater of terrestrial origin – anthropogenic

(C1) Groundwater enriched in mineral content by irrigation.

Irrigation is augmenting water required for optimal crop evapotranspiration. Water vapour leaving the crops during this process is almost without dissolved solids, thus much less mineralised than the irrigation water supplied. Large-scale irrigation may also lead to shallow groundwater tables (water-logging) and non-beneficial evaporation directly from that water table. Consequently, a residue of relatively mineralised water is left in the soil. From there it may adsorb to the soil matrix (soil salinity), drain to the surface water system or percolate below the root zone. It may reach an aquifer and contribute to a progressive increase in salinity of its groundwater. In addition, irrigation by means of application of brackish water from some source (for example wastewater) may create salinisation of the underlying groundwater system. It is assumed that the groundwater salinisation because of irrigation is restricted to the first meters to tens of meters below the groundwater table.

(C2) Groundwater enriched in mineral content by anthropogenic pollution anthropogenic

Pollutants may enter the groundwater system and contribute to increased salinity of groundwater. Typical examples of such anthropogenic pollutants are road salt (applied in winter), fertilisers, domestic, industrial and agricultural effluents, spilled oil and gas field brines and brines from desalination plants. Groundwater salinisation effects of these processes will be rather localised.

(D0) Saline groundwater of mixed origin

This category refers to mixes between different types of saline water as described above or to water resulting from one or more of these categories mixed with fresh groundwater. Brackish transitional zones between saline groundwater wedges and overlying fresh groundwater bodies are a typical example.

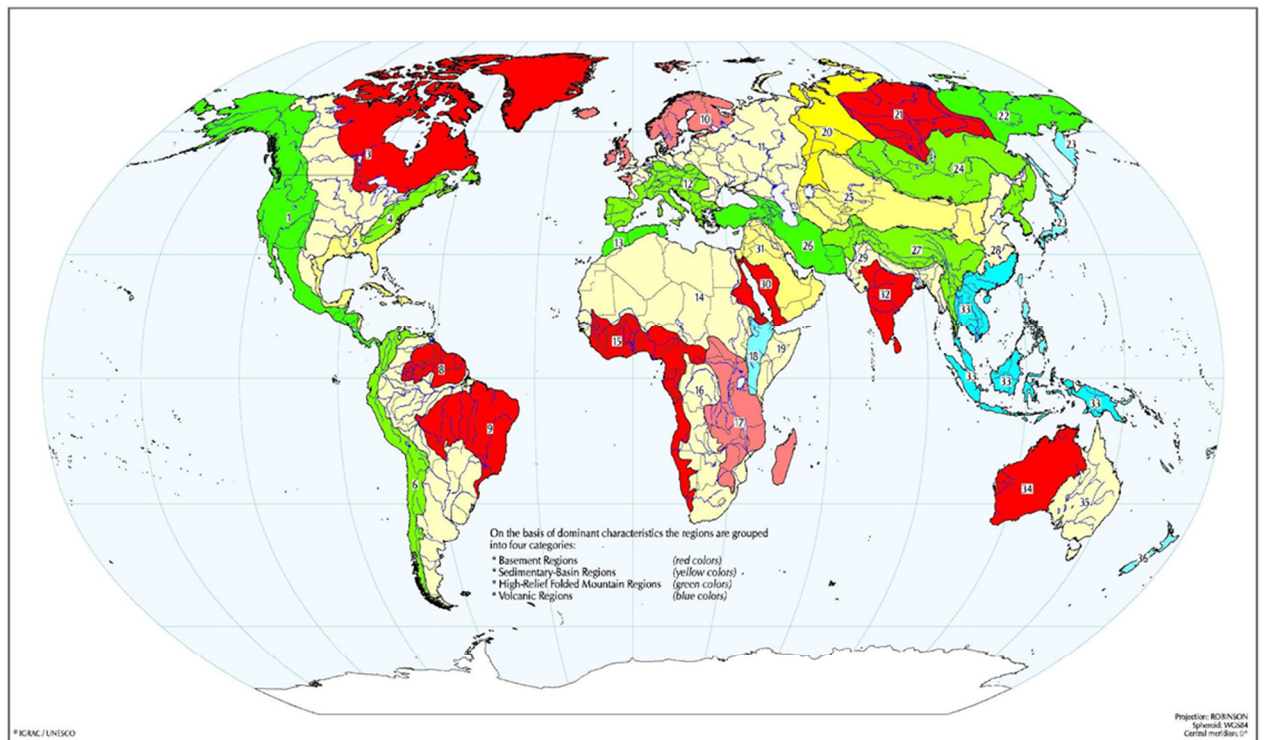
Given the characteristic large residence times of groundwater, the time dimension should not be overlooked when defining the origin of saline groundwater. E.g., saline groundwater may have originated in past geological periods when prevailing climatic or water-table

conditions were different from what they are nowadays. Furthermore, bodies of saline groundwater may have migrated since (Frank van Weert, Jac van der Gun 2009)

2.2.12 Existing Studies on saline water

Known studies on salinity include Global Overview of Saline Groundwater Occurrence and Genesis. This was a synthesis known studies on Saline Ground Water. The objective of the study was “to broadly inform groundwater resources managers, engineers, policymakers and politicians world-wide on the subject of managing saline groundwater with the aim to enhance their general understanding, promote early diagnosis of possible changes and widen their inspiration for selecting effective measures for intervention”. This study attempted to identify global groundwater regions, and IGRAC says the Global Groundwater regions are in 4 distinct types which include:

- *Basement regions*: predominance of basement outcropping at the surface or located at relatively shallow depths, hence relatively poor groundwater conditions and limited groundwater storage (red colours in Figure 10).
- *Sedimentary Basement regions*: predominance of sedimentary basins, offering good conditions for groundwater flow and storage. These regions contain the world’s most prospective groundwater resources (yellow colours in Figure 10).
- *High-relief Folded Mountain regions*: regions dominated by folded mountains producing high topographic relief. Groundwater occurrence in such regions usually is fragmented pockets, with high lateral variations over relatively small horizontal distances (green colours in Figure 10).
- *Volcanic regions*: regions where volcanic rocks and volcanism are strongly conditioning groundwater conditions (blue colours in Figure 10) (Frank van Weert, Jac van der Gun 2009).



GLOBAL GROUNDWATER REGIONS			
1 Western mountain belt of North & Central America	10 Baltic and Celtic shields	19 Horn of Africa basins	28 Plains of Eastern China
2 Central plains of North & Central America	11 Lowlands of Europe	20 West Siberian platform	29 Indo-Gangetic-Brahmaputra Plain
3 Canadian shield	12 Mountains of Central and Southern Europe	21 Central Siberian plateau	30 Nubian and Arabian shields
4 Appalachian highlands	13 Atlas Mountains	22 East Siberian highlands	31 Levant and Arabian platform
5 Caribbean islands and coastal plains of North and Central America	14 Saharan basins	23 Northwestern Pacific margin	32 Peninsular India and Sri Lanka
6 Andean belt	15 West African basement	24 Mountain belt of Central and Eastern Asia	33 Peninsulas and Islands of South-East Asia
7 Lowlands of South America	16 Sub-Saharan basins	25 Basins of West and Central Asia	34 Western Australia
8 Guyana shield	17 East African basement and Madagascar	26 Mountain belt of West Asia	35 Eastern Australia
9 Brazilian shield and associated basins	18 Volcanics of East Africa	27 Himalayas and associated highlands	36 Islands of Pacific

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Figure 10: Global groundwater regions

Frank van Weert, Jac van der Gun, Josef Reckman Identified 36 Global groundwater regions which are highlighted in Appendix 4. The study highlighted the main occurrence, origin and dimension of shallow saline groundwater. Among the 36 GGWR are the sub-Saharan region basin and East Africa Basin and Madagascar, regions which include Zambia.

The two African regions that include Zambia cited in the study comprise of sedimentary basin region and basement region:

The sedimentary basin region includes (Republic of Congo, Democratic Republic of Congo, Angola, Zambia, Zimbabwe, Botswana, South Africa, and Mozambique.) and the key findings are that this region includes large inland depressions in basement rocks of Central and Southern Africa that have been filled by sediments of various origins. The sedimentary areas are moderately elevated and have flat relief.

Topographical high of crystalline rocks, which separate two Southern basins, is included in this region. The region has a humid climate in the Northern parts and a dry climate in the South. Groundwater resources are abundant.

- a) Congo basin
- b) Kalahari-Ethosha Basin
- c) Kalahari Precambrian Belt (Western part)
- d) Karoo Basin
- e) Cape Fold Belt
- f) Coastal Basins of Mozambique

Large regional aquifers are found in unconsolidated sediments (e.g. in Congo basin) and fractured sandstones (e.g. Karoo Aquifer system). Limestone and dolomite layers (e.g. Katanga System) form local aquifers. Shales and crystalline rocks are poor aquifers. Some of the aquifers receive limited modern recharge.

The basement regions include (Sudan, Democratic Republic of Congo, Uganda, Kenya, Tanzania, Zambia, Mozambique, Zimbabwe, Madagascar.) and the key findings are this region includes moderate elevated, flat areas of the East African Shield, affected in the Eastern parts by rifting. The region is dominated by outcropping crystalline Basement rocks, with the local occurrence of volcanic rocks and sediments. Climate is humid in the Northern parts and dry in the South. Groundwater resources are limited.

- a) East Congo Precambrian Belt
- b) Luffilian Arch (Katanga system)
- c) East Kalahari Precambrian Belt
- d) East Africa Basement (including rifted zones)
- e) Tanzania coastal basin
- f) Sediments of Madagascar
- g) Basement of Madagascar

one of the studies that is known to have used a similar methodology (Vertical Electrical Sounding) was undertaken in Nigeria. The key finding of the study was that a vertical electrical sounding method has been applied and the results were able to delineate different geoelectric sections which were correlated with available borehole logs; to determine their corresponding geological formations. The promising wells from the resistivity survey were mapped based on the nature and properties that constitute the aquifer layer and the overburden material and thickness (Bashir, Izahm, and Main 2014).

The most comprehensive study on water in Zambia was undertaken by JICA in 1995. The study covers broad areas such as Socio-economy, Meteorology, hydrology, hydrogeology, domestic Water Supply, Industrial Water Supply, Current Water use Survey, Agriculture, Livestock and Fishery, irrigation, Forestry, Hydroelectric Power Generation, Navigation, Flood Control, Dam Geology, Dam development Plan, Dam Geology, Water Supply Plan, Water Quality and Environment, Laws and Institutions, Landsat Satellite Imagery, Analysis Topographic Survey, Groundwater Monitoring, Well Inventory Survey and Database. The study provides overall guidance on how best the country can tackle its water need in the different sectors (Yachiyo Engineering 1995).

A detailed study done in Zambia was undertaken by Chongo *et al.*, (2015) used Airborne and transient electromagnetic mapping to study salinity and was undertaken in the Machile Zambezi Basin, southern, western Zambia. The key finding of the study was the combination of ground-based and airborne TEM methods were effective in mapping the regional electrical resistivity structure of the Zambezi basin from which groundwater salinity variation could be inferred in addition to the regional tectonic structure or geological fault system. Calibration of VTEM data with accurate ground-based Walk TEM data ensured the strong agreement between the airborne TEM inverted using an SCI scheme and ground-based data inverted as single site 1D inversions (Chongo et al. 2015)

The significance of this study, therefore, is that in Zambia, and in particular in Luangwa district, there is no known study that has been undertaken using Vertical electrical sounding with Schlumberger configuration method to identify saline zones. This study, therefore, adds to the body of knowledge on saline water in Zambia using this unique methodology to provide guidance in mapping the lowest resistivity zones which are related to salinity.

CHAPTER 3: METHODOLOGY

3.1 Methodology

This study was more quantitative in nature utilising scientific measurement to ascertain water quality in the sampled boreholes. Luangwa district has a total of 176 boreholes of which 25 are suspected to have saline water.

3.2 Sampling strategy

A cluster sampling strategy was utilised for this study; the boreholes were classified into a cluster, i.e. those suspected to have saline water as cluster 1 and cluster represented none salinity boreholes. Among the 25 suspected boreholes with saline water 13 were boreholes were randomly selected among functional boreholes, taking into account geographical dispersion of the boreholes so as to have a sample that adequately represents the district while only two boreholes were sampled among those known to have clean water, this was mainly for control or comparison purposes. The Ministry of Water Development Sanitation and Environmental Protection database on the boreholes in Luangwa District acted as the sampling frame. This multi-layered sampling strategy significantly reduced selection bias.

3.3 Data Collection

The data was collected on all existing saline boreholes in the district using the resistivity method (Schlumberger), pH, Ec, Fe.

A form was designed to collect quantitative data (Appendix 1), mainly on resistivity and GPS coordinates (using Garmin GPSMAP64) to identify location each sampled borehole. A notebook was used to record supplementary indicators. The main types of data that was collected onsite include:

- Electroconductivity (Ec)
- pH
- Iron level (Fe)
- Resistivity test (Vertical electrical sounding)
- GPS coordinate
- Water samples collected taken to UNZA Lab (10 out of 16 samples)

The water samples collected from the existing saline boreholes was analysed on site by measuring pH, Ec meter and Fe meter; Water samples were collected from 10 of the 16 sampled sites and sent the UNZA lab for further analysis by running, Chloride and sulphate tests.

3.4 Method

This study utilised the VES method. Vertical Electrical Sounding (VES) provides depth and thickness estimates based on the resistivity values. Saline layers are generally represented by low resistivity values compared with portable water or massive rocks. Schlumberger array was adopted for conducting VES. The maximum current electrode separation (AB) was ranging up to 300 meters, which theoretically provide 100 metres depth of layers homogeneity investigated. The data will be interpreted in terms of horizontally stratified earth model by using VES interpretation software - RESIX-Plus both smooth and manual model. Also, by using the software SUFER 10, the smooth model is plotted to show graphically the low resistivity associated with the saline zone for each VES.

The study used shapefiles for different features and GPS coordinates (using ArcGIS 10.4) to generate various Maps and resistivity profile lines of sampled boreholes within Luangwa District and to show their (boreholes) spatial distributions.

3.5 Data analysis

This study involved an analysis of water samples from 16 sampled suspected saline boreholes in Luangwa district. The water samples collected from the existing saline boreholes were analysed on site by measuring pH, Ec meter and Fe meter; the same sample was analysed at UNZA Lab for Chloride and Sulphates contain (Table 4).

3.6 Limitation of the methodology

According to the Luangwa District Local Authority, the district has a total of 176 boreholes. The District Council suspects 25 out of the 176 boreholes to have saline water. This study sampled only 16 out of the 25-suspected saline boreholes, (representing about 64% of saline suspected boreholes) due to time and cost constraints. Further, the study concentrated on analysing the resistivity profiles of the sampled boreholes and did not place emphasis on the effect of the altitude of each borehole location on water quality during data analysis. In addition the chemistry analysis was only restricted to sulphate and chlorite. Besides due to

time and cost limitations, although the initial plan was to have resistivity traverses and borehole construction inspection using a borehole camera, this activities could not materialise as the borehole camera could not be used due to suspended particles or dropped down rising main in some boreholes. The study did not include the individual borehole construction reports

CHAPTER 4: PRESENTATION OF FINDINGS

This chapter will present the findings of the study by describing the findings of each of the sampled boreholes.

4.1 Geophysics Profile

The findings for each sampled borehole are presented in Appendix (5), with two examples shown in Figures 11 and 12. The Figures displayed on the left side of the Figures shows the apparent resistivity data plotted using the RESIXP smooth model while on the right-hand side of each Figure the display highlights the levels of resistivity in relation with depth in each borehole using SURFER10.

For illustrative purposes, the best (Figure 11) and the worst-case scenario (Figure 12) among the sampled boreholes are displayed below.

4.1.1 VES LUG014

Figure 11 below (best case scenario) shows that slightly low resistivity on ground level, with blue representing high resistivity, green represents medium resistivity while red represents low resistivity. As it can be seen on this particular borehole, the resistivity was increasing as depth increased.

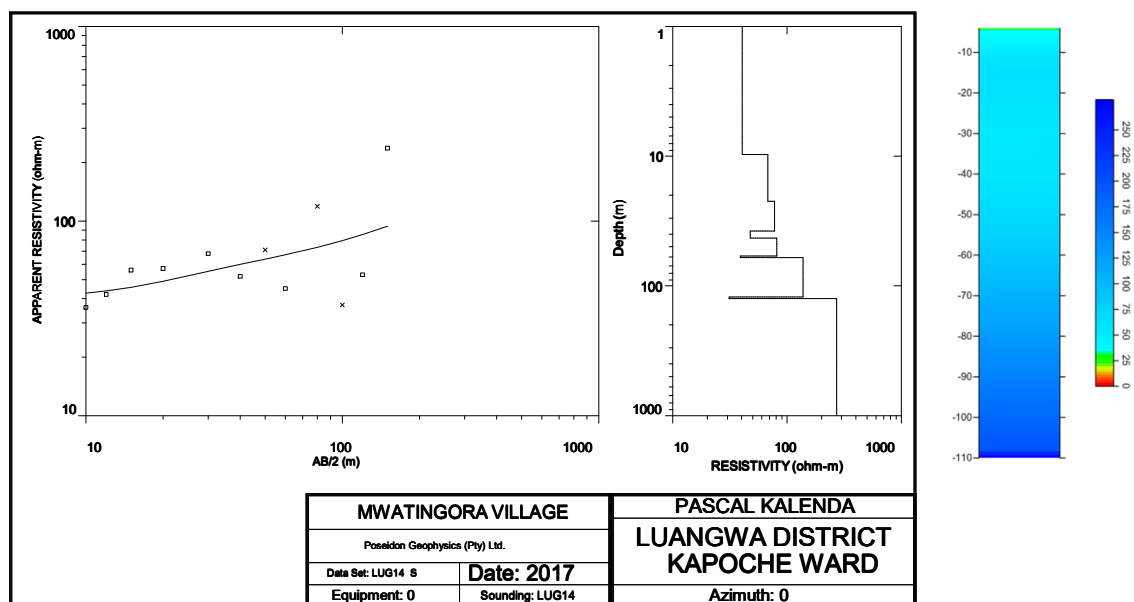


Figure 11: VES LUG014 results

4.1.2 VES LUG016

Figure 12 (worst case scenario) shows that a slightly higher resistivity (32 Ωm to 34 Ωm) between 28 mbgl to 30 mbgl and low resistivity (0 Ωm to 12 Ωm) from 0 mbgl to 110 mbgl with the lowest resistivity is observed from 51 mbgl to 110 mbgl. For more details, see Figure 12 below

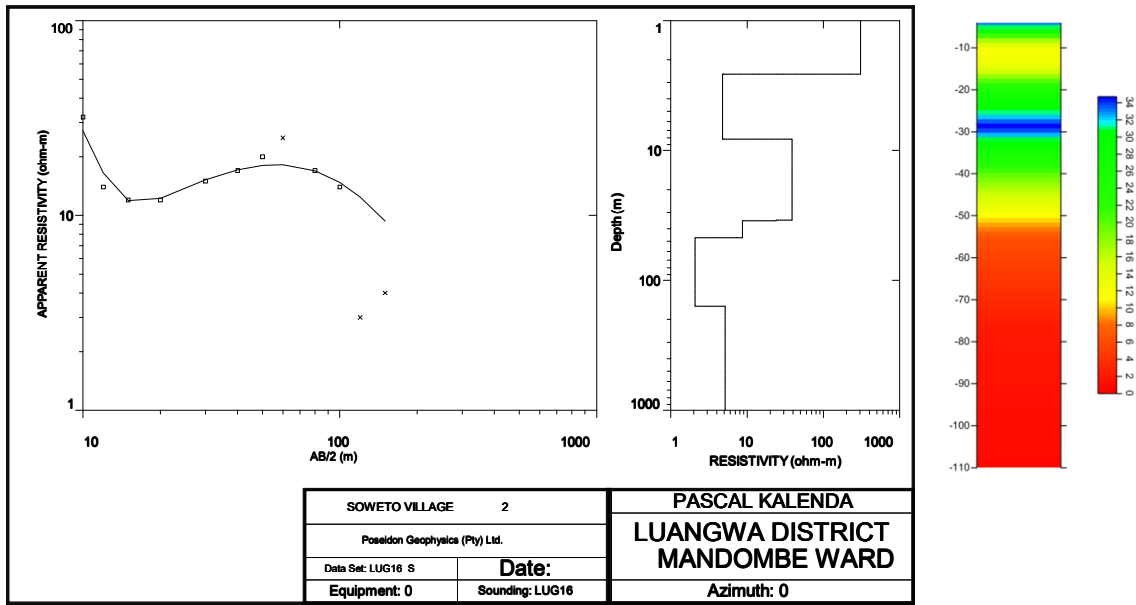
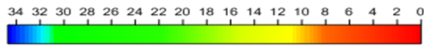


Figure 12: VES LUG014 results



The Legend above represent the resistivity levels as follows:

- 0 Ωm – 7 Ωm in red for lower resistivity
- 7 Ωm – 14 Ωm in yellow
- 14 Ωm – 30 Ωm in green
- >30 Ωm in Blue for Higher resistivity

Similarly, other studies have attempted to shows resistivity depth slices at different depths and interpreted groundwater salinity based on correlation with borehole data (Podgorski *et al.*, 2010) See the rest of VES results in appendix 5

Study results show that 14 of the sampled 16 boreholes had Saline water, representing 87.5% of the suspected saline boreholes. The resistivity profile developed for Luangwa district clearly show the sites and depths associated with salinity. The profiles depict the depth of

low resistivity associated with salinity. The average depth of existing boreholes in Luangwa district is about 53 meters.

The resistivity profiles lines shown in Figure 13 for the sampled 16 boreholes are presented in three separate Figures (14, 15 and 16) which are highlighted and discussed below; due to available data spread on a long distance the graph represent an apparent resistivity in between the sampled boreholes;

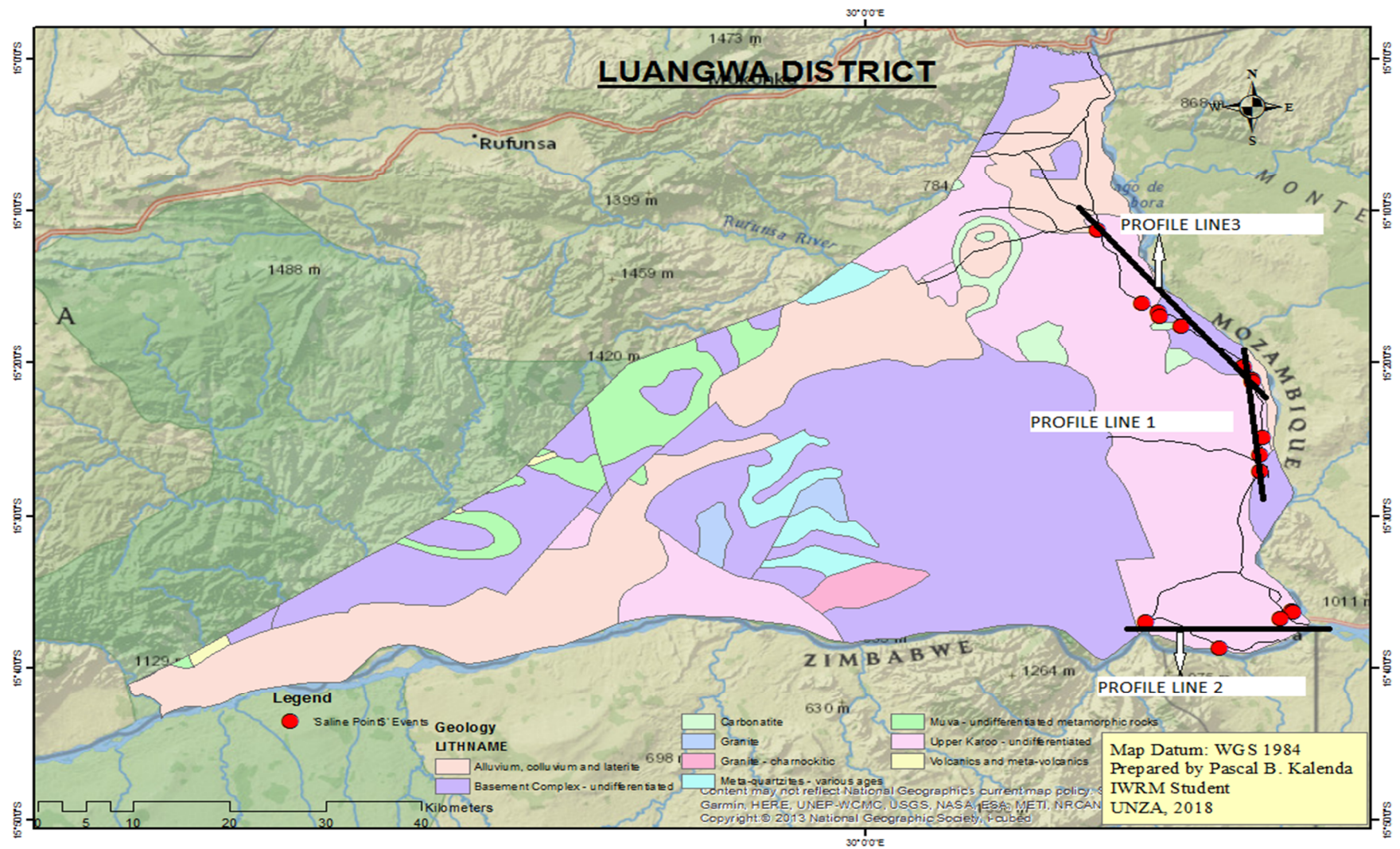


Figure 13: Resistivity Profiles line

The resistivity profile line 1 highlighted in Figure 14 below shows that the apparent resistivity of borehole varies VESLUG009 shows low resistivity from surface to around, VESLUG010 shows low resistivity from 5 mbgl to 40 mbgl, VESLUG012 shows low resistivity from surface up to around 30 mbgl, VESLUG013 shows high resistivity at the surface with low resistivity starting from 5 mbgl to 30mbgl, VESLUG014 shows low resistivity from 0 to 40 mbgl while VESLUG015 shows low resistivity from surface to about 10 mbgl.

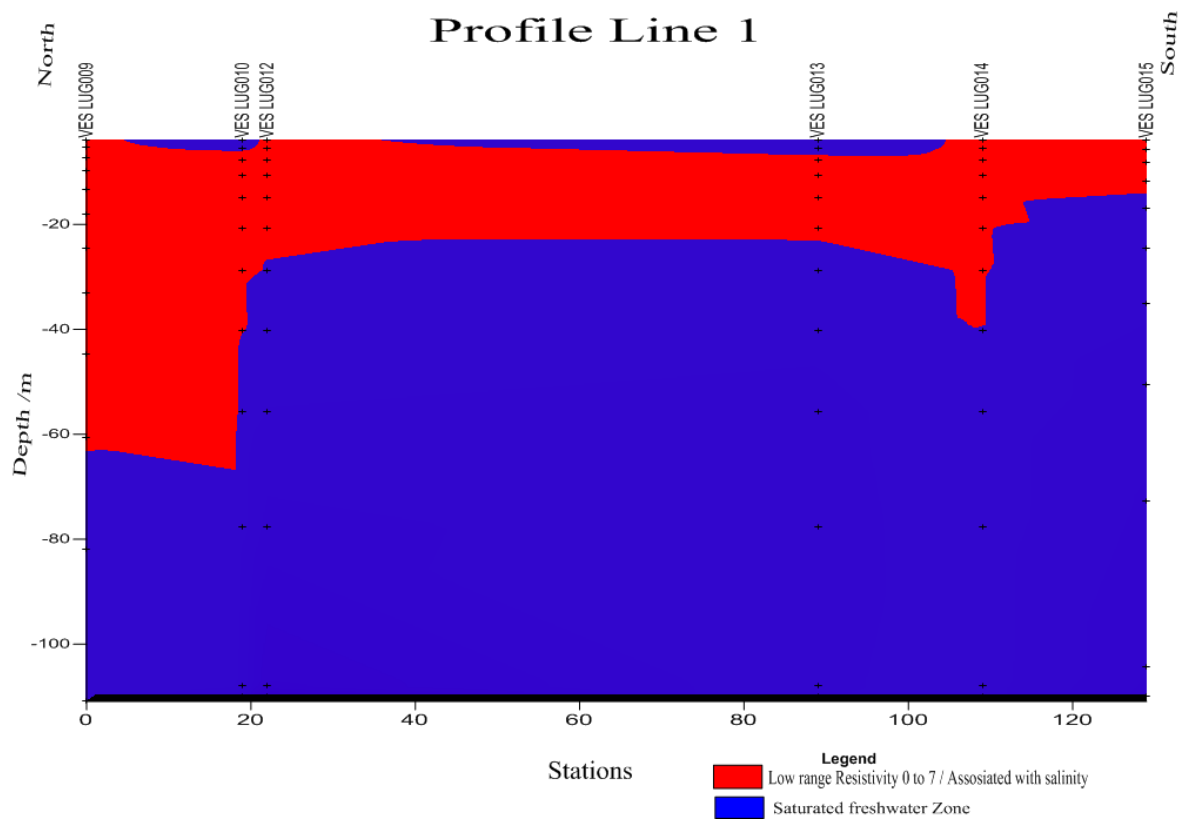


Figure 14: Resistivity profile line 1

The resistivity profile line 2 highlighted in Figure 15 below (VESLUG011, VESLUG003, VESLUG016, VESLUG002 and VESLUG001) shows various lower resistivity in various depths, VESLUG001 shows lower resistivity ranging from 0 to 7 Ω m from 5 mbgl to 22 mbgl, VESLUG003 shows higher resistivity from surface to about 10mbgl and low resistivity from 10mbgl to 50 mbgl., VESLUG016 shows lower resistivity from 0 to 110mbgl, while VESLUG002 and VESLUG001 shows lower resistivity from 0 to 100 mbgl with pocket of higher resistivity around 30 mbgl, 40 to 50 mbgl and 70 to 90 mbgl.

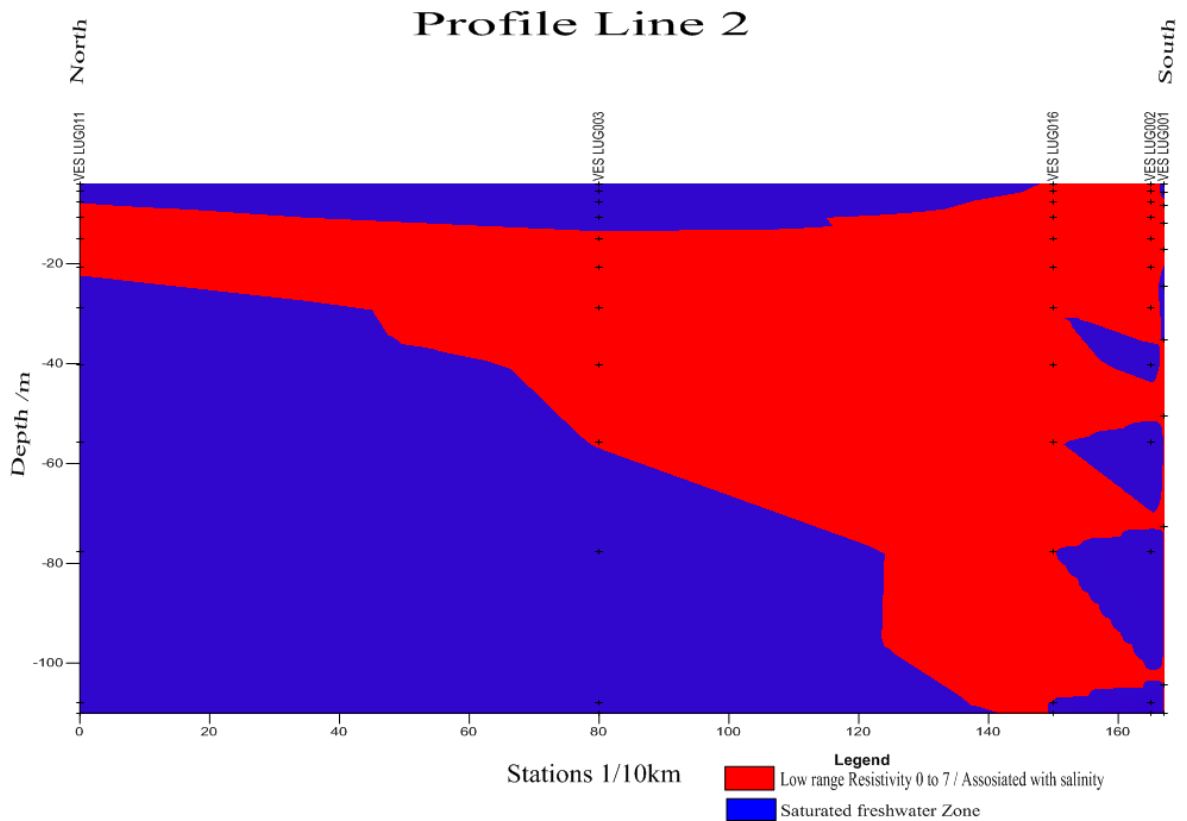


Figure 15: Resistivity profile Line 2

Similarly, on resistivity profile line 3 in Figure 16, below, boreholes (VESLUG004, VESLUG005, VESLUG006, VESLUG007, VESLUG008, VESLUG009 and VESLUG010) shows low resistivity at various depth; VESLUG004 shows low resistivity of 3 Ω m around 15 mbgl as well as from 50 mbgl to 110 mbgl; VESLUG005 shows low resistivity all the way to 110 mbgl except around 20 mbgl where the resistivity is over 100 Ω m while VESLUG012 shows low resistivity from 0 to 15 mbgl and the resistivity increases with depth up to a 1000 Ω m from 0 to 40 mbgl.

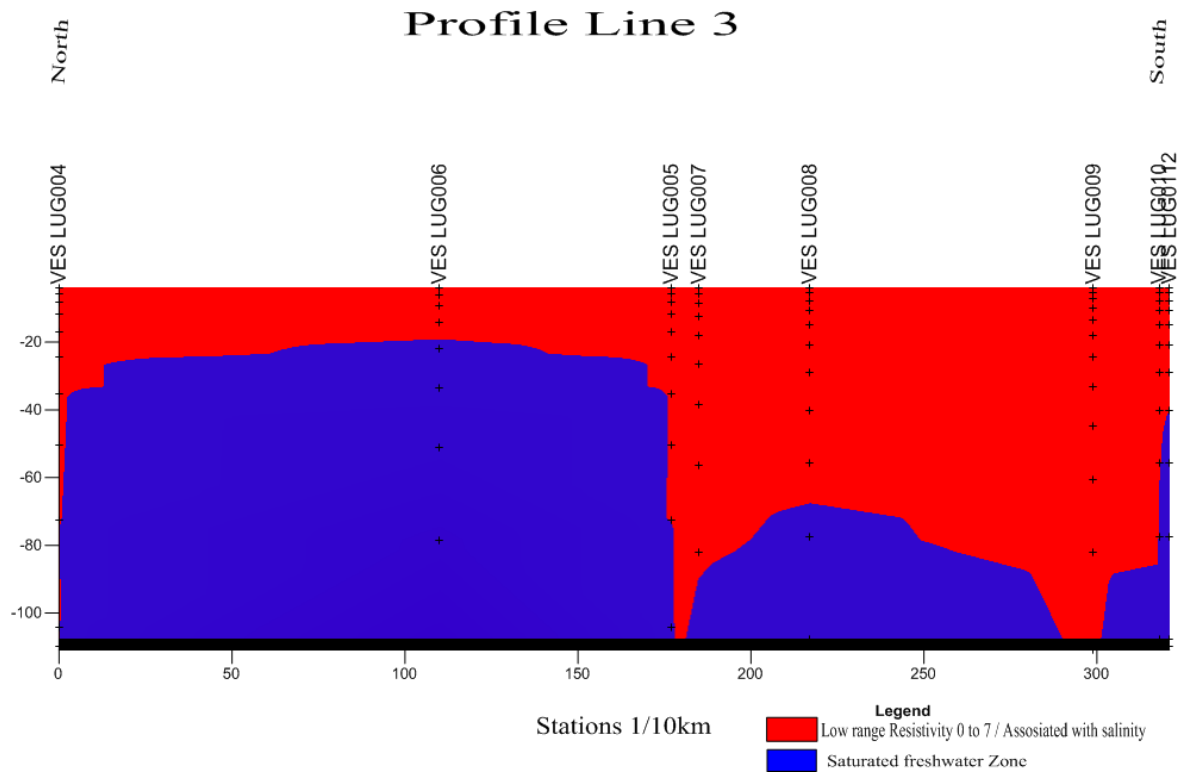


Figure 16: Resistivity profile Line 3

4.2 Water quality

Field data on water quality measured Ec and was compared with the laboratory analyses which measured Chloride and Sulphate. Multiplying Chloride by a factor of 0.0018066 provides an estimate of salinity. Ec measurement that is out of range gives an indication of expected water quality.

Table 4 Field and Laboratory water analysis

	LAB data			Field Data				
	Chloride (mg/l)	Sulphate (mg/l)	Salinity (mg/l)	Salinity (ppt)	Ec (ppm)	Ec ($\mu\text{S}/\text{cm}$)	TDS(mg/L)	
LUG001	5,848	1,635	10,565.00	10.56	4,176	6,515	4,365	
LUG003	58	77	104.78	0.10	919	1,434	961	
LUG004	58	51	104.78	0.10	658	1,026	688	
LUG005	109	437	196.92	0.20	1,177	1,836	1,230	
LUG006	36	2.2	65.04	0.07	225	351	235	
LUG007	108	457	195.11	0.20	1,322	2,062	1,382	
LUG008	320	429	578.11	0.58	1,771	2,763	1,851	
LUG009	2,349	2,816	4,243.70	4.24	3,746	5,844	3,915	
LUG010	650	1,728	1,174.29	1.17	1,157	1,805	1,209	
LUG016	23	100	41.55	0.04	1,251	1,952	1,308	

To show the relationship between the groundwater quality and resistivity, a scatter diagram between groundwater TDS (from borehole data) versus resistivity is plotted as shown in Figure 17.

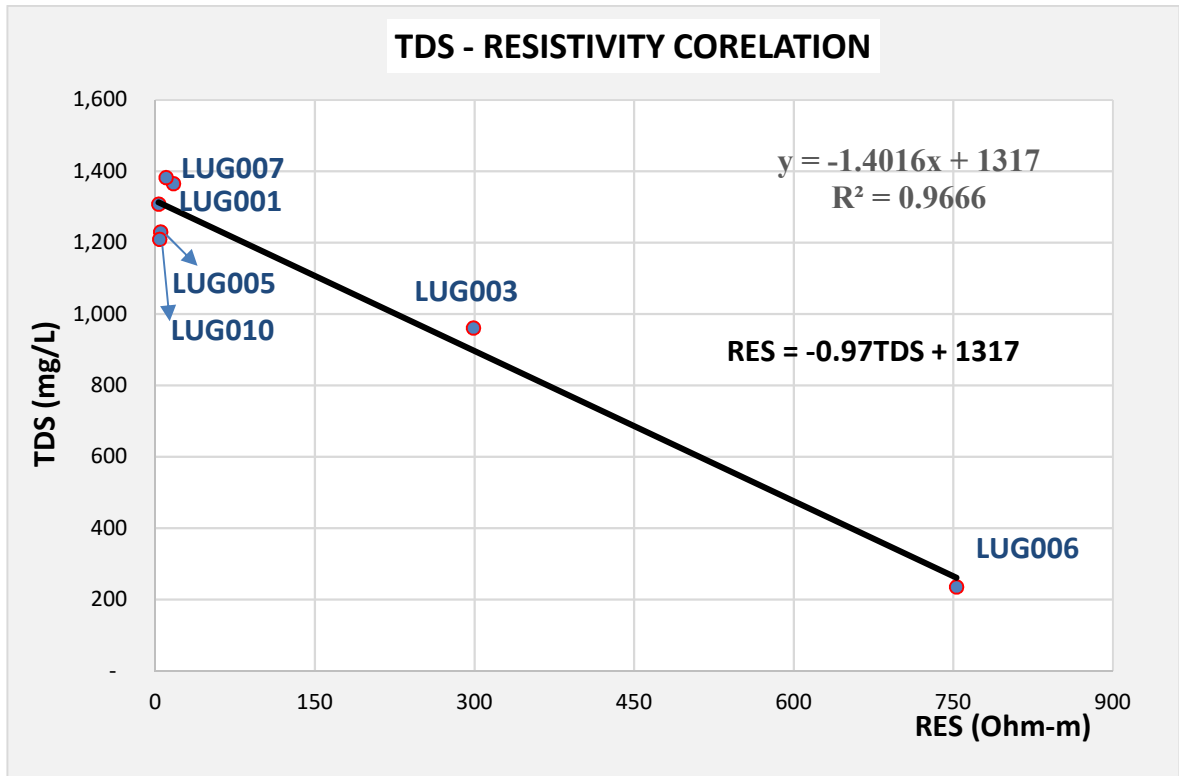


Figure 17: Relationship between Groundwater TDS and Resistivity

The fitted line shows a 96% correlation suggesting that the groundwater quality primarily controls resistivities.

CHAPTER 5: DISCUSSION OF FINDINGS

This chapter will discuss the findings of the two scenarios presented in chapter 4 (best and worst-case scenario) of the sampled borehole and proceeds to interpret the findings and their implications for the districts water resource.

Geophysics survey highlight resistivity profiles this can guide reduce chances of saline boreholes. For instance, the sinking of borehole VESLUG009 above could have been improved by placing a sanitary seal at 65 mbgl to avoid leaching as low range resistivity(0–7.Ωm) extends to over 60 mbgl. Salinity in VESLUG010 and VESLUG014 could have been minimised by casing off the boreholes to about 40 mbgl while water in other borehole VESLUG012 would have required casing of about 35 mbgl. VESLUG013 and VESLUG015 would have required casing of 25 mbgl and 15 mbgl respectively to protect the water from contamination with low range resistivity associated with salinity see Figure 15 for profile details. Casing off the areas with low range resistivity can reduce salinity if the water in the borehole is below the depth of the low range resistivity areas coupled with a sanitary seal in the borehole construction design depending on the saturation zone. In addition, the profile shows boreholes clustered in areas likely to have saline water.

Similarly, in Figure 15 above depending on the water strike and sanitary seal in borehole design, only one borehole (VESLUG011 with a casing of approximately 30 mbgl), could have been sunk in the area around profile line 2 had geophysics surveys been conducted to guide the sinking of boreholes as the rest of the boreholes (VESLUG003, VESLUG016, VESLUG002) lie in areas of low range resistivity (1–10 Ωm) which is associated with salinity and are all beyond the 53 mbgl average borehole depth. With the help of the geophysics survey, more boreholes could have been sited in the areas with low range resistivity of less than 30 mbgl.

Research has shown that the low resistivity (0.01–10 Ωm) in unweathered rocks is associated with Graphite, Graphitic rocks, yield salt (salinity) to brackish water; resistivity levels between (10 – 100 Ωm) in weathered rocks are associated with Saprolite, and metamorphic rocks which yield fresh water, and resistivity levels between 100–1.000.000 Ωm in unconsolidated sediments associated with Gravel and sands while sedimentary rocks sandstones and conglomerates which yield sea ice and permafrost respectively as described in Figure 11 below (Davis, Scientific, and Ley-cooper 2016).

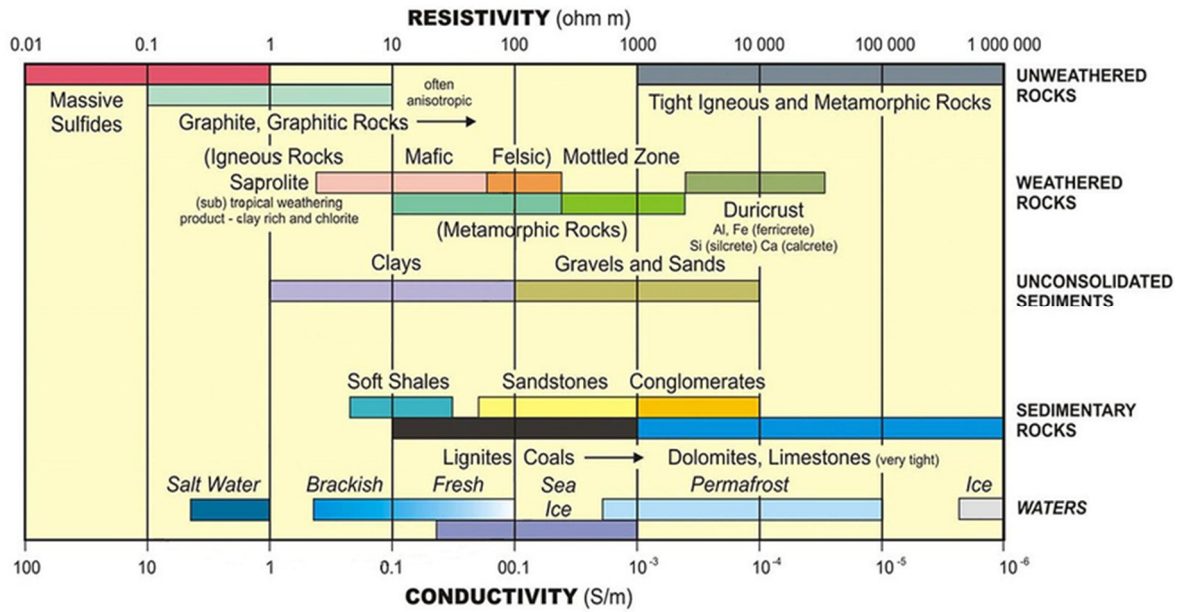


Figure 18: Resistivity of common earth materials

A simple schematic that displays the expected conductivity or resistivity of common earth materials. Overlapping values of conductivity show that the inverted conductivity values of the subsurface may not allow for unique determination of material.

Illustration in Figure 18 agrees with other study have that shown that resistivities in the 5–15 Ωm range correlate with light brown fine-grained sand and brackish water, whereas low resistivities of $\leq 5 \Omega\text{m}$ correspond to clays and saline water (Podgorski et al. 2010). This is also in tandem with the findings from (Chongo *et al.*, 2015) 's study that indicates that "the electrical resistivity distribution is indicative of a full graben related to the Okavango–Linyati Fault system as a result of propagation of the East African Rift Valley System (which Luangwa valley is part of) into Southern Africa. The saline lacustrine sediments infilling the Machile Graben are responsible for the low formation resistivity (below 13 Ωm) and high salinity (above 7000 $\mu\text{S}/\text{cm}$) observed in the groundwater and are probably related to the complex evolutionary history of Palaeo-Lake Makgadikgadi" equally the findings of this study show that salinity is associated with low levels of resistivity of between 2–10 Ωm .

Conducting geophysics surveys, therefore, improves the siting of boreholes, as sites with low resistivity would easily be mapped and probably avoided or improve borehole construction design. Based on Figure 27 in the appendix, which shows low resistivity ranging from 12 mbgl to 40mbgl, given that borehole was sunk up to 69 mbgl in a sandstone

formation, the construction design could have included a sanitary seal at 45mbgl, this could have reduced the leaching. (see drilling report for Figure 27 in appendix 5).

The scattering in the data (Figure 18) points suggests that porosity is also controlling the resistivities. It is also apparent from the graph that freshwater aquifers are represented by resistivities greater than 15 Ωm . These resistivity ranges are similar to those observed in the Lower Okavango Delta (Podgorski et al. 2010).

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

In this Chapter the conclusions and recommendations arising from the study.

6.1 Conclusions

This study has shown the importance of undertaking geophysics surveys prior to sinking boreholes, especially in Luangwa district where the results showed that over 87% of the sampled boreholes had saline water. If geophysics surveys were conducted prior to sinking boreholes in Luangwa district, a number of boreholes with saline water would not have been sunk or had their construction design improved as the resistivity profiles would have shown the areas likely to have saline water. The study has therefore shown that geophysics survey can guide the siting of boreholes as well as the depth to which boreholes must be sunk or placing of the sanitary seal to avoid saline water, especially in Luangwa District which lies within the Karoo Basin which is known to have saline water due to sedimentation.

Geophysics surveys improve borehole siting by either indicating the depth at which fresh water is available within saline basins and showing the required casing or placing of the sanitary seal to avoid water contamination or by showing geographical locations that are in non-saline basins. The study mapped the existence of 25 saline suspected boreholes and shown the resistivity ranges of geological material in the in Luangwa District as well as established the extent of ground salinity depth in the area. The study further assessed the correlation between resistivity and salinity, showing that low resistivity range of 1–10 Ωm is likely associated with salinity and has recommended borehole construction design and drilling depth for groundwater development depending on a water strike

The following are the additional study conclusions:

1. The use of geophysics survey is a critical activity to the success of groundwater supply investment.
2. The geology formation is the contributing factor of salinity in the district, the district is predominant upper Karoo formation, and all saline boreholes are situated in that formation as shown in Figure 2.
3. The high levels of E_c can act as a proxy of salinity as shown in the analysis as shown in the water quality results.

6.2 Recommendations

The following are the recommendations:

1. The government of the Republic of Zambia through the ministry of water development sanitation, and environmental protection, and cooperatives partners in the water sector, as well as WARMA, need to invest in the geophysics studies throughout the districts and mapping of saline-prone areas.
2. The ministry to make geophysics survey mandatory for all drilling activities in the districts.
3. The District To have specific boreholes construction design develop for the district in terms of drilling depth, sanitary plug, grout seal, screen levels.
4. To have an independent socio impact assessment on all saline affected communities.
5. The Ministry of Water Development, Sanitation and Environmental Protection and the District need to develop a database on all drilled boreholes in the district

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APPENDICES

Appendix 1: Data Collection form

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Appendix 2: Laboratory results



SCHOOL OF ENGINEERING
CIVIL ENGINEERING DEPARTMENT
ENVIRONMENTAL ENGINEERING LABORATORY

P.O Box 32379, Lusaka
Direct Telefax: 260-1-290962
Telegram: UNZA LUSAKA
Telex: ZA44370

CHEMICAL EXAMINATION OF WATER

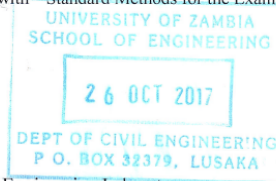
Attn : P. Kalenda
UNZA- IWRM
Lusaka
Sampled by : Client
Receipt date : 23.10.2017
Report date : 26.10.2017

Laboratory Results

Sample ID	Chloride (mg/l)	Sulphate (mg/l)
LUG 001	5,848	1,635
LUG 003	58	77.22
LUG 004	58	50.71
LUG 005	109	437
LUG 006	36	2.20
LUG 007	108	457
LUG 008	320	429
LUG 009	2,349	2,816
LUG 010	650	1,728
LUG 016	23	100

Tests carried out in conformity with "Standard Methods for the Examination of water and Wastewater APHA, 1998".

J. Kabika
Co-ordinator- Environmental Engineering Laboratory



Appendix 4: Village visited and code

CODE	S	E	DISTRICT	NAME	Ec(ppm)	PH
LG001	-15.60468	30.39957	Luangwa	Kamowa Village	2000	6.69
LG002	-15.60597	30.40090	Luangwa	Pepo's House		
LG003	-15.64479	30.33251	Luangwa	Chilombwe Primary school	919	8.15
LG004	-15.18681	30.21780	Luangwa	Chitope RHC	658	6.77
LG005	-15.27624	30.27539	Luangwa	Luangwa Secondary School	1177	7.77
LG006	-15.26740	30.25905	Luangwa	Chilukusha Village	225	6.89
LG007	-15.28119	30.27646	Luangwa	Chilukusha Community School	1322	7.71
LG008	-15.29147	30.29691	Luangwa	Shonkhomoka Village	1771	6.93
LG009	-15.33734	30.35424	Luangwa	M'lalanjala Village	1873	6.77
LG010	-15.35152	30.36262	Luangwa	Kaluluzi RHS(Kaneme RHC)	1157	6.90
LG011	-15.61654	30.26286	Luangwa	Kavalamanja Primary School	488	7.61
LG012	-15.35425	30.36315	Luangwa	Mpingo with Solar BH	1241	7.01
LG013	-15.41514	30.37240	Luangwa	Kaposhe Primary and Secondary School	1212	7.01
LG014	-15.43315	30.37008	Luangwa	Mwatingora	372	7.30
LG015	-15.45147	30.37059	Luangwa	Chitambili	1954	7.18
LG016	-15.61324	30.38922	Luangwa	Soweto	1251	7.12

Appendix 5: Field VES data for sixteen boreholes

Intergrated Water Resources Management

The University of Zambia

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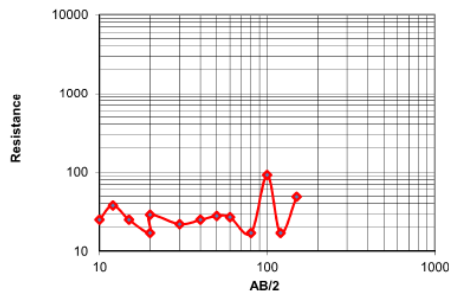
VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

Location and Geology VES: LUG1 Kamowa Village	16-Oct-17	Location and Geology VES: LUG2 Pepo's House	16-Oct-17
---	-----------	---	-----------

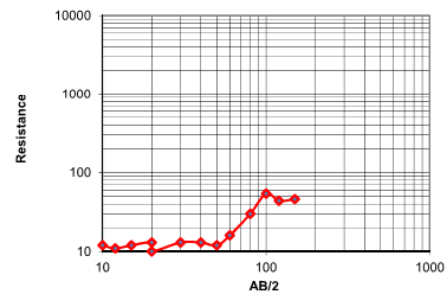
VES:		LUG1			
Position:	S: -15.60468	E: 030.39961			
	2	10	GC	SD	Ohmm
10	25		19	0.1	
12	38		28	1.2	
15	25		4	1.4	
20	17		6	1.4	
20		29	6	0.6	
30		22	0.01	0.3	
40		25	2	0.4	
50		28	5	0.4	
60		27	0.1	32.2	
80		17	9	0.1	
100		92	14	7.3	
120		17	7	7.7	
150		49	0.1	1.4	

VES:		LUG2			
Position:	S: -15.60597	E: 030.40090			
	2	10	GC	SD	Ohmm
10	12		5	0.1	
12	11		6	0.1	
15	12		9	0.3	
20	13		7	0.3	
20		10	7	0.4	
30		13	9	0.4	
40		13	0.01	1.1	
50		12	4	0.9	
60		16	1	1	
80		30	0.2	1.1	
100		54	7	2.3	
120		44	18	45	
150		46	10	0.9	

VES LUG 1



VES LUG 2



Interpretation VES:			
From	To	Ohmm	Interpretation
0	1		
1			

Interpretation VES:			
From	To	Ohmm	Interpretation
0	1		
1			

Gradient Array										
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

Comment and Access

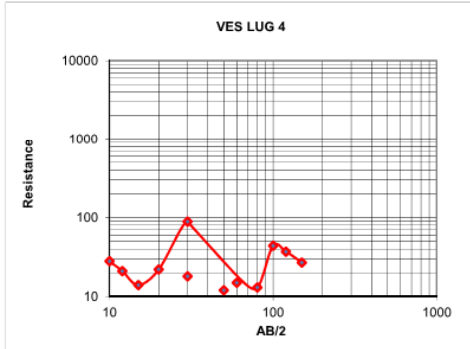
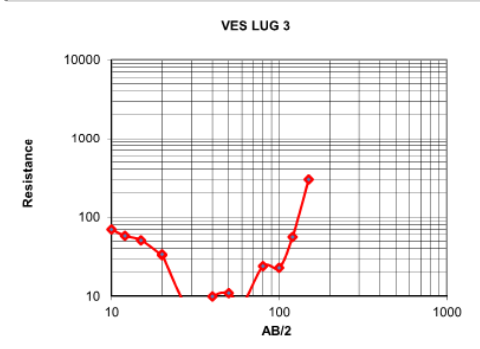
SCHLUMBERGER

VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

Location and Geology VES: 17-Oct-17 LUG3 Chilombwe Primary school	Location and Geology VES: 17-Oct-17 LUG4 Chitope RHC
---	--

VES:		LUG3			
Position:	S: -15.64480	E: 030.33252			
	2	10	GC	SD	Ohmm
10	70		8	0	
12	58		6	0.1	
15	51		7	0.2	
20	33		0.2	0.2	
20		34	0.2	0.2	
30		6	5	17.9	
40		10	6	0.2	
50		11	4	2.5	
60		8	5	7.2	
80		24	3	0.7	
100		23	1.2	5.1	
120		56	2	3	
150		299	7	2.2	

VES:		LUG4			
Position:	S: -15.18680	E: 030.21776			
	2	10	GC	SD	Ohmm
10	28		0.2	0.1	
12	21		0.2	0.3	
15	14		0	0.4	
20	22		3	1.4	
30	89		4	3	
30		18	4	3	
40		-	-	-	
50		12	0.3	2.1	
60		15	3	3.1	
80		13	8	23.3	
100		44	5	2.5	
120		37	7	1.6	
150		27	0.1	2.6	



Interpretation VES:

From	To	Ohmm	Interpretation
0	1		
1			

Interpretation VES:

From	To	Ohmm	Interpretation
0	1		
1			

Gradient Array

50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

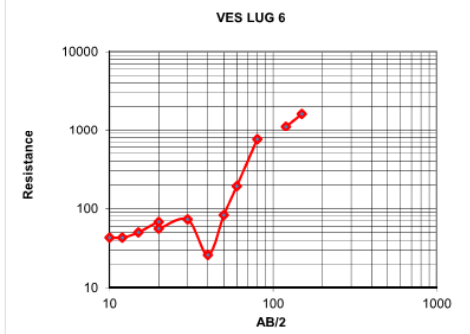
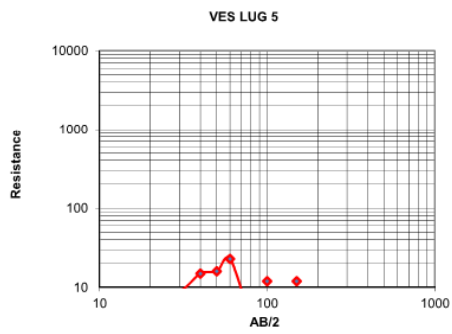
Comment and Access

VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

Location and Geology VES: LUG5 Luangwa Secondary School	17-Oct-17	Location and Geology VES: LUG6 Chilukusha Village	17-Oct-17
---	-----------	---	-----------

VES:		LUG5			
Position:	S: -15.27625	E: 030.27538			
	2	10	GC	SD	Ohmm
10	8		8	0.2	
12	7		4	0.1	
15	7		3	0.4	
20	8			0.1	
20		8	2	0.1	
30		9	3	0.2	
40		15	5	1.3	
50		16	4	0.2	
60		23	6	3.3	
80		5	1	38.1	
100		12	2	5	
120		-	-	-	
150		12	4	0.1	

VES:		LUG6			
Position:	S: -15.26740	E: 030.25905			
	2	10	GC	SD	Ohmm
10	43		9	0.1	
12	43		11	0.2	
15	50		11	0.5	
20	68			0.9	
20		56	13	0.9	
30		73	10	0.7	
40		26	9	0.2	
50		83	8	0.3	
60		193	14	0.6	
80		753	0.1	0.7	
100		-	-	-	
120		1119	15	0.8	
150		1624	15	0.6	



Interpretation VES:

From	To	Ohmm	Interpretation
0	1		
1			

Interpretation VES:

From	To	Ohmm	Interpretation
0	1		
1			

Gradient Array

50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

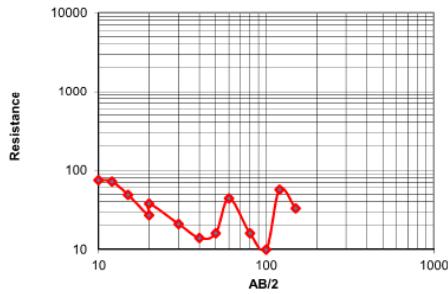
Comment and Access

VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

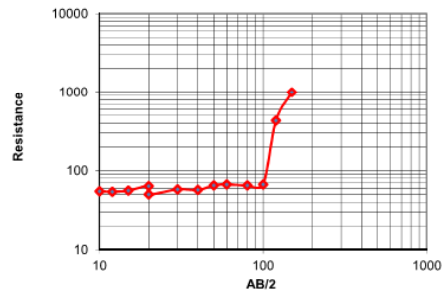
Location and Geology VES: LUG7 Chilukusha Community School	18-Oct-17	Location and Geology VES: LUG8 Shonkhomoka Village	18-Oct-17
--	-----------	--	-----------

VES:		LUG7		VES:		LUG8					
Position:	S: -15.28119	E: 030.27646			Position:	S: -15.29147	E: 030.29691				
	2	10	GC	SD	Ohmm		2	10	GC	SD	Ohmm
10	75		3	0.9		10	55		0.5	0	
12	72		0.2	0.2		12	54		0.1	0	
15	49		1	0.5		15	56		0.1	0.2	
20	27		5	5.2		20	64		0.1	0.3	
20		38		5.2		20		50		0.3	
30		21	5	1		30		58	0.1	0.1	
40		14	2	1.9		40		57	0.3	0.2	
50		16	2	1.7		50		65	0.1	0.3	
60		44	8	3.2		60		67	0.1	0	
80		16	1	3.9		80		65	0.1	0.8	
100		10	5	0		100		67	5	0.1	
120		57	0.1	0		120		433	3	4	
150		33	0.6	17.5		150		992	10	113	

VES LUG 7



VES LUG 8



Interpretation VES:				Interpretation VES:			
From	To	Ohmm	Interpretation	From	To	Ohmm	Interpretation
0	1			0	1		
1				1			

Gradient Array										
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

Comment and Access

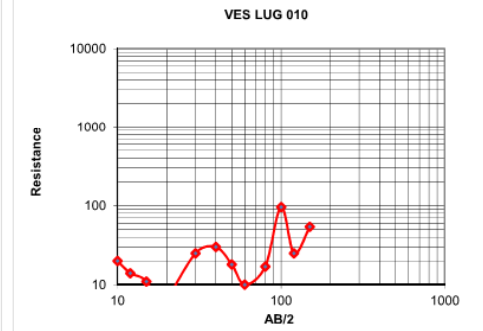
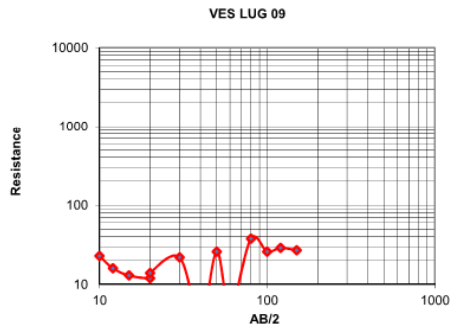
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VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

Location and Geology VES: LUG09 M'lalanjala Village	18-Oct-17	Location and Geology VES: LUG010 Kaluluzi RHS(Kaneme RHC)	18-Oct-17
---	-----------	---	-----------

VES:		LUG09			
Position:	S: -15.33734	E: 030.35424			
	2	10	GC	SD	Ohmm
10	23		6	0.3	
12	16		0.1	0.4	
15	13		0.1	0.4	
20	12		0.1	6.8	
20		14		6.8	
30		22	0.1	0.3	
40		3.6	0.1	27.1	
50		26	1	2.4	
60		5	9	75	
80		38	0.5	4.6	
100		26	2	0	
120		29	5	11	
150		27	0.1	33	

VES:		LUG010			
Position:	S: -15.35152	E: 030.36262			
	2	10	GC	SD	Ohmm
10	20		1	0	
12	14		3	0.2	
15	11		1	0.1	
20	4		7	0.2	
20		6		0.2	
30		25	0.5	0.3	
40		30	0.2	0.5	
50		18	0.1	4	
60		10	2	0	
80		17	1	0	
100		96	0.1	1.8	
120		25	3	0	
150		54	1	0	



Interpretation VES:

From	To	Ohmm	Interpretation
0	1		
1			

Interpretation VES:

From	To	Ohmm	Interpretation
0	1		
1			

Gradient Array

50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

Comment and Access
 LUG010 The Fe was 16.6
 LUG009 the Ec was 4000ppm

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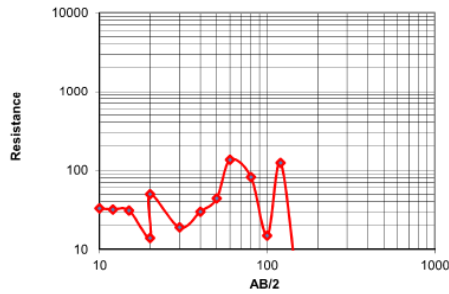
VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

Location and Geology VES: LUG011 Kavalamanja Primary School	19-Oct-17	Location and Geology VES: LUG012 Mpingo with Solar BH	19-Oct-17
---	-----------	---	-----------

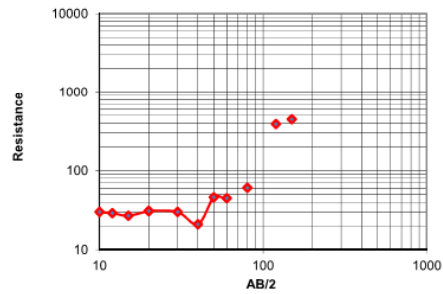
VES:		LUG011			
Position:		S: -15.61653	E: 030.26288		
	2	10	GC	SD	Ohmm
10	33		4	1.8	
12	32		8	0.8	
15	31		10	0.5	
20	14			2.7	
20		50		2.7	
30		19	4	1.7	
40		30	10	3.2	
50		44	0.2	6.5	
60		135	8	2.1	
80		82	11	2.5	
100		15	2	0	
120		124	4	7.9	
150		4	0.4	-	

VES:		LUG012			
Position:		S: -15.35425	E: 030.36315		
	2	10	GC	SD	Ohmm
10	30		0.2	0	
12	29		0.1	0.1	
15	27		0.2	1.1	
20	31			4	0.4
20		31		0.4	
30		30	0.2	1.4	
40		21	0.2	0	
50		46	0.2	1.3	
60		45	0.2	1.6	
80		61	0.2	4.1	
100		0	6	27	
120		390	0.2	0.9	
150		448	0.8	1.4	

VES LUG 09



VES LUG 010



Interpretation VES:			
From	To	Ohmm	Interpretation
0	1		
1			

Interpretation VES:			
From	To	Ohmm	Interpretation
0	1		
1			

Gradient Array										
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

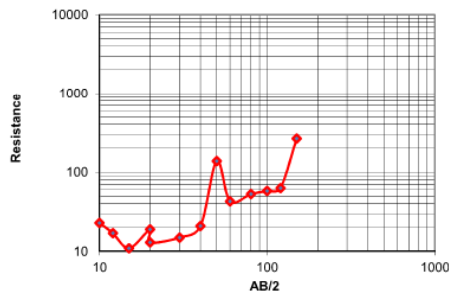
Comment and Access
Both equipped with Solar pump

VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

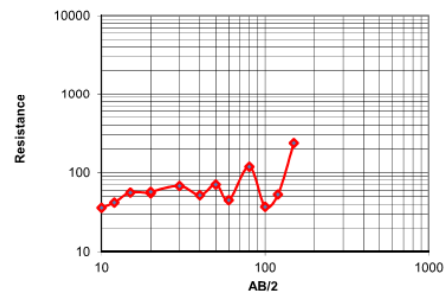
Location and Geology VES: LUG013 Kaposhe Primary and Secondary School	19-Oct-17	Location and Geology VES: LUG014 Mwatingora	19-Oct-17
---	-----------	---	-----------

VES: LUG013		VES: LUG014									
Position:	S: -15.41514 E: 030.37240	Position:	S: -15.43315 E: 030.37008								
	2	10	GC	SD	Ohmm		2	10	GC	SD	Ohmm
10	23		0.2	0		10	36		0.2	0.1	
12	17		0.2	0.7		12	42		0.2	0.1	
15	11		0.2	1.6		15	56		0.2	0.6	
20	19		0.5	5.1		20	55		0.2	1.8	
20		13		5.1		20		57		1.8	
30		15	3	5		30		68	5	1.2	
40		21	0.2	0.6		40		52	0.7	0.1	
50		138	12	1		50		71	0.2	2.2	
60		43	2	0		60		45	1.3	6.2	
80		53	0.2	2		80		119	3.2	1	
100		58	0.2	1.1		100		37	0.2	2.2	
120		63	0.1	0		120		53	0.2	1.8	
150		266	1	1.3		150		237	0.6	10	

VES LUG 013



VES LUG 014



Interpretation VES:				Interpretation VES:			
From	To	Ohmm	Interpretation	From	To	Ohmm	Interpretation
0	1			0	1		
1				1			

Gradient Array										
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

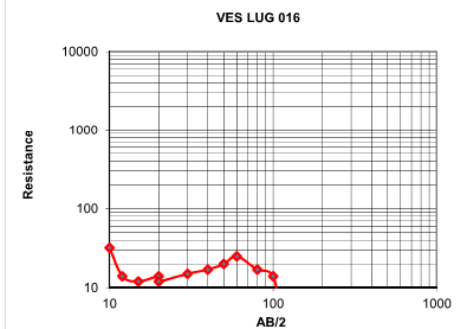
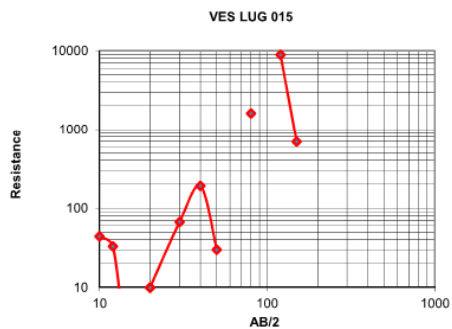
LUG014 is a good BH @ 300m from a saline BH

VERTICAL ELECTRICAL SOUNDING AND GRADIENT ARRAY SURVEY FORM

Location and Geology VES: LUG015 Chitambili	20-Oct-17	Location and Geology VES: LUG016 Soweto	20-Oct-17
---	-----------	---	-----------

VES:		LUG015			
Position:	S: -15.45147	E: 030.37059			
	2	10	GC	SD	Ohmm
10	44		14	0.2	
12	33		5	0.9	
15	2		7	0	
20	10				
20		10	0.1	0	
30		67	10	0	
40		191	6	0	
50		30	8	0	
60		-	-	-	
80		1613	25	3.1	
100		-	-	-	
120		8899	20	0.7	
150		693	0.1	0	

VES:		LUG016			
Position:	S: -15.61324	E: 030.38922			
	2	10	GC	SD	Ohmm
10	32		1.3	0.1	
12	14		0.1	0	
15	12		0.2	0.4	
20	14				
20		12	0.2	1.3	
30		15	4	0	
40		17	4	0	
50		20	6	0.4	
60		25	2	0	
80		17	2	0	
100		14	5	0	
120		3	6	0	
150		4	6	0	



Interpretation VES:			
From	To	Ohmm	Interpretation
0	1		
1			

Interpretation VES:			
From	To	Ohmm	Interpretation
0	1		
1			

Gradient Array										
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:
50/40	45/35	40/30		35/25	30/20	25/15	20/10	15/5	10/0	S:
										E:

Appendix 6 : VESLUG001 to LUG016 results

VES LUG001 results

Figure 19 below shows that low resistivity is observed around 12 mbgl and between 47 mbgl to 105 mbgl while the lowest resistivity is between 60 mbgl to 80 mbgl. For more details, see Figure 19.

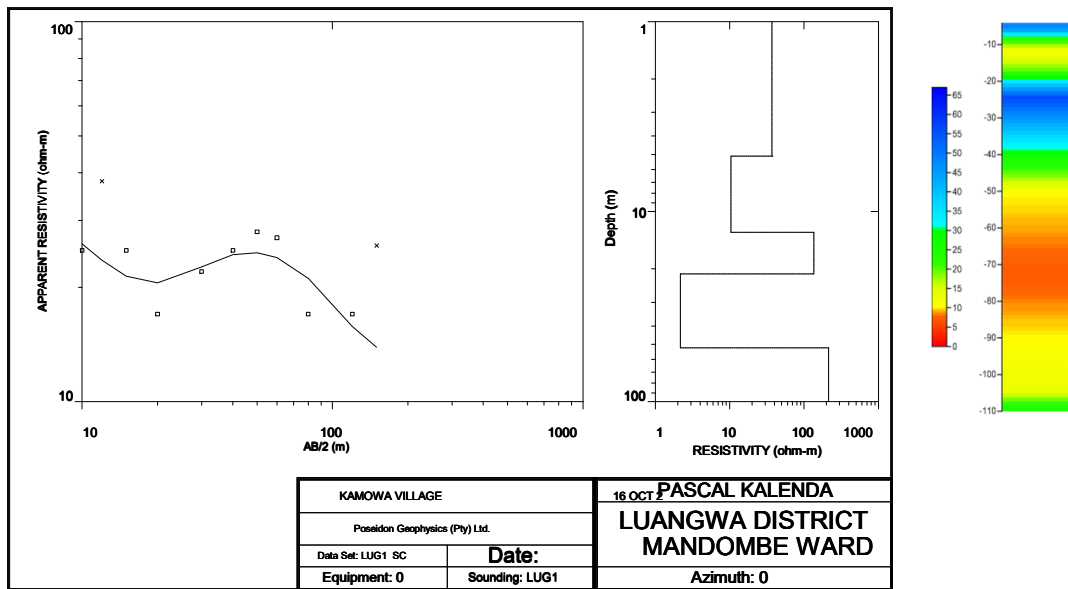


Figure 19 : VES LUG001 results

VES LUG002 results

Figure 20 below shows that lowest resistivity is observed from 0 to 35 mbgl. For more details, see Figure 20.

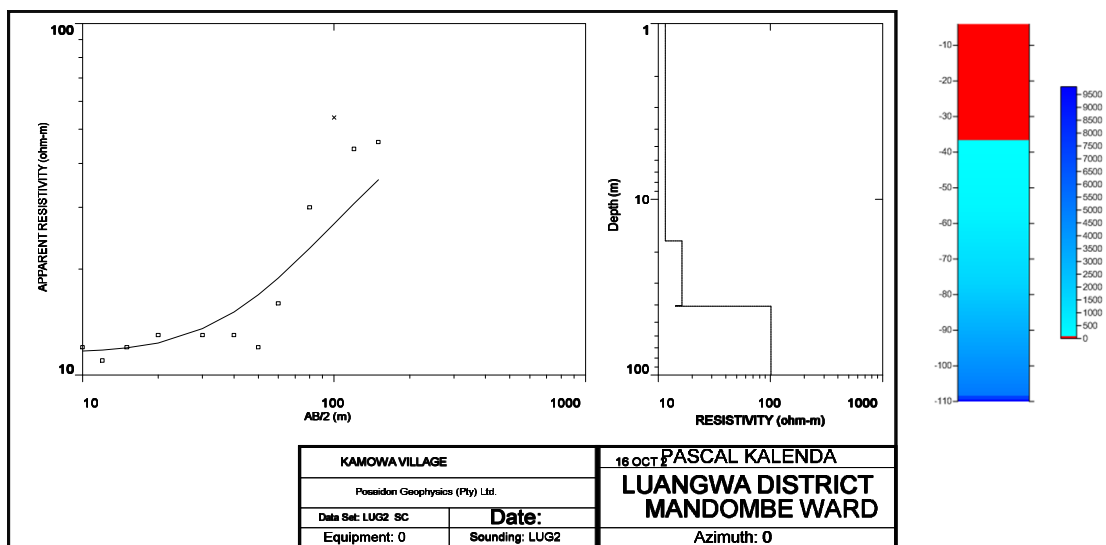


Figure 20 : VES LUG002 results

VES LUG003 results

Figure 21 below shows that low resistivity around 18 mbgl and around 40mbgl with the lowest resistivity is observed from 21 mbgl to 37 mbgl. For more details, see Figure 21.

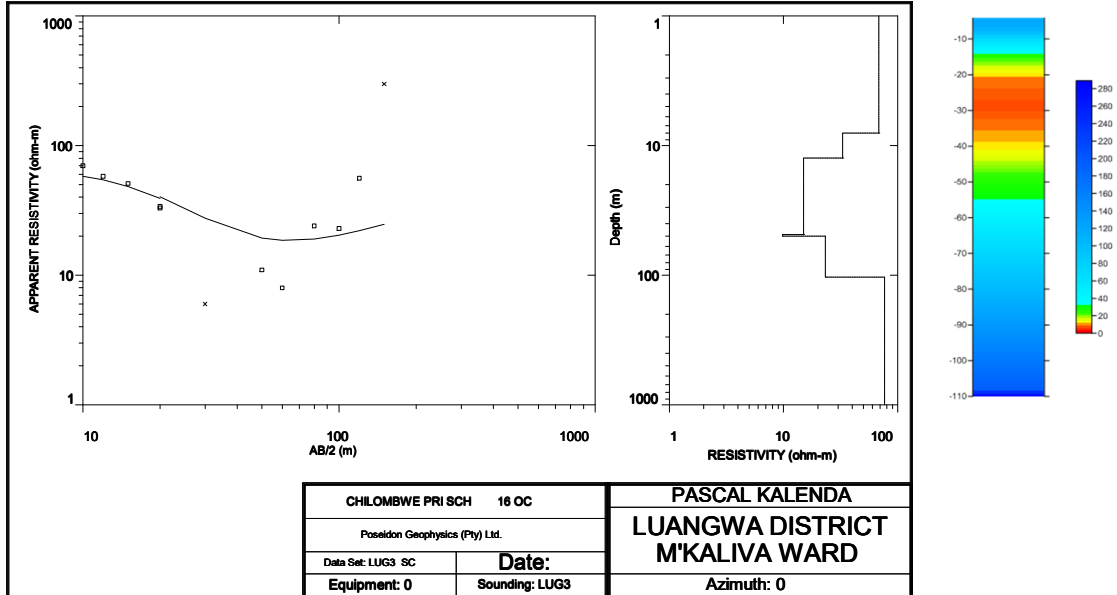


Figure 21 : VES LUG004 results

VES LUG004 results

Figure 22 below shows that low resistivity around 18 mbgl and between 29 mbgl to about, 37 mbgl with the lowest resistivity is observed from 19 mbgl to 28 mbgl. For more details, see Figure 22.

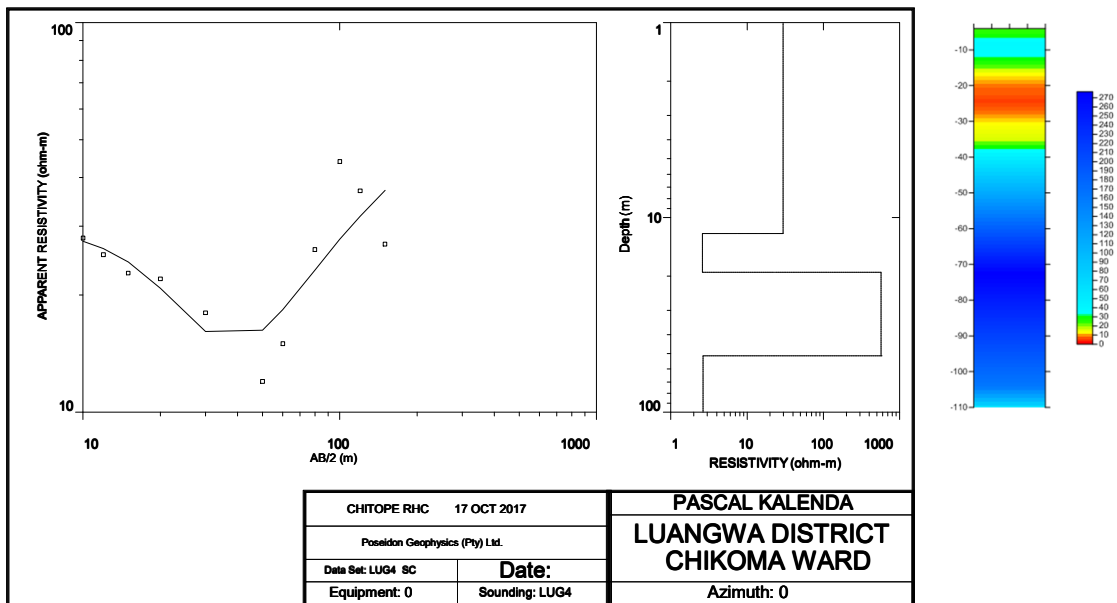


Figure 22 : VES LUG004 results

VES LUG005 results

Figure 23 below shows that lowest resistivity between 7 mbgl to 15 mbgl with the lower resistivity is observed from 50 mbgl to 59 mbgl and the lowest 59 mbgl to 110 mbgl. For more details, see Figure 23.

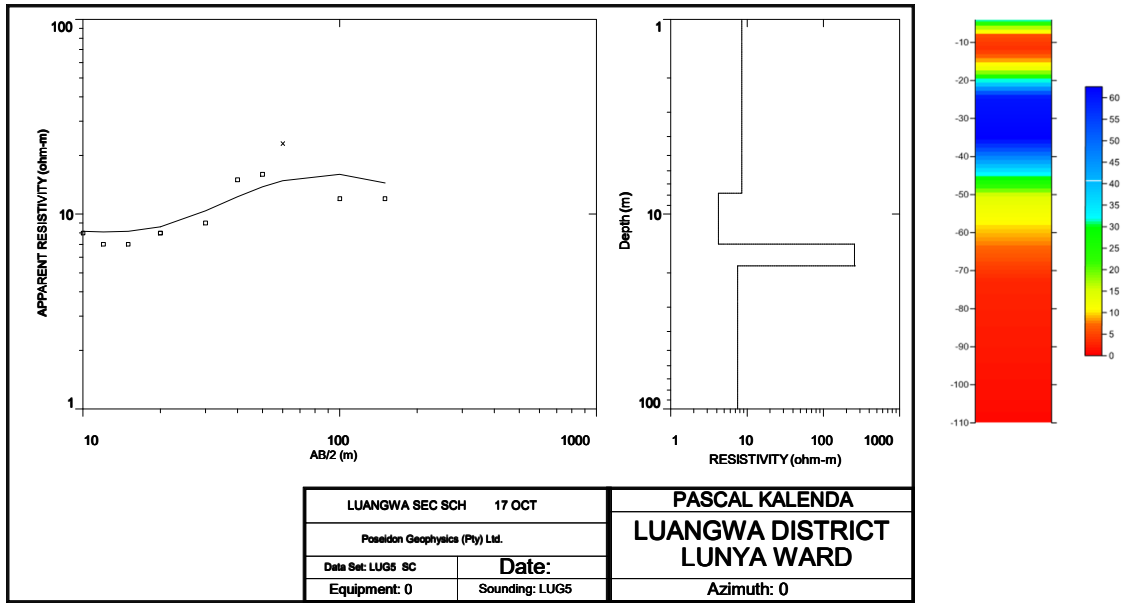


Figure 23 : VES LUG005 results

VES LUG006 results

Figure 24 below shows that lowest resistivity is observed from 0 to 20 mbgl. For more details see Figure 24.

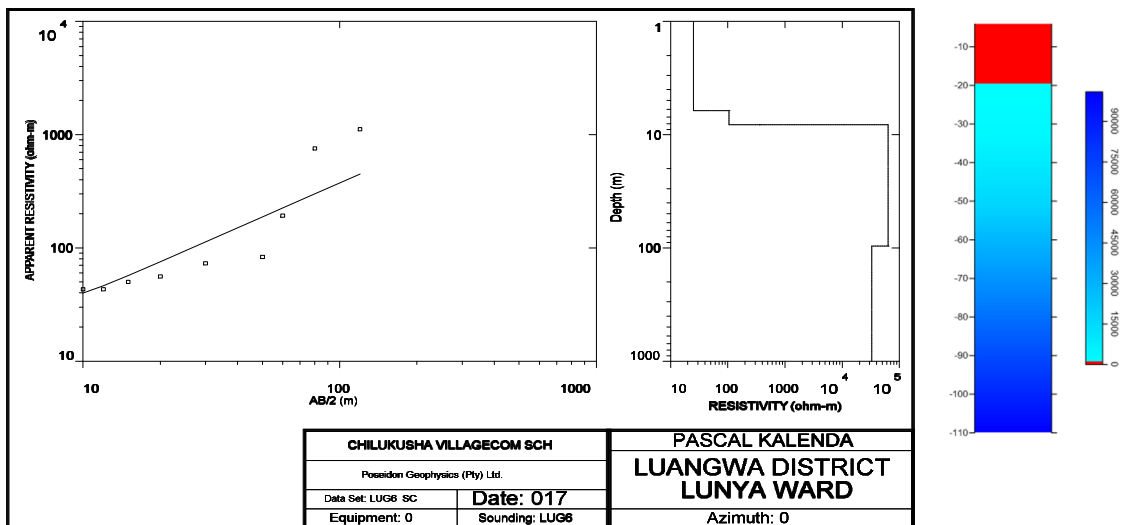


Figure 24 : VES LUG006 results

VES LUG007 results

Figure 25 below shows that low resistivity between 17 mbgl and around 33 mbgl with the lowest resistivity is observed at 28 mbgl. For more details see Figure 25.

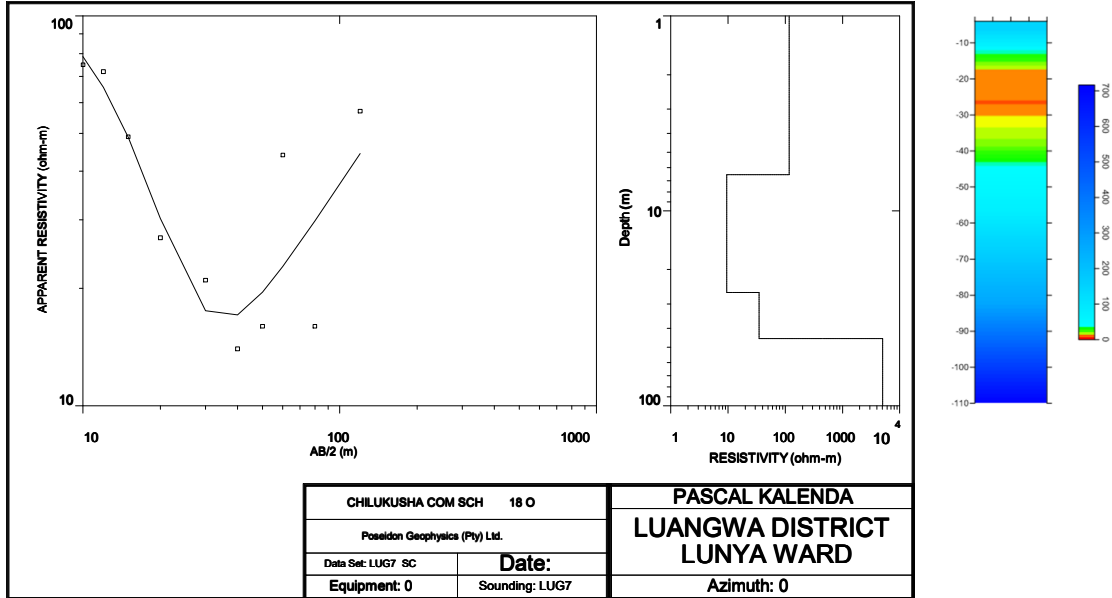


Figure 25 : VES LUG007 results

VES LUG008 results

Figure 26 below shows that there no low resistivity. For more details see Figure 26.

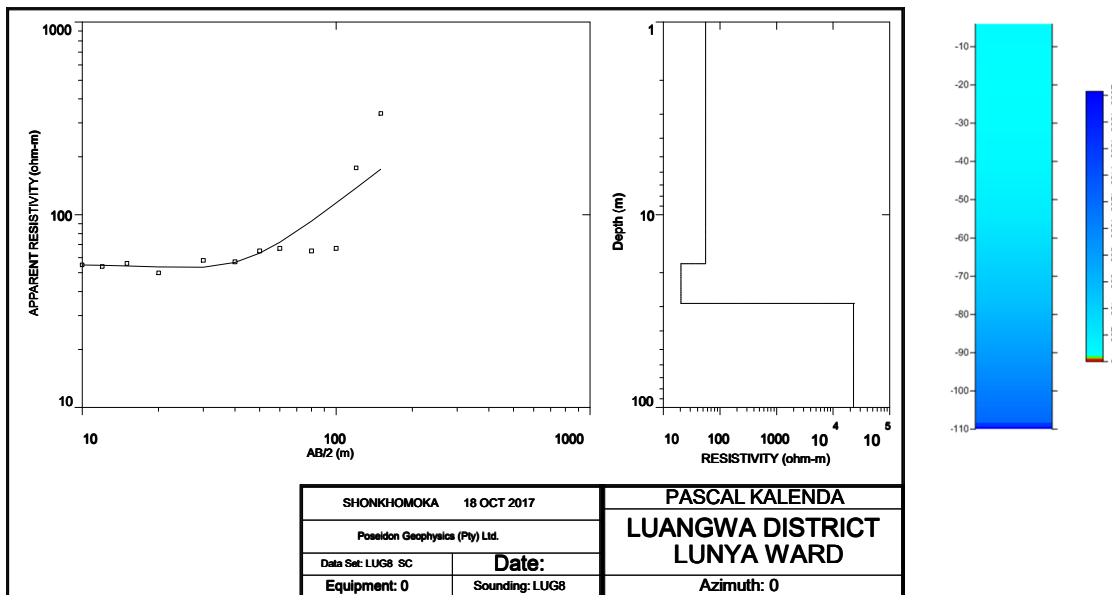


Figure 26 : VES LUG008 results

VES LUG009 results

Figure 27 below shows that low resistivity from 12 mbgl to 40 mbgl with the lowest resistivity is observed from 15–35 mbgl. For more details see Figure 27.

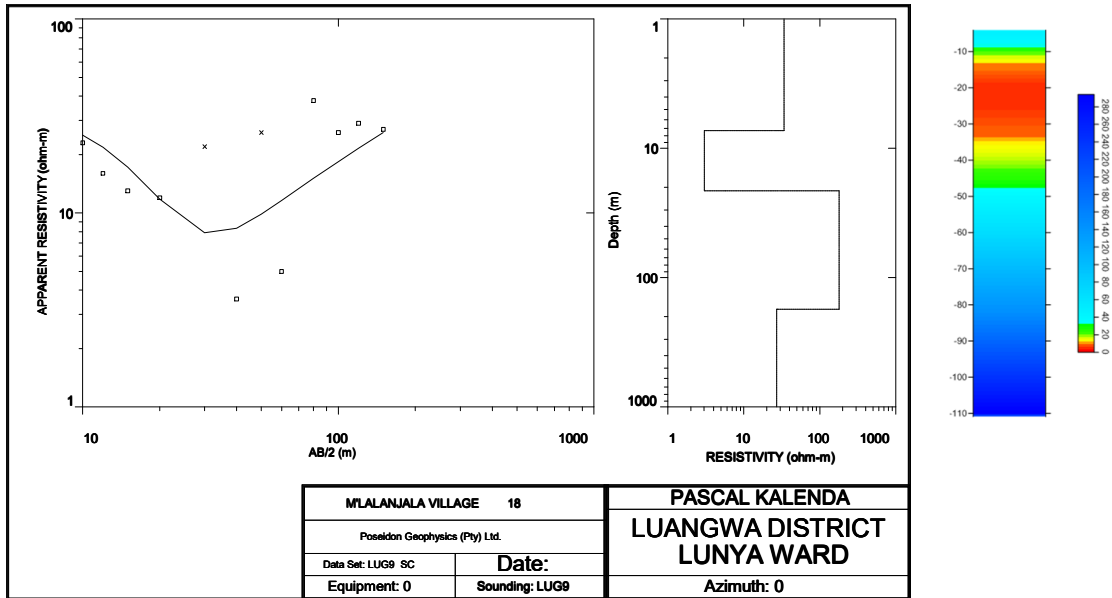


Figure 27 : VES LUG009 results

VES LUG010 results

Figure 28 below shows that lowest resistivity is observed from 8 mbgl to 12 mbgl and from 28 mbgl to 56 mbgl. For more details see Figure 28.

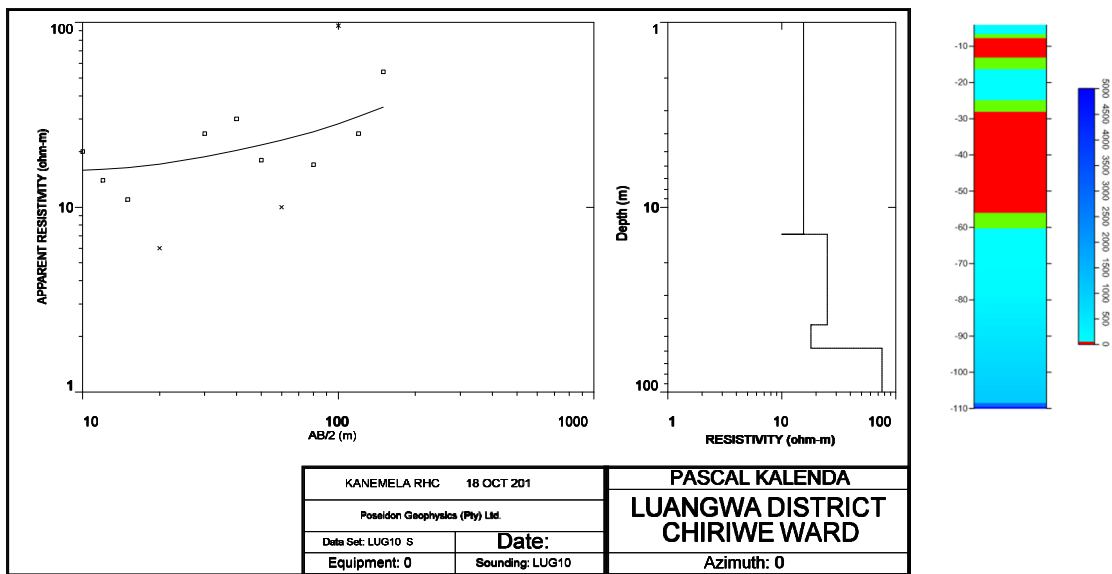


Figure 28 : VES LUG010 results

VES LUG011 results

Figure 29 below shows that low slight resistivity around 12 mbgl. For more details see Figure 29.

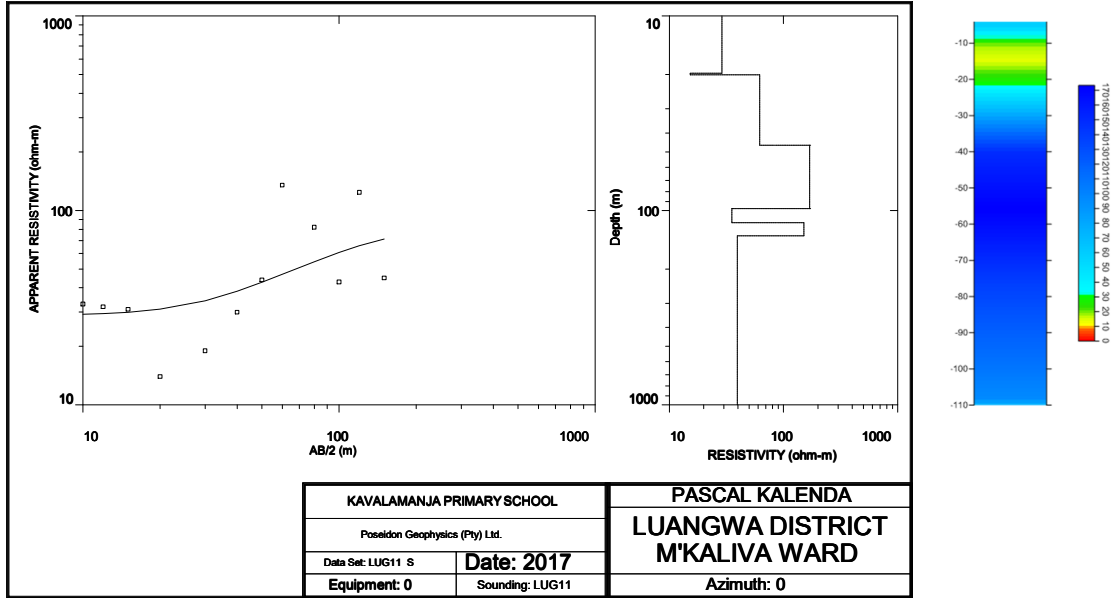


Figure 29 : VES LUG011 results

VES LUG012 results

Figure 30 below shows that the lowest resistivity is observed from 0–27 mbgl. For more details see Figure 30.

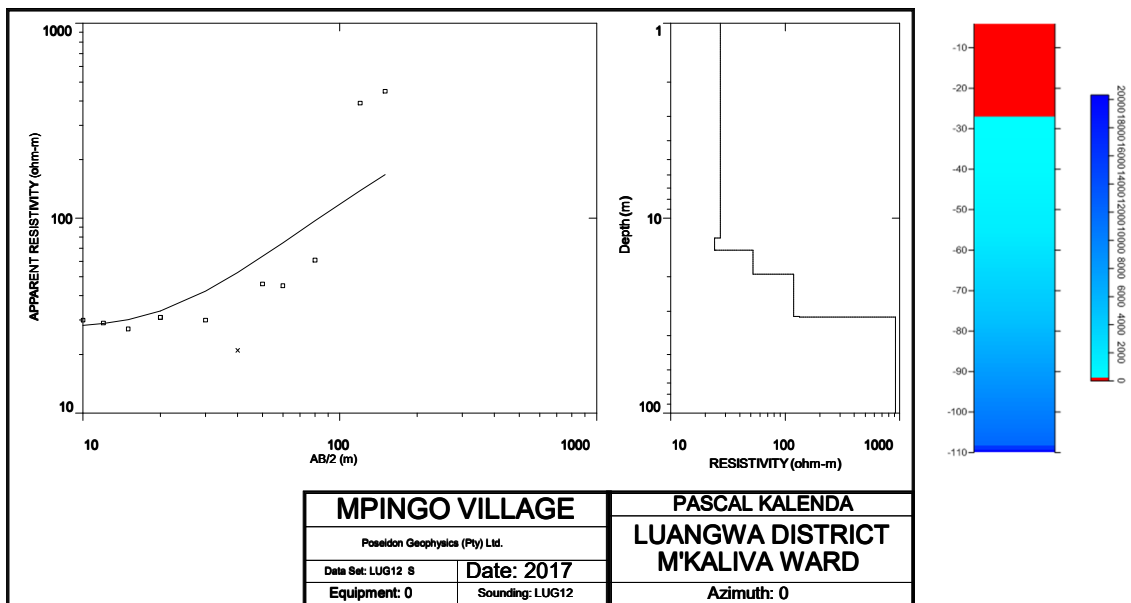


Figure 30 : VES LUG012 results

VES LUG013 results

Figure 31 below shows that low resistivity from 7 mbgl to 20 mbgl with the lowest resistivity is observed from 10 mbgl to 16 mbgl. For more details see Figure 31.

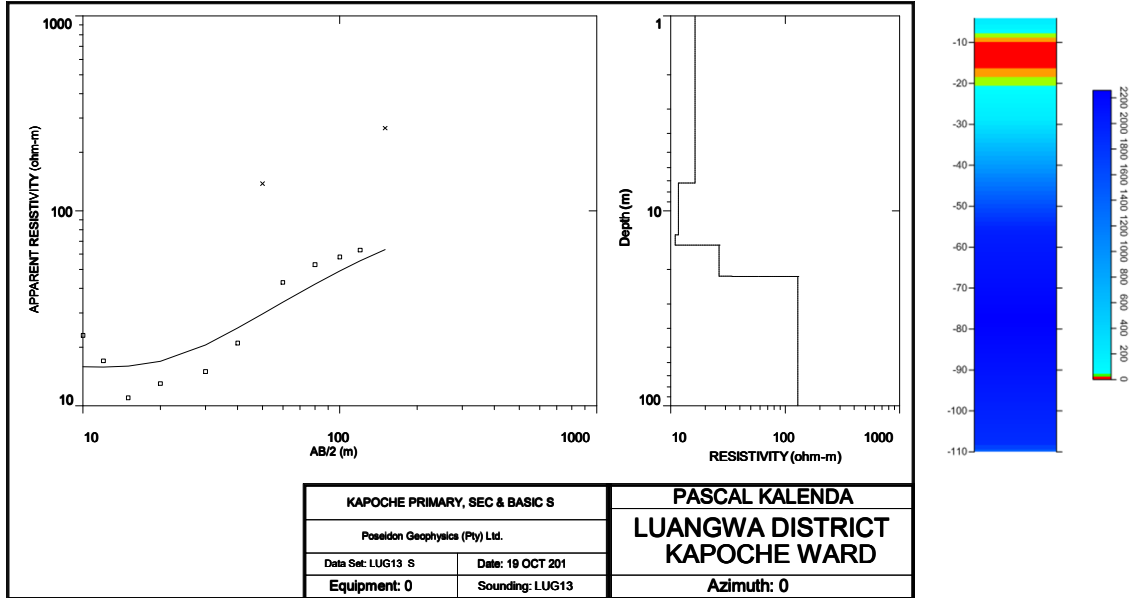


Figure 31 : VES LUG013 results

VES LUG015 results

Figure 32 below shows that low resistivity from 0–13 mbgl with the lowest resistivity is observed from 0–10 mbgl. For more details see Figure 32.

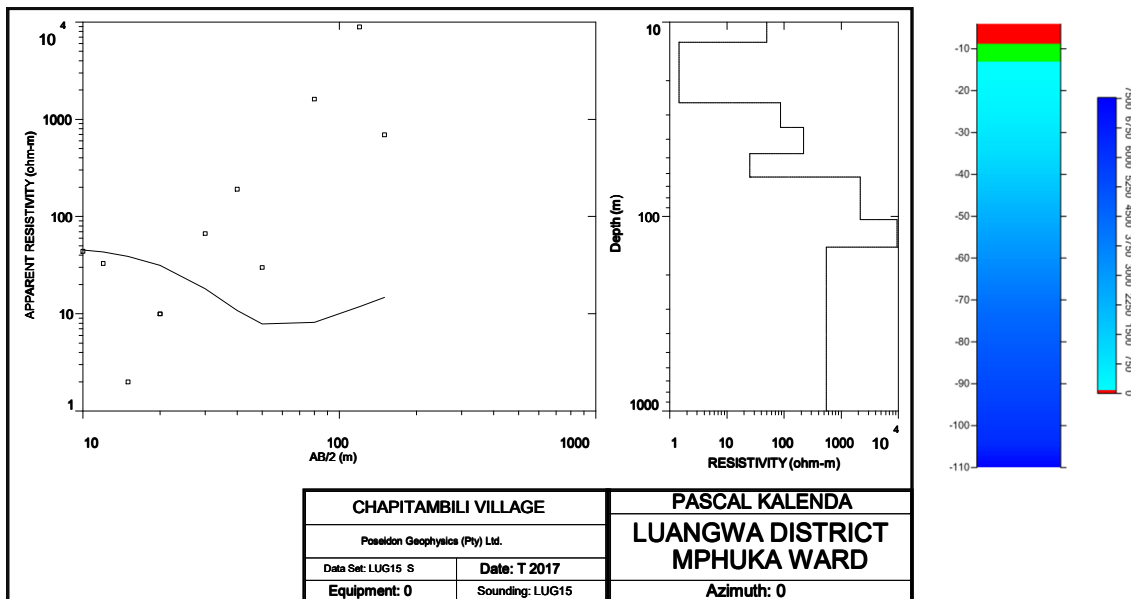


Figure 32 : VES LUG015 results