

FOURAH BAY COLLEGE



UNIVERSITY OF SIERRA LEONE

Comparing the Groundwater Potentials of the Freetown Igneous Complex and the Granite-Greenstone Terrain in Sierra Leone Using Geophysical Survey Data and Borehole Logs

By

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A dissertation submitted to the Department of Geology, Faculty of Pure and Applied Sciences, Fourah Bay College, University of Sierra Leone, in partial fulfillment of the requirement for the award of Bachelor of Science degree with Honors in Geology.

October, 2019.

Declaration

I, James Bangura declare that this dissertation for Bachelor of Science degree with honors in Geology at Fourah Bay College, University of Sierra Leone is my work in design and execution. The dissertation has not been submitted previously by anyone, for a degree at this university or any other university. All effort has been taken to acknowledge the material which was referenced.

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Date

Abstract

The purpose of this study was to determine the groundwater potential of the Freetown Complex and the Granite Greenstone Terrain in Sierra Leone. The geology of the Granite Greenstone Terrain constitutes medium- to coarse-grained granite which is typical of the older Achaean formation. Grey and pink granites are exposed in most parts of the area. These rocks have less porosity. The Freetown Complex on the other hand is younger (Jurassic to Triassic) and therefore has limited fractures and thin weathered layers (Overburden) with varying thicknesses.

Though several parameters are used to identify the groundwater prospects of an area, this research was narrowed to evaluate the groundwater potential through Geophysical survey (Electrical resistivity). Vertical electrical sounding (VES) were carried out in the locations mentioned above to understand the geology and also to verify the extent of weathering, fractures and other features like joints, dykes etc. and the geological and hydrogeological parameters were analysed. Four locations were dealt with; Saint Ambrose School and Lebanese School for the Freetown Complex and Makalie town and Makeni Government Hospital for the Granite Greenstone Terrain. The field data obtained have been analyzed using computer software (Zondip) which gives an automatic interpretation of the apparent resistivity. The VES results revealed heterogeneous nature of the subsurface geological sequence. Geological and Topographic maps were prepared using coordinates during the data collection. Influencing factors of groundwater potential of the area were considered in detail.

Borehole logs were used to clearly explain the vertical variation in formation properties; (i.e. the extent of weathered layers, fractures in bed rock and unaltered crystalline basement rocks). Borehole diagrams were also utilized which clearly account for the variation in thicknesses of weathered zones between the Granite Greenstone Terrain and the Basic Complex. Pumping tests data were also attached to some of the existing data collected to determine the yield of wells to validate the groundwater potential zones and compare the sustainability rate of those boreholes.

Keywords

Groundwater, Geology, Granite Greenstone Terrain, Basic Complex

Dedication

“If someone has done it before at any point in history, then what’s possible for one is possible for all” - Eric Thomas.

This work is dedicated to all those who have a glowing desire to be educated in challenging circumstances and to all those who thrive to make the burdens of these people theirs.

Acknowledgement

My deepest appreciation goes to the Lord Jesus Christ. He has upheld me with His righteous right hand throughout this dissertation.

My heartfelt gratitude goes to Mr. Morlai Kanu for overseeing this project and providing all helpful support; including the provision of Syscal Junior Resistivity machine and vehicle for to see the acme of this project.

Additionally, an inexpressible thanks goes to the entire staff of Geology Department; a special recognition to my Head of Department Dr. Mustapha O. Thomas, I am very grateful to Dr. K.E.F. Anderson, Dr. Kekuda Sesay, Mr. Yusuf A. Lahai, Mr. Bunting K. Williams, Mr. Tamba Komba and Mr. Henry Deen whose effort were indispensable in my tertiary academic pilgrimage.

My profound thanks to the Laboratory Technicians; Mr. Johnny Kamara, his service was a great building block in visualizing theoretical knowledge and Mr. Mendy Bangura, who, although no longer with us, continues to inspire by his dedication to the students he served over the course of his career.

Furthermore, I am also indebted to credit the National Mineral Agency (NMA) for providing necessary resources that aided the completion of this research.

Also, I am grateful to the Disciple Making Team for Christ (DMTC) for the godly counsel, making my burdens theirs and broadening my vision to grasp my huge inner potential.

Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of studying and through the process of researching and writing this dissertation. This accomplishment would not have been possible without them.

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CHAPTER 1: INTRODUCTION

1.1 Background

The project started in May and ended in October 2019 with the aim of determining the groundwater potential of the Freetown Complex and the Granite Greenstone Terrain in Sierra Leone.

In a lot of arid, semi-arid and rural regions, groundwater is a major contributor to total water supply (Van Camp, Walraevens, & Radfsr, 2015). Groundwater supply in urban areas; like Freetown, is an indispensable source that complements the increased demand in major water sources. It is very essential to maximize this resource due to the increasing pressure from pollution and growing demand on surface water supplies in both the Freetown Complex and Granite Greenstone Terrain localities.

Majority of the population in the project areas depend on groundwater for domestic and other use. Nevertheless, these masses remain vulnerable as a result of inadequate availability and poor quality of groundwater. The growing population and urbanization, coupled with economic development is resulting in higher water uses.

As opposed to surface water reservoirs, groundwater reservoirs are not usually directly recharged, are limited and can be exhausted. Thus, groundwater is the fundamental contributor of freshwater. Many cities have embarked on hydrogeological studies for multiple reasons. These include minimization of saline water intrusion, determination of flow of groundwater scheme, recharge quantity and quality and declination of the water table. This has improved the knowledge and understanding of the aquifer systems, which has resulted to optimised abstractions, abatement, informed groundwater planning, development and allocation (Jasmin & Mallikarjuna, 2011). For this reason, many cities have adequate water supply and if the same approach could be used for areas within the Freetown Complex and Granite Greenstone Terrain, water shortages would be reduced significantly. Failure of boreholes will also be minimised as groundwater potential zones will be highlighted. Informed decisions have always proved to minimise loss of time, money and effort.

1.2 Significance of Study

For effective and strategic plan in the future with regards groundwater allocation for domestic use and or economic development, understanding of groundwater potential is indispensable.

A better understanding of the way an aquifer functions and the ability to assess its capacity and recharge patterns is essential because it results in the optimum and sustainable use of groundwater (Morris, et al., 2003). Sustainable use of groundwater is when the present day use of groundwater does not deprive future generations from enjoying the same benefits of the resource (Jha & Chowdary, 2007).

Groundwater storage in aquifers is replenished from recharge. Therefore, knowledge of groundwater potential is very vital. Knowledge of groundwater potential and aquifer characteristics such as recharge schemes and rates can help to note the occurrence of underdevelopment or overexploitation. This would promote model that can forecast recharge using past trends, thus a key tool that provides valuable information to water managers. Such information is important for regulation of abstractions, safe yield and recharge rates.

1.3 Methodology

In geological mapping, methodology can be categorized into three;

- Pre-field activities
- Field activities
- Post-field activities

1.3.1 Pre-Field Activities

These are the activities undertaken prior to the commencement of field work. This involves desk study of the project area and the utilization of relevant materials. It covers the preparation of field tools and equipments to ensure efficiency of the entire research.

1.3.2 Field Activities

Electrical resistivity investigation was carried out around the Freetown Complex and Granite Greenstone Terrain in order to study the groundwater potential of these areas. Vertical Electrical Sounding (VES) using Schlumberger array was carried out as well as Resistivity Profiling. Data were collected from different localities within the study area and the GPS coordinates for each of these localities were recorded as well.

Borehole data were also collected as the process of borehole drilling was undertaken. Samples were described and data were logged appropriately.

Below are the equipments used during the course of field work;

- Syscal Junior Irish switch (Meter)
- Electrodes
- Cables
- Crocodile clips
- Topographic map
- Global Positioning System (GPS)
- Compass/ Clinometer
- Measuring tape
- Geologic hammer
- Hand lens
- Safety goggle
- Hard hat
- Reflector

- Safety boots
- Pencil and pen
- Field note book
- Ruler
- Camera

1.3.3 Post Field Activities

The work doesn't end in the field. Post activities include preparation of geological map, analysis of data obtained in the field using computer software and writing of report.

1.4 Objectives of the Study

The main objective of this project is to determine the groundwater potential of the Freetown Complex and the Granite Greenstone Terrain using geophysics and borehole data.

1.5 Characteristics of the Project Area

1.5.1 Geology

1.5.1.1 The Freetown Complex

Latitude and longitude (WGS84); 8° 29' 4" 13° 14' 4"

The Freetown Complex is a major intrusion characterized by prominent layering of repeated sequences of troctolitic, gabbroic and anorthositic rocks. Differential resistance of these rocks to weathering and erosion has given rise to parallel ranges of mountains from which the country Sierra Leone has its name. The intrusion is part of a funnel shaped body in which the 'funnel's' center lies in the Atlantic, westward of the Peninsula (Briden, Henthorn, & Rex, 1977).

Layered structures are concordant with the floor of the intrusion. The layered series can be divided into four major zones in each of which there is a generalized upward sequence of olivine-rich to plagioclase-rich rocks, and within which prominent rhythmic layering on the scale of thickness of several hundred feet can be recognized. Despite the great thickness (20,000 feet) of the layered series, and the strong differentiation in terms of mineral proportions, there is no progressive variation in the composition of minerals. In this respect the Freetown Complex appears to be unique among the layered intrusions of comparable size that have been closely studied (C.L, 2001). The complex provides an abundance of critical data on monomineralic rocks, olivine and anorthosite, and also on magnetite-ilmenite seams. Pyroxene granulites are widely distributed and can be shown to have originated in two distinct ways; principally as cognate inclusions derived from the coarse-grained rocks of the Complex by metamorphic recrystallisation (often under conditions of shearing stress), but also as basic dykes intruded while the surrounding rocks were very hot (Wells, 1962) (Kudo & Weill, 1970).

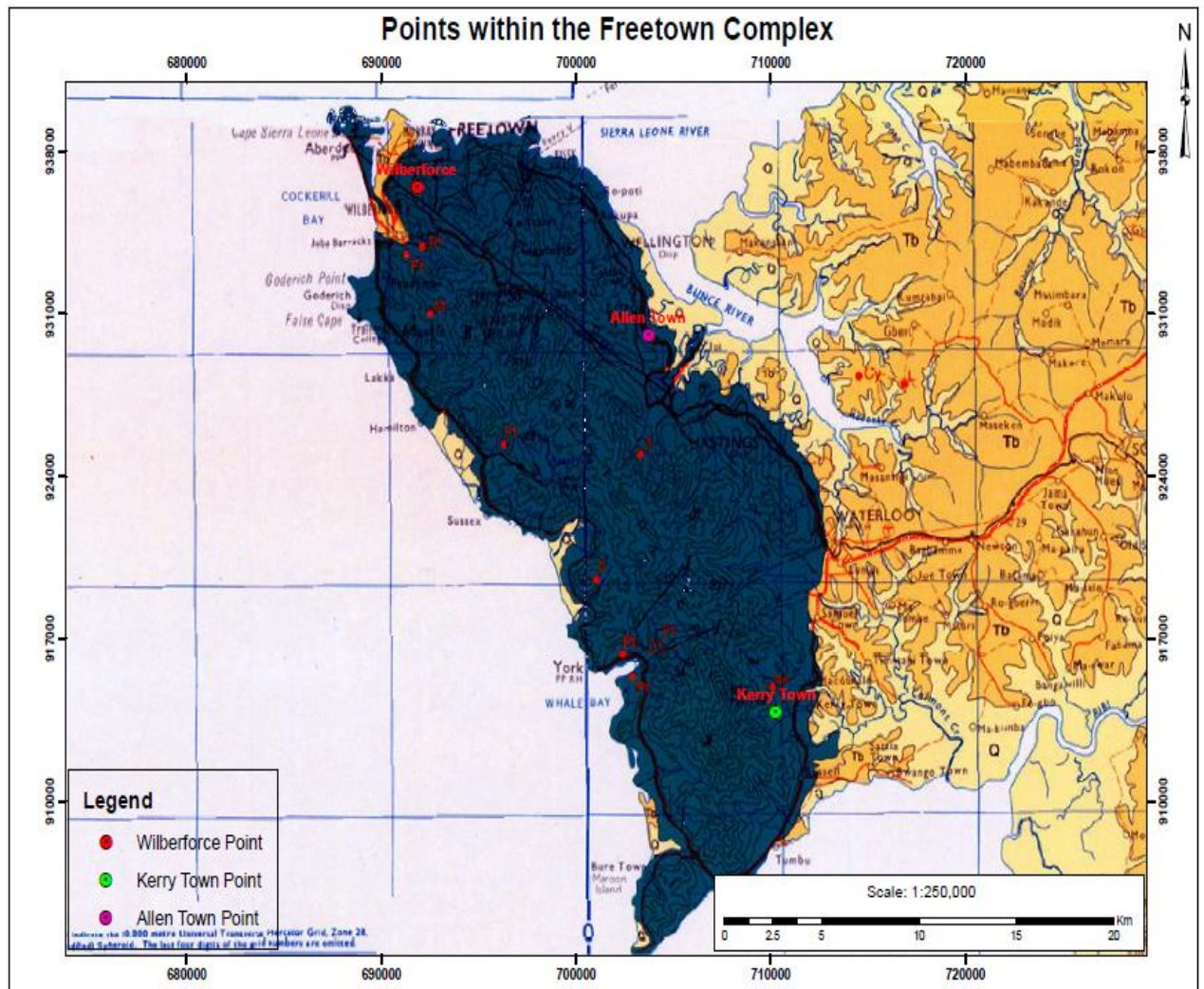


Figure 1.1: Geological map of the Freetown Complex

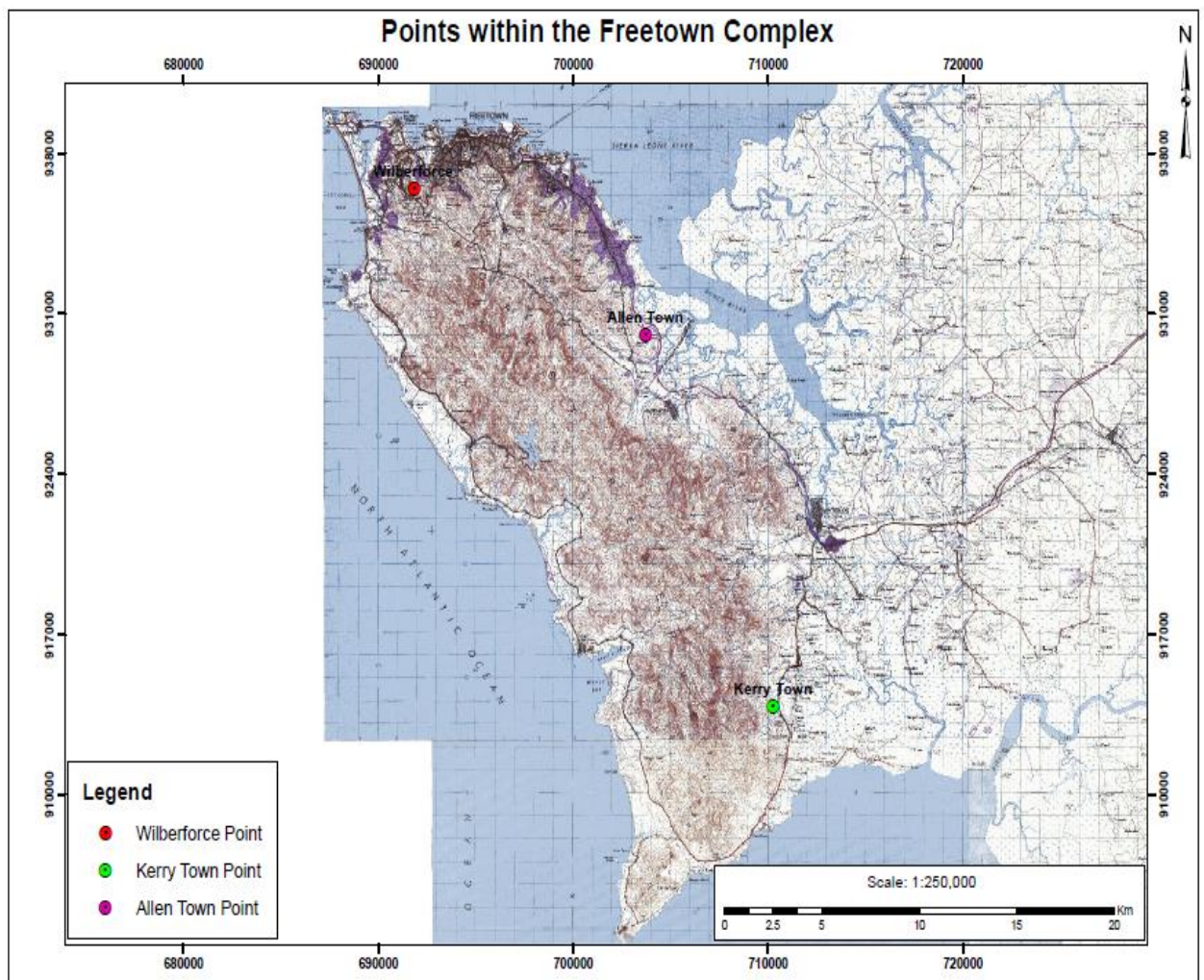


Figure 1.2: Topographic map of the Freetown Complex

1.5.1.2 The Granite Greenstone Terrain

The granite greenstone terrain is one of the two pene-contemporaneous tectonothermal units of the Archaean of Sierra Leone, it is also known as the Liberian granite-greenstone terrain; the other division of the Archaean is the Kasila Group Mobile Belt with its associated klippen, the Marampa Group. The granite-greenstone terrain consists of the Sula Group supracrustals, deformed and metamorphosed over an underlying gneissose granite migmatite Basement, yielding ages of about 2700 Ma. Late kinematic granites are found at the margins of the greenstone belts, and as high-level developments of the reactivated Basement (Williams, 1978).

Four belts of weakly metamorphosed volcano-sedimentary material, of about 2700 Ma, are enclosed by older granulites, gneisses and migmatites in the eastern part, and a basal ultramafic unit followed by mafic to feldspathic differentiate and then a terminal sedimentary formation has been recognized in all the four belts and their average ratio is ultramafic : mafic (greenstone) : sedimentary unit (2: 5 : 3) (Dickinson, 1971).

The belts are linear and tightly folded along N-S to NE-SW axis which is also the regional grain of the structures in the older basement complex that engulfs them. Structural and geochronological evidences suggest that the deformation of these volcano-sedimentary supracrustals began during the Liberian tectonism (c. 2700 Ma) and culminated at the beginning of the Eburnean (2200 Ma). Diapiric rise of K-rich younger Archaean granites which sharply transgressed all the earlier rocks and their structural trends, marked the last geotectonic event in the Archaean of this part of West Africa (Brooks, 1977).

Chromite cumulate and asbestiform deposits characterize the layered ultramafic unit, whilst gold and associated base metal sulphides which were derived from the volcanic units became hydrothermally concentrated close to the contact between the volcanic units and the overlying sediments, and also in the fault zones. Iron ore deposits are restricted to the sedimentary units where they occur as banded iron formation. It is only in the huge metasedimentary piles of the Sula-Kangari belt that deposits of iron ore occur in commercially viable quantities.

The patterns of distribution, deformation and mineralization in these greenstone belts appear to fit closely into island arc model of plate tectonic theory (Wilson & Marmo, 1958).

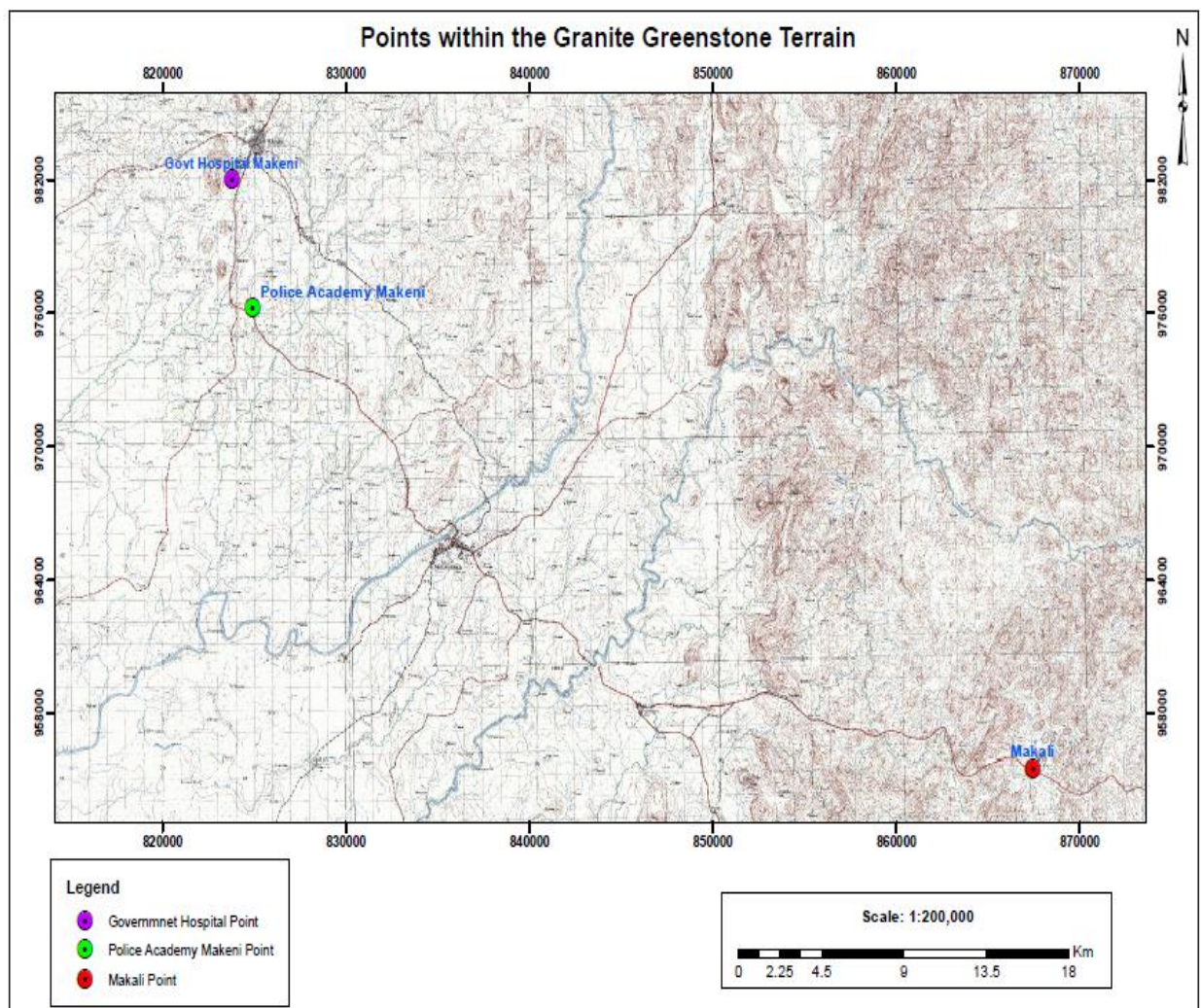


Figure 1.4: Topographic Map of the Granite Greenstone Terrain

1.5.2 Climate and Weather

In general, variation in climate is minimal across the country. Rainfall increases by a slight margin from the north to the south. Average air temperatures in Sierra Leone fluctuate from 27°C in March to 25°C in August (Climate Research Unit, 2017). Data shows that average temperatures have increased 0.2°C since 1901, possibly linked to global warming (Gregory, 1965).

Precipitation is greatest in the Freetown Peninsula, due to the influence of relief, at 5,200 mm/yr on the seaboard banks. In general, the highlands on the peninsula forms a hydrologic divide that separates the western and eastern banks into different rainfall patterns, although the difference is negligible compared to other parts of the country.

The northern region receives the least amount of rainfall, < 2,400 mm/yr (Gregory, 1965).

1.5.3 Physiography and Vegetation

Geographically, Sierra Leone can be characterized as a coastal, tropical landscape with a limited range of uniform landforms and climate characteristics. The principle physiographic feature of Sierra Leone is the western Freetown peninsula, which hosts the nation's capital city, with moderate elevations set against large areas of low coastal plains.

The characteristic vegetation type of the Granite Greenstone Terrain is Savannah woodland with a thick undergrowth of impenetrable elephant grass. Tree cover is more dense in the upland region where areas of primary rainforest are locally still preserved. Gallery forest lines the banks of the larger watercourses (Bontemps, et al., 2009).

1.5.4 Hydrology

Sierra Leone is considered to have an abundant supply of surface water.

All five perennial rivers (Little Scarcies, Rokel, Jong, Sewa and Moa) flow northeast to southwest, draining most of the country's land surface.

The Rokel Estuary and Western WRA channeled their exit through the Freetown Complex.

The topography of Northern Sierra Leone, where the Granite Greenstone Terrain lies, particularly in the east, is deeply incised by a rejuvenated drainage system. The Great Scarcies, Little Scarcies, Mongo, Mabo, Sei, and Bagbe rivers are the major watercourses that drain westward and southwards into the Atlantic Ocean. The eastern boundry of the area lies along the Niger River drainage divide, the headwaters of which lie in extreme south-east (Ministry of Energy and Water Resources, 2012).

1.6 Limitations

- There was great difficulty when operating the Syscal junior Resistivity machine in the rain.
- The establishment of settlements prevented easily access to outcrops.
- Natives restricted the field work. Some were scared of their land not being snatched; when the resistivity work was carried out, and when measuring tape were being used, the process was misconstrue to be a land survey. Others demanded huge cash to grant permit.

1.7 Precautions

Precautions are of prime importance and if neglected would lead to undesired outcome.

- The Syscal Junior machine should not be operated in the rain.
- Coordinate should be taken accurately for boreholes and Resistivity Survey points.
- Safety kit should always be intact.
- Data should be well noted on the field note book to prevent loss.

CHAPTER TWO

2.1 THE GEOLOGY OF SIERRALEONE

The Republic of Sierra Leone is a country on the southwest coast of West Africa between latitude 7 and 10 degrees N, and longitude 10.5 and 13 degrees W. It is bordered by Liberia to the east and southeast, Guinea to the north and northeast and the Atlantic Ocean to the west and south. Sierra Leone has a tropical climate, with environmental diversity which ranges from savanna to rainforest, and a total area of 71,740 km² (27,699 sq mi) (Alie, 1990).

2.1.1 Summary of the Geology of Sierra Leone

A generalized description of the geology of Sierra Leone is given below. According to Keyser & Mansaray, 2004 Sierra Leone occupies the central portion of an Archean craton that was disrupted by the opening of the Atlantic Ocean. The eastern cratonic fragment extends from the Western Sahara and Anti-Atlas Mountains eastward to the Hoggar and southward to Mauritania, Senegal, Guinea, Sierra Leone, Liberia, Ivory Coast, and Ghana. The western portion of the craton forms the Guyana Shield, which extends from northeastern South America. The geology divided into two major tectono-stratigraphic units. The eastern unit is part of the stable Precambrian West African Craton and consists of high-grade metamorphic rocks and granitic gneisses. The western unit contains elements of an orogenic belt named the '*Rokelides*' or '*Rokel River Group*' that was deformed during the Pan-African tectonothermal event, about 550 Ma ago. A minor, 20–40 km wide coastal strip is made up of Pleistocene to Recent marine sediments.

Based on the description above, most of Sierra Leone is underlain by a series of ancient, folded, crystalline rocks of varying lithology, of Precambrian age. These rocks are over 2.1 billion years old and are overlain unconformably by the Rokel River and Sayonia Scarp Groups of late Precambrian to late Ordovician age, and the much younger Bullom Group sediments of Tertiary to Recent age (Figure 2.1). Prior to the deposition of the Bullom Group, a period of intensive igneous activity occurred in the Mesozoic period which gave rise to the Freetown gabbro complex and associated minor sills and dykes.

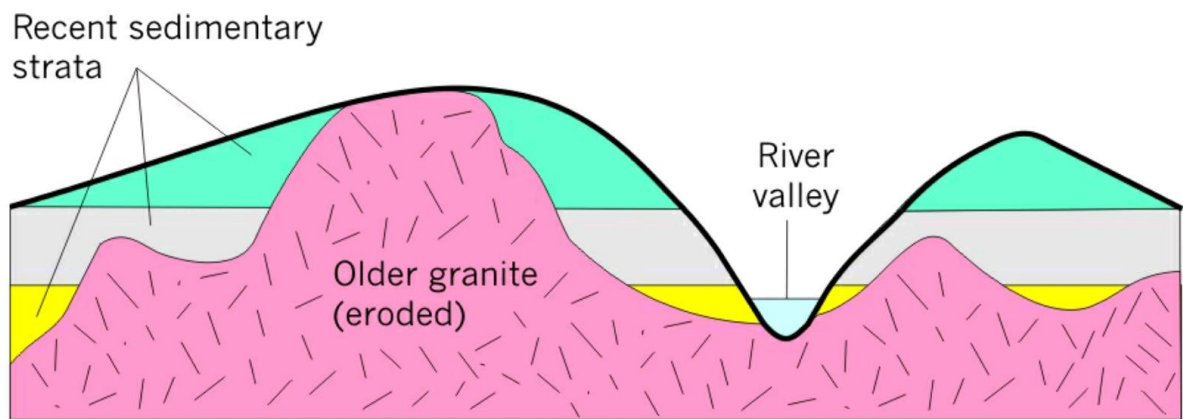


Figure 2.1: Generalized model geologic cross-section of Sierra Leone (Fileccia et. al 2017).

Explanation: The geologic cross-section above is not drawn to scale, the cross section illustrates unconformity, where the horizontal beds are lying out of conformity on the eroded surface of the older rock. The older granite intrusion (pink) was exposed to the atmosphere and eroded during an extended period, after which a new environment (e.g. marine) led to the deposition of sedimentary strata (yellow, grey, green). As the rock grains settled underwater, they slowly covered the basin. Following a subsequent marine regression, a new erosion cycle took place bringing the area to the current morphology.

The geology of Sierra Leone is divided into three main parts. These are:

- 1) The basement (infracrustal suite)
- 2) Supracrustal suite
- 3) Intrusives (youngest)

2.2 The Basement (Infracrustal Suite)

The greater part of Sierra Leone is occupied by an ancient granitic shield containing gneissic relics of still older formations. They date from the early Archean and include coarsely crystalline granites, quartz granulites, and hematitic granulites. Upon them, apparently unconformably, lie serpentines, amphibolites, conglomerates, and iron-stones of the ophiolitic Kambui Group which forms the Sula Mountains and the Kangari, Kambui, Nimini, and Gori ranges of hills. As these have also been deformed and metamorphosed together with the underlying gneisses and intruded by late and post- orogenic granites it seems clear that there have been several epochs of granite formation. This is the largest of the units and it houses other older formations.

The basement is subdivided into three granitic rock types (MacFarlane, Crow, Arthurs, & Wilkinson, 1974)

1. Syn-Kinematic Granitic Migmatites
2. Homogeneous Syn-Kinematic Granites
3. Late Kinematic Granites

2.3 The Supracrustal Suite

These are rocks of different lithologies and ages outcropping principally in a stratigraphic sequence. These are subdivided into six main groups. These are

- 1) Kambui Super Group
- 2) Kasila Group
- 3) Marampa Group
- 4) Rokel River Group
- 5) Saionya Scarp Group
- 6) Bullom Group

2.3.1 The Kambui Super Group

The supracrustal rocks of this group can be divided into two units on the basis of their size, stratigraphic thickness, lithologies, metamorphic grade, and distribution (Rollison, 1978). The western group includes the larger greenstone belts of the Sula Mountains, Kangari, south Nimini, and the Gori hills greenstone belts, which are up to 130 km long with thick succession (up to 6.5 km) metamorphosed to amphibolite grade. Banded iron-formation is a relatively minor lithology, although this unit includes the Marampa and Tonkolili iron ore fields.

In south eastern Sierra Leone, Liberia and western Ivory Coast there are small schist relics (maximum 40 km long) with thinner stratigraphic succession (rarely greater than 1 km) in which banded iron-formation is dominant and gabbro-anorthosite complexes are minor.

Rollison, 1978 states that geochronological evidence suggests that the two groups of supracrustal rocks are contemporaneous and that they represent a primary zonation of the Archean in southern West Africa. The ophiolitic Kambui schist group is subdivided into three groups; a lower ultramafic, a middle mafic, and an upper sedimentary group. The ultramafic group includes tremolite-chlorite-schists, talc-chlorite-schists, and anthophyllite-schists and serpen-finite interbedded with amphibolite and more rarely with metasediments. The mafic group is made up entirely of amphibolites which vary in size, are pillowed, and have vesicular and amygdaloidal structures, indicating that the original basaltic pile was composed of pillowed and massive lavas and intrusive sills with chilled margins. Amphibolites from the Kambui belt are olivine tholeiitic in composition. In the sedimentary group the commonest rocks are greywacke, turbidite, and quartzite with minor amounts of fuchsite-quartzite, conglomerate, metachert, and banded iron-formation.

2.3.2 The Kasila Group

A distinctive group of mafic gneisses and granulites lies along the south-western part of the West African craton in Sierra Leone and passes south-eastward into Liberia. The rocks of this group were formerly recognized as part of a gneiss belt compositionally different from the gneisses of the east, successively referred to as older schist and gneisses, (Dixey, 1925), the Kasila series, (Pollett, 1951), the Kasila Group, (Allen, 1969). They consist of gabbros, amphibolites, hornblende schists, garnet-mica schists, and charnockitic and anorthositic granulites with a predominantly NW to SE strike and

showing some signs of isoclinal folding and intensive shearing. The lithology of this Group is dominated by fine- to medium-grained basic granulites with minor horizons of quartz magnetite, quartz diopside, and sillimanitic rocks. The granulites are intruded by deformed gabbros, anorthosites and ultramafics in which relict igneous textures have survived the Pan-African reworking in zones where shearing was less intense. The outcrops within the Kasila are poorly exposed; as a result lithological boundaries have been drawn between major rock types such as the basic granulites and metasedimentary.

Two formations are recognized here (Keyser and Mansaray, 2004).

- 1) The Tapri formation
- 2) The Magbele formation

2.3.3 Marampa Group

Lying to the west of the Proterozoic Rokel River Group sediments there is a group of biotite-muscovite-schists, garnet-biotite-schists, and feldspathic and hematitic schists forming outcrops along a 60 km zone. In the westernmost outcrops greenish chlorite-schists and muscovite-schists predominate. Inliers of granite are exposed, but their relationship with the Marampa schists is not clear due to poor exposures. It is a strip of roughly 20km lying east of the Kasila Group and lies in low thrust faulted contact with the underlying granitic basement, (Macfarlane et al, 1981). At the Ghafal and Masaboin hills the Marampa schists have been affected by tight folding along northeast axes and by open folding along northwest axes.

The Marampa Group is included in the Archean supracrustal formations, but their thin successions are dominated by banded iron-formation (Williams H.R 1978). Thus, they may be of a different age from the other belts.

Their lower metamorphic grade may simply reflect their tectonic situation, however, and the presumption must be that they represent Archean supracrustals affected by the Eburnean metamorphism or that the Pan-African episode has reset their isotope ratios giving them an Eburnean age. It has NNE-SSW trending volcano sedimentary group. Has typical greenstone lithology but the structural and metamorphic characteristics are in sharp contact.

The rocks are intensively deformed with complex fold structures, thus it was affected by the Pan African event (Ca 600Ma). Principally consists of two formations (Macfarlane et al 1974, 1981, Keyser and Mansaray 2004).

1) Upper Meta-Sedimentary Roktolon Formation

This overlies the matoto formation and consists of meta-sediments which include quartzite with pebble horizons and cross bedding, fuchsite quartzite and magniferous quartzite (Wright et al 1985) and also banded iron formation.

It comprises three (3) members

- I. The Mabole Member
- II. The Masimera Member

III. The Masagboign Member

2) Lower Meta-Volcanic Matoto Formation

This consists of pillow basalt, meta-andesite hornblende epidote schist, talc chlorite schist, and subordinate metavolcanics. The ultrameta-volcanics consists of talc, serpentine, chlorite etc. Has predominant mylonite zone about 1-6m thick at the contact between the lower Matoto formation and the Granite Greenstone Terrain. The economic potential of this group is mainly the iron ore which occurs as schist comprising of haematite and magnetite with quartz. It is characterized by the green schist facies metamorphism in the east and amphibolites in the west (Macfarlane et al 1981, Williams, 1988).

2.3.4 Rokel River Group

The Proterozoic to Paleozoic Rokel River Group extends southward from Guinea into Sierra Leone where it occupies a belt c. 30 km wide, trending SSE for some 225 km into southern Sierra Leone. The Rokel River Group was folded and slightly metamorphosed by the Rokelide Orogenic Event ≈ 500 Ma ago, the time of the Pan-African thermo-tectonic event. This group occurs adjacent to the Marampa Group. It was deposited unconformably on a basement complex. The groundwater potential of this group varies. The sandstones are good aquifers where they occur while the shale acts as aquitards. The group records the initiation of depositional basin, floored by glacial deposits succeeded by littoral and deeper water sediments and filled in with deltaic deposits derived from the east (William & Culver, 1991).

The group is subdivided into six formations;

- I. The Tabe formation
- II. Makani formation
- III. Teye formation
- IV. Mabile formation
- V. Taia formation
- VI. Kasewe Hills Formations

2.3.5 Saionya Scarp Group

The Paleozoic Saionya Scarp Group covers an area of 50 km² in northern part of Sierra Leone and extends northwards into Guinea. The Saionya Scarp Group rests unconformably on Archaean granitic rocks and on Rokel River Group conglomerates, the latter folded during the Pan-African thermo-tectonic event (Culver & Williams, 1979). This Group sedimentary sequence is 190 m thick and is intruded by several dolerite sills, up to 90 m thick, of probable Triassic age. The Group has been subdivided into the Moria and Waterfall Formations.

2.3.6 The Bullom Group

Bullom Group sediments occupy the low-lying coastal plain of Sierra Leone. These deposits extend up to 50 km inland and are found at heights of up to 40m above present sea level. Outcrops are

rare and generally poor with the exception of 25m high sea-cliffs at Bullom, North of Freetown (Culver, Williams, & Morel, Sierra Leone, 2006).

The Bullom Group consists of a laterally variable sequence of poorly consolidated, near horizontal, often iron-stained gravels, sands and clays with occasional intraformational laterites and lenticular seams of lignite. The clays are generally kaolinitic, red, purple and white in colour and in the Bullom cliffs contain plant remains. In a borehole drilled to a depth of c. 120m (100m below present sea level), East of the Freetown Peninsula, a sparse fish and mollusc fauna obtained from borehole sludges indicated an age not older than Eocene and possibly as young as Miocene for near basal sediments.

The sands, sometimes graded, but rarely cross-bedded, are generally poorly sorted, with a clay matrix; partially disintegrated feldspars occur. Quartz grains are very angular and under the scanning electron microscope show no evidence of marine or prolonged fluvial activity.

Interbedded with the sands are occasional grit beds, stringers of rounded quartz pebbles, and horizons of kaolin clay clasts. Intraformational laterites occur within the sands and often form puddingstone horizons. Rare, thinly bedded calcareous clays and grits have also been recorded. The group exhibit virtue of groundwater potential which has been development for community water supply in areas where they occur, especially along the coastal plain which is the home for the bulk of the farming and fishing population. This is tertiary in age.

2.3.6.1 Recent Deposits

The beach sands of various colours and grain size are found along the coast where they overlie the poorly consolidated sediment of the Bullom group. The river valleys and transported sediments derived from the weathering of bedrock form a layer gravel that promotes recharged or precipitation.

2.4 Intrusive

During the early Mesozoic i.e. separation of the African plate from the American rifting was accompanied by Magmatism. This comprises largely of batholithic rocks which are basic and alkaline intrusions. They are the youngest of all the rock types in the Country as they generally intrude either the basement or super crustal rocks. They show variation in mineralogy.

Two varieties are recognized during the Basaltic Magmatism in Sierra Leone.

- 1) The Freetown complex
- 2) Dolerite dykes and sills

2.4.1 The Freetown Complex

The Freetown peninsula and the Banana Islands are part of an apparently funnel-shaped body of gabbroic rocks of which the greater part lies out to the sea. The complex consists of a 6 km thick series of cumulate rocks of gabbroic composition, containing layers of dunite, troctolite, olivine-gabbro, gabbro, leucogabbro and anorthosite (Culver, Williams, & Morel, Sierra Leone, 2006). The complex is intruded into the gneisses of the Kasila Group and overlain by sediments of the Bullom

Group whose lower beds are of Eocene age and lies unconformably on the basement. The Sedimentary structures such as cross-bedding are common in the gabbro layers and some 6,000m of thickness is exposed (Culver, Williams, & Morel, Sierra Leone, 2006).

Tertiary and more recent weathering lead to lateritisation across a large part of Sierra Leone, affecting mainly the greenstone belts and the extensive dolerite intrusions. The bauxite deposits formed within the Kasila group are of this weathering process.

The complex has been reliably dated as 193 ± Ma. The outcrop limits of the complex define an arc. Layering dips radially inwards from this arc and a hypothetical 'centre' is deduced to lie 16 km WSW of York. The complex principally consists of ranges of mountains separated into zones based on mineralogical composition and topography. The orientation of these set of mountains implies that the complex was formed probably from numerous injection of magma rising intermittently from magma chamber.

The layering may be divided into four (4) major zones on the basis of large-scale variations in mineralogy and topographic expression. Each zone can be seen as the result of a single magmatic event. The base of each zone is olivine-rich, and the top anorthositic. Within the zones are many rhythmic units on a hectometre scale, and within each rhythm is a centimeter to metre-scale banding. Both zones and rhythms tend to be more olivine-rich at their bases and plagioclase-rich at their tops, so in effect rhythms are small-scale duplications of zones.

Rhythmic layering and banding is more developed in the basal portions of zones and rhythms, while massive, lenticular anorthositic rocks, which are locally transgressive into overlying rocks, characterize the tops of zones. Mineralogically, the Freetown Complex displays few of the characters expected in large layered intrusions.

The minimal cryptic layering present is unrelated to height above the base of a zone or rhythm. Order of cumulus crystallization is ilmenite-magnetite as immiscible droplets, olivine, pyroxene, plagioclase; this gives rise to the following stratigraphy of rhythms and zones:

- a) Vertical column
- b) Rhythmic layering
- c) Igneous lamination
- d) Cryptic variation
- e) Horistic layering

The Freetown igneous complex consists of the units given below in their appropriate sequence;

- 1) Anorthosite - > 90% plagioclase
- 2) Leuco gabbro- plagioclase, hypersthene
- 3) Gabbro/Norite – plagioclase, augite (hypersthene)
- 4) Olivine gabbro- plagioclase, two pyroxenes, olivine
- 5) Troctolite- plagioclase, olivine
- 6) Dunite- > 90% olivine.

The complex is cut by a series of dikes and veins. Sulphides are ubiquitous but occur in small amount, either as crystallized droplets of immiscible liquid trapped as inclusion in olivine and plagioclase, or as late-stage hypothermal vein and replacement. Copper, nickel, platinum and gold have been recorded in association with sulphides (Culver & Williams, 1979).

2.4.2 Dolerite Dykes and Sills

Dolerite dykes and sills are widespread in Sierra Leone. Dolerites are most common close to the coast, intruding Precambrian rocks and those of the Rokel River Group as coast-parallel dyke swarms traceable into Liberia. Further inland, the dykes become thinner and occur with more variety of trends, paralleling major NE, ESE faults. The dykes show a variation in mineralogy, but there is a consensus of opinion that they are consanguineous.

Some contain olivine and orthopyroxene, while others show only relicts of these minerals. All dykes consist mainly of a zoned labradoritic plagioclase and brownish synneusis clots of augite occurring as subophitic intergrowths.

Porphyritic dykes, containing abundant 3cm laths of plagioclase with marginal sub-parallel alignment of crystals, also occur. Magnetite, ilmenite, and graphic quartz-feldspar intergrowth are common accessory phases (Culver & Williams, 1979). Dolerite sills form resistant caps of two major mountains in Sierra Leone, Bintumani (1,948 m) and Saionya Scarp (1,000m). Sills occur at progressively lower levels when traced westwards, forming similar tabular structures up to 120m thick in the Rokel River Group at a height of 150 m.

The progressive decrease in sill elevation with respect to sea level towards the coast may be evidence for a post-Triassic continental margin subsidence associated with the opening of the Atlantic Ocean and the formation of new continental. The small sills on Bintumani are banded on a meter scale, suggesting cumulate formation. The three (3) separate sills on Saionya Scarp make up a total intrusion thickness of 200m, and these indicate a large scale mineralogical variation due to crystal settling. The sills have mineralogical composition similar to that of the dykes, and are presumed to be structurally and temporally related.

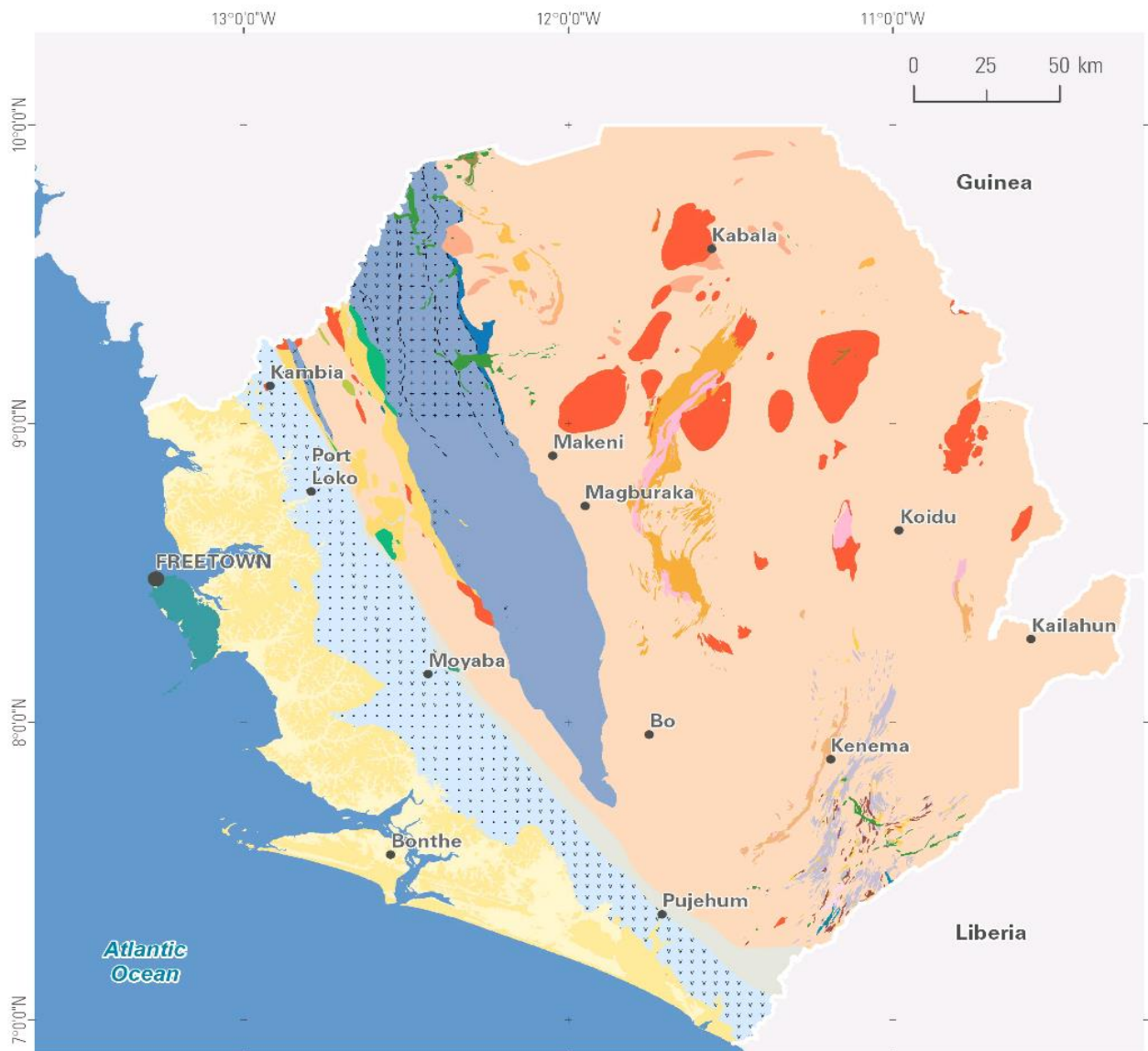


Figure 2.2: Geologic map of Sierra Leone (Keyser & Mansaray, 2004)

Geological Formation	
Jd - Dolerite	Lmr - Rokotolon
Jf - Freetown complex	Lmr - Rokotolon, Banded Iron Formantio
LAn - Anorthosite metagabbro	Ls
LG - Leonean granite	Lsa
LG Mylonite zone	Lse
LM - Migmatites / hybrid rocks	Lt
Lam - Pre-Liberian amphibolite	Om - Moria
Lb - Bagbe alkalic complex	Ow - Waterfall
Lba	PLI - Loko Hills
Lbi	PLg - Migmatitic gneiss and granitoid
Lf	PLa - Pre Leonean amphibolite
Lg - Liberian granite	Prtm - Tabe-Makani
Lk	Q - Bullom (alluvium, beach sand etc)
Lkm - Magbele	Tb - Bullom (sand, clay, clayey sand, lignite)
Lkt - Tapr	EB - Basic intrusive
Lme	Er - Rockel River
Lmg - Mano Moa	Erk - Kasewe
Lmg - Mano Moa, banded ironstone	Erm - Maboale
Lmm - Matoto	Ert - Taia
	Erte - Teye

Figure 2.3: Legend of Geologic map of Sierra Leone (Keyser & Mansaray, 2004)

Explanation: The map shows the distribution of geologic materials and geologic structures across Sierra Leone that are visible at the Earth's surface. Formations, hard rocks and unconsolidated sediments are distinguished according to their mineral composition, age and environment. Each color represents a different geologic unit. Each unit is assigned a set of letter symbols, usually a combination of an initial capital letter followed by smaller letters. The capital letter represents the age of the geologic unit. The small letters indicate either the name of the unit or the type of rock. A total of 28 geologic formations have been mapped, ranging from Archean (3.5 billion years ago) to Quaternary (2 million years ago). The base of this map is modified from Keyser & Mansaray, (2004). The base was comprised of four plates at 1:250,000 scale, and was based on a compilation of historical works dating 1961 - 1981.

		Sedimentay / volcanic rocks		Intrusive rocks					
Lithology		acronym /symbol			Group	Formation	Age	Ma before present	
1	alluvium, beach sand etc.	Q			Bullom		Tertiary / Quaternary	65	
2	sand, clay, clayey sand, lignite	Tb							
3	Kimberlite dykes			K		Kimberlite dykes	Cretaceous	142	
4	dolerite			Jd		dolerite dykes	Triassic / Jurassic	206	
5	dunite, gabbro, troctolite, olivine gabbro, leucogabbro, anorthosite			Jf		Freetown complex			
6	laminated argillite with rhytmities	Ow			Sayonia Scarp	Waterfall	Ordovician	495	
7	shale, arkosic ss, cngl.	Om				Moria			
8	basic intrusive			€B	Rokel river €r	Basic intrusive	Upper Cambrian	545	
9	variegated shale, laminated siltstone, orthoquartzite, subarkose, arkose	€rm	€r			Mabole €rm	Cambrian		
10	grey mudstone and shale, occasional beds of grey clayey siltstone, fine grained ss, laminated silty shale	€rt				Taia €rt			
11	andesitic lava, spilitic basalt, dacite, dacitic tuff	€rk				Kasewe Hills			
12	purple and grey shale with intebedded quartzwacke bands	€rte				Teye			
13	grey shale interbedded with quartzite, arkose, subarkose, cngl.	Prtm				Tabe-Makani			
14	pelitic and psammitic metasediment, haematite, quartzite and specularite schist; banded iron formations	Lmr		Marampa		Rokotolon	Archean		2500
15	massive and banded meta andesite, ultrabasic lava, pillow lava	Lmm				Matoto			
16	nepheline syenite, syenite, alkali granite			Lb		Bagbe alkalic complex			
17	biotite granite, porphyroblastic granite, granitoid			Lg		Liberian granite			
18	quartz-feldspatic gneiss, coarse amphibolite, garnetiferous gneiss lava	Lkm		Kasila	Magbele Lkm				
19	hypersthene gneiss with feldspatic bands, olivine-bearing metagabbro	Lkt			Tapr Lkt				
Various lithology: pelitic metasediments, basic lavas, gneiss, garnet/ ultrabasic schists, quartzite, banded ironstone, amphibolite, hornblende schist....		Green stone belts	(Lt, Lk, Lbi, Lme)		Kambui supergroup	Sula mountains, Kangari hills, Kambui hills, Nimini hills, Gori hills, Serekolia, Sankarama			
			(Ls, Lg, Lf, Lba, Lse, Lsa)						
20								2900	
21	anorthosite metagabbro			LAn					
22	amphibolite, coronite	Lam				Pre-Liberian amphibolite			
23	granulite, quartzite, banded iron formation	Lmg				Mano Moa (Lmg)			
24						Migmatites / hybrid rocks (LM)			
25	porphyroblastic banded gneiss, pyroxen-augen gneiss, migmatitic gneiss, granitoid, mylonite			LG		Leonean granite			
26	amphibolite	Pla				Pre Leonean amphibolite	3500		
27	amphibolite, quartzite, banded ironstone	PLi			Loko Hills				
28	migmatitic gneiss and granitoid			PLg	Loko Hills	Migmatitic gneiss and granitoid			

Figure 2.4: Geologic column of Sierra Leone (Fileccia et. al 2017)

CHAPTER 3: GROUNDWATER POTENTIAL OF THE PROJECT AREA

3.1 GROUNDWATER EXPLORATION AND DEVELOPMENT

Though groundwater resources are widely distributed, nature does not provide groundwater at the place of our choice. The occurrence and distribution of groundwater resources are confined to certain geological formations and structures. The groundwater at all locations may not be directly used if the quality is poor. These limitations can be solved using the proper exploration techniques. The term 'explore' comes from a Latin word *explorare*, meaning learn or investigate. The proper exploration of groundwater involves apart from source location, the well design and construction. These are all integral part of the scheme of exploration and management.

Several processes are involved for the exploration and development of groundwater. Geophysics and boreholes construction are the most complex of the processes involved. Boreholes are usually drilled after different phases of exploration including reconnaissance, geological/hydrogeological investigations and or geophysical surveys. Knowledge about the geology of the area and proper geophysical techniques are fundamental to locate feasible water points.

A borehole is distinct from other holes sunk in the ground, it requires proper design, professional construction and careful drilling. Boreholes for groundwater extraction consists of vertically drilled hole, a strong lining which prevents collapse of walls this include means of allowing clean water to enter the borehole space (screen), surface protection and a medium for extracting the water.

Hand dug wells and surface water catchments are vulnerable to contaminations as a result of agricultural activities, poor sanitation, animals and declines in water level caused by drought.

Interestingly, borehole water does not require treatment and is less susceptible to fall in water level during periods of drought or limited rainfall (Technical Review, 2010)

3.2 Factors influencing groundwater potential

1. Land Use/ Land Cover (LU/LC)

The effect of Land use/ Land cover (LU/LC) on groundwater potential is very prominent. The extensive land cover change in Sierra Leone was the loss of woodland and forested area across the country. Even though the country is located within the upper Guinean forest ecosystem, it is unlikely that it was ever heavily covered by dense forest (Munro & van der Horst, 2012). Between 1975 and 2013, Sierra Leone lost 30% of its forest cover, or about 1,100 sq km, at an average annual rate of 0.8%. However this rate has slowed since the end of the civil war, averaging 0.4% of annual forest loss between 2000 and 2013. Woodland is one of the dominant land cover type. (Munro & van der Horst, 2012)

Cropland expansion, slash-and-burn agriculture, logging, mining and cattle grazing activities were the dominant factors affecting vegetation and land use. Because a large part of the population obtains its substance from farming, agriculture expansion is mostly driven by population growth. Types of land cover/ land use are forest plantations, crop farms, open denuded soils surfaces, water bodies like lakes and rivers and settlements. Each LU/LC has a certain influence on groundwater

potential indirectly through infiltration, runoff and evaporation (Fashae et al., 2013; Sreela et al., 2013). Vegetation cover decreases evaporation and runoff favours infiltration. Therefore, vegetation increases chances of groundwater recharge and can be an indication of high groundwater potential (Leduc et al., 2001). Forest plantations require large amounts of water, which they abstract from the vadose zone and in other cases from beneath the water table hence forest plantations indicate high groundwater potential. In settlements and built up areas, infiltration is low because of roads, pavements and buildings covering the soil surface and consequently, low groundwater potentials are expected (Sreela et al., 2013).

In summary, in terms of depletion, the depletion of water resources in Sierra Leone arises primarily from deforestation activities and poor land use. The resources are also threatened by rapid population growth, population from mining, increased uncoordinated industrial activities, degradation of the environment causing soil erosion, drainage of wetlands, and pollution of rivers (Ministry of Energy and Water resources, 2010).

2. Geomorphology and slope

(Avinash, Jayappa, & Deepika, 2011) asserted that geomorphology is a good proxy for groundwater potential analyses. The landform and landscape features are well-reflected by geomorphology. The slope is a type of geomorphological feature, which highly influences groundwater infiltration and recharge. Where steep slopes are present, groundwater potential is low because there is more surface runoff than infiltration (Fashae et al., 2013). In areas characterised by flatlands and/or valleys, groundwater potential is high because it is easier for the water to form pools and infiltrate than to runoff on the surface.

3. Geology

It is common knowledge in the field of hydrogeology that geology influences groundwater movement, storage and subsequently, potential. In a study on three sites by (Krishnamurthy et al., 1996) it was noted that geology is also a major theme in groundwater analysis. A study by (Pradhan, 2009) also assigned the second highest weight to the geology of all the themes used for groundwater zonation in Bharangi River basin, India.

4. Lineaments

Lineaments are linear features, which occur on the earth's surface, different from the surrounding features, and reflect what the unseen subsurface can be (O'Leary, Friedman, & Pohn, 1976). Examples of lineaments are joints, faults, fracture zones, dykes, lithological contacts and foliations (Holland, 2011); (Mogaji, Aboyaji, & Omosuyi, 2012). It has become prominent throughout the last few years to use lineaments studies in the assessment of potential groundwater zones. Jha et al. (2007) and (Sander, 2007) pointed out a number of studies in which exploration and assessment of groundwater resources were done using lineaments mapping as a core of the exploration. Furthermore, (Morelli & Piana, 2006) studied the correlation between structures mapped in the

field and those mapped using the lineament technique. They found a high correlation, which therefore allows the structures of an area to be indicated by lineaments.

5. Soil

Infiltration and, consequently, groundwater, is highly dependent on the type of soil and soil texture. Sandy soil has large particle constituents, which makes it have high transmissivity and infiltration values. On the contrary, clay soils have small particle constituents, resulting in low transmissions. In terms of groundwater potential, sandy soils are assigned higher weights, clay soils are assigned lower weights and loamy soils are assigned intermediate weights (Jha *et al.*, 2010; Avinash *et al.*, 2011; Fashae *et al.*, 2013).

6. Rainfall

Groundwater recharge mainly comes from rainfall. Rainfall is a major hydrological parameter which influences groundwater potential and viability (Avinash *et al.*, 2011). Part of the rain water, which falls on the ground, is infiltrated into the soil. A part of this infiltrated water is utilized in filling the soil moisture deficiency while the remaining portion percolates down to reach the water table, which is termed as rainfall recharge to the aquifer. In areas where fossil groundwater is available, rainfall may not indicate groundwater potential but it will indicate sustainability of groundwater exploitation and can be used to estimate optimum water extraction levels.

3.3 Aquifer Systems in Sierra Leone

3.3.1 Introduction

An Aquifer means a geological formation which has structures or textures that hold water or permit appreciable water movement through them (National Water Act No 36, 1998).

3.3.2 Importance of aquifer systems in Sierra Leone

Aquifer systems are the storage medium from which groundwater is abstracted in most parts of the country. They should be managed judiciously and always be protected from over-exploitation and contamination to sustain the future generations of Sierra Leoneans.

3.3.3 Hydrogeological units in Sierra Leone

(Adekile & Danert, 2014) put forward a simplified hydrogeological classification having four categories that relates to four geological units. In Sierra Leone the key distinction in hydrogeology is between the relatively low permeability and productivity aquifers formed by the crystalline Precambrian Basement Complex, consolidated metasedimentary rocks and igneous intrusions; and the higher permeability and storage of the Bullom Group unconsolidated sand aquifer in the coastal zone. The most important of these units is the Basement complex, it extends to over 75% of the country, which can be vertically subdivided into an upper weathered zone overlying poorly fractured bedrock. The upper zone is widespread and is a primary source of groundwater for hand-dug wells across the country. Sierra Leone is divided into four hydrogeological units:

1. Unconsolidated sedimentary deposits,
2. Consolidated metamorphic,
3. Igneous rocks and
4. Basement complex.

1. Unconsolidated sedimentary deposits

These are typical of the Bullom Group and are of Tertiary to Quaternary period. They are further divided into alluvial (valley fill) and coastal deposits of the Bullom Group formation. Alluvial sediments constitute sands, gravels and clays which overlie the basement rocks, usually up to 15 m thick. They have primary porosity and can have elevated permeability. The storage of groundwater and flow is dominantly intergranular. In this unit the data on borehole yields is limited, however, yields are likely between 0.3 and 5 liters/second (l/s). Coastal sediments of the Bullom Group are loose sands and clays (inland alluvial & coastal), usually 10 - 20 m thick, and can form a moderately productive aquifer with potential borehole yields up to 3 (l/s). Groundwater flow in coastal sediments is intergranular and storage capacity can be high. Below this, are interbedded sands and clays which are typically 30 - 80 m thick. Boreholes in this unit can often abstract up to 6 l/s (Lapworth, Carter, & MacDonald, 2015).

2. Consolidated metamorphic of Sayonia Scarp and Rokel River formations

The consolidated hydrological unit ranges from Upper Proterozoic. It constitutes a weathered (regolith) layer that lies near-surface with clay as the dominant material. Underneath this are ancient consolidated metasedimentary rocks, with very limited intergranular porosity. Groundwater storage and flow occurs within fractures in the rock (secondary porosity), which are often along old bedding planes, although there is limited information on potential borehole yields in the formation. They are characterised by shales, schist, metaconglomerates and quartzites, metacherts and banded iron formations (BIS), with volcanic bands (Lapworth et al. 2015).

3. Igneous intrusives

The Igneous intrusive includes the Freetown Complex and other intrusions and are mostly Mesozoic. The igneous rocks consist of fractured gabbros (secondary porosity). Groundwater is likely to flow through the igneous rocks largely in fractures, but thin weathered zones may also contribute. Similarly, there is limited information on borehole yields in this formation.

4. Basement Complex, Leonean and Liberian Granites

The major formations of the Basement Complex are the Marampa and Kasila groups and they are mainly Precambrian (Archaean). There is typically layer of regolith- a highly weathered rock overlying the unweathered bedrock which is known to have a primary porosity. The regolith has often transformed to a thick tropical soil. This is generally up to 20 m thick. The upper section of this weathered zone often has relatively little clay - the clay minerals have often been leached out, leaving metal oxides.

These metal oxides are often in the form of indurated or gravelly layers, of high permeability, and can allow rapid horizontal groundwater flow (primary porosity). The weathered rock materials close to the lower extension of the weathered zone are mostly clay, and thus have much lower permeability. Yields from shallow boreholes abstracting from this zone are observed in the range 0.3 to 1.5 l/s. This shallow aquifer is not seasonally sustainable and tends to dry up rapidly during the dry season and groundwater drains rapidly away through the permeable material. Its vulnerability to contamination is positive, because of limited attenuation potential in the subsurface and rapid horizontal and vertical groundwater flow pathways for seasonal rainfall recharge. At the base of the weathered zone, the underlying crystalline bedrock is often extensively fractured and not rich in clay, and can store and transmit groundwater through fractures. The average thickness of the fractured aquifer zone is 35 m, but it can be as thick as 60 m. Borehole yields in this formation are typically between 0.3 and 1.5 l/s. Groundwater pathways are usually longer than in the shallow weathered aquifer, and groundwater flow can be rapid over distances of tens of meters. This deeper, fractured aquifer zone is typically a more sustainable groundwater source than the upper weathered zone. It also has more potential for the natural attenuation of contaminants, because of the overlying clay zone and the longer pathways. (Lapworth et al. 2015)

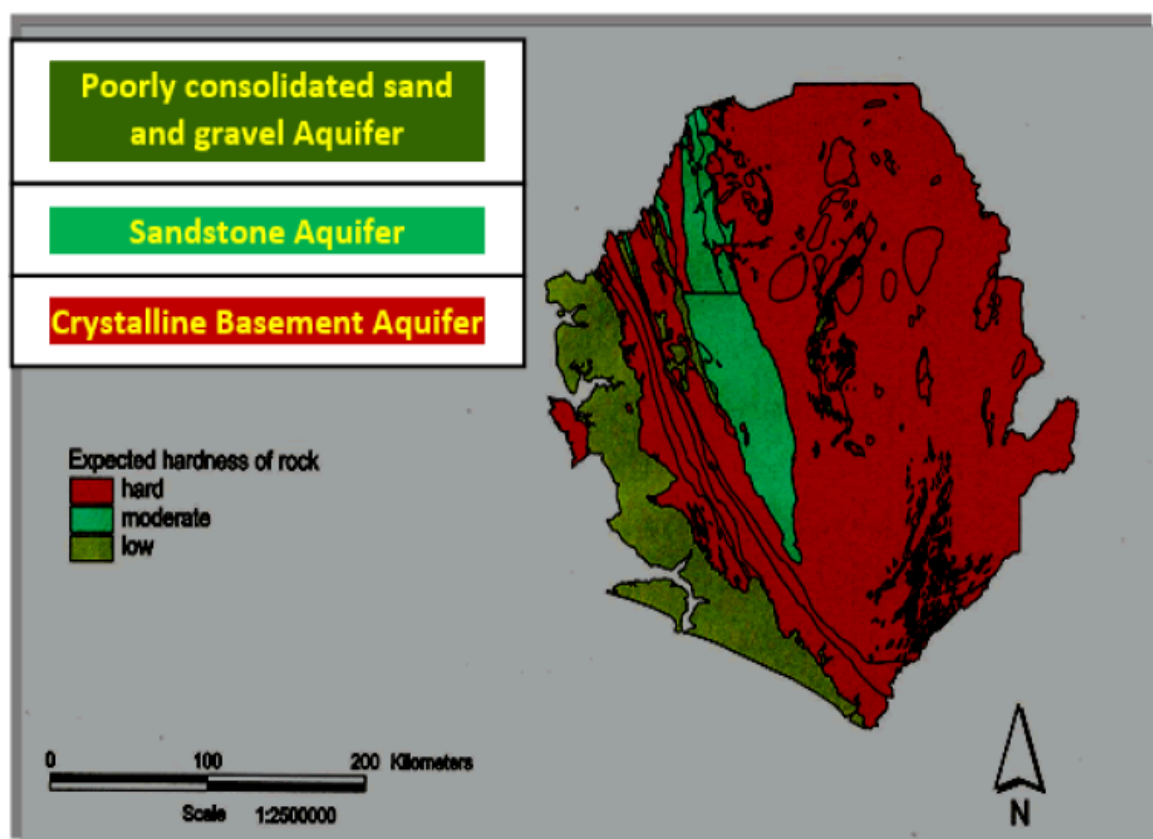


Figure 3.1: Aquifer map of Sierra Leone (Adekile & Danert, 2014)

3.3.4 Aquifer Productivity

The permeability of the rock types in Sierra Leone can be further refined based on permeability considerations often derived from pure analogy between geology (lithological rock type) and hydrogeology (hydraulic conductivity values) (Struckmeier & Margat, 1995). This provides a measure of aquifer productivity. Recharge is sometimes used in assigning aquifer productivity and small-scale hydrogeological maps, such as the Hydrogeology Map of Africa and the World Hydrogeological Map, often depict aquifer recharge as a measure of aquifer productivity.

3.3.5 Aquifer Classification

Aquifer productivity classes were adopted from Struckmeier, Margat (1995):

Table 3.1: Aquifer categories according to groundwater potential

Aquifer category	Specific capacity (l/s/m)	Transmissivity (m ² /d)	Permeability (m/d)	Approx. Yield (l/s)	Groundwater potential
A, C	>1	> 75	>3	> 10	High: withdrawals of regional importance (supply to towns, irrigation)
B, D	0.1 - 1	5 - 75	0.2 - 3	1 - 10	Moderate: withdrawals for local water supply (small communities, small-scale irrigation)
E	0.001 - 0.1	0.05 - 5	0.002 - 0.2	0.01 - 1	Limited: smaller withdrawals for local water supply (hand pump, private consumption)
F	< 0.001	< 0.05	< 0.002	< 0.01	Essentially none: sources for local water supply are difficult to ensure

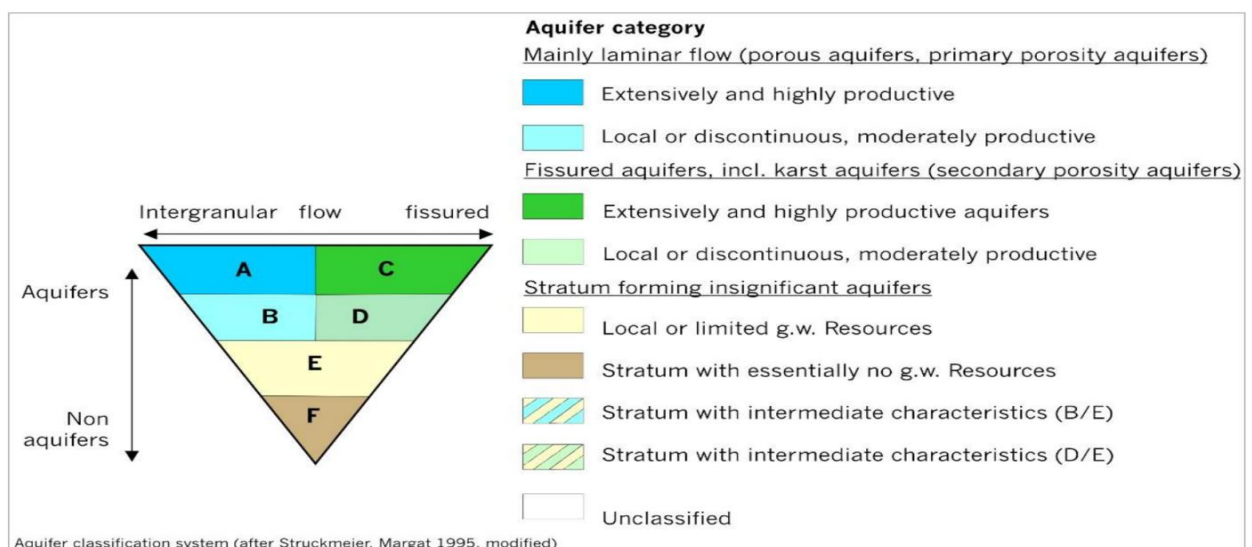


Figure 3.2: Aquifer categories according to groundwater potential

The color scheme was applied to the aquifer potential classification above to represent hydrogeological characteristics. Dark blue and dark green colors represent aquifers with high potential. Light blue and light green colors represent aquifers with moderate potential. Formations with limited potential are colored in light brown while strata with essentially no groundwater are in dark brown. For groundwater systems with high or moderate potential the coloring scheme also considers the dominant type of groundwater flow within the rock. Blue colors are used for systems in which flow is mainly intergranular while green colors represent systems formed by hard rock, including karst rock, in which flow occurs in fissures, fractures or dissolution cavities.

3.3.6 Aquifer Condition in the Project Area

The Basement Complex rocks and sedimentary formation are intruded by two sets of igneous rocks. The first and older set is represented by the Freetown gabbros and dolerite dykes that run parallel to the Atlantic Ocean. The second set are kimberlite pipes, the source of the diamonds in the country. Groundwater occurrence in the intrusions is the same as on the Precambrian rocks. The Freetown gabbros are weathered and jointed. The dolerites tend to weather into clays, with limited porosity and transmit very little water (Adekile & Danert, 2014).

For the other portion of the study area, the Granite Green Stone Terrain, the aquifers are largely unconfined, this depicts that the water table forms the upper surface of the zone of saturation. The aquifers are poorly unconsolidated, porous media which constitutes sands and gravel. The altered and fractured zones of the granite basement rock are water-bearing. The occurrence, distribution and movement of groundwater is determined and controlled by the porosity developed by joints, fractures and fissures within the basement rocks. It is likely that the aquifers in the project areas receive some recharge from surface source (Jalloh et al., 2016).

The estimation of recharge may be carried out using water balance model to calculate the actual evapotranspiration which is then fed into the hydrologic equation to determine groundwater recharge: for the water balance model certain input parameters are considered, these parameters are: Temperature, Precipitation, Potential evapotranspiration, and surface runoff. The Sierra Leone rivers have a surface runoff coefficient of 0.12. The hydrologic equation is given as;

$$RG = P - (Sr - Ev)$$

Where: Rg=Groundwater recharge (mm); P=Precipitation (mm); Sr=Surface runoff (mm); Ev=Evapotranspiration (mm).

The major rocks found here that have major potential of groundwater storage are;

The weathered layer: most of the hand dug wells in the area penetrate this aquifer but recharge is primarily low as a result of low transmissivity.

The Overburden-hard rock zone: Penetrating this aquifer is hard, but with favorable climatic conditions, weathering of the hard rock enables exploitation of this aquifer. Because water is filtered as it passes through the rocks, wells that penetrate this aquifer produce good quality water.

The Hard Rock: This aquifer is very reliable but to penetrate this aquifer special drilling techniques and the drilling method need to be applied. One of the techniques normally employed is down the hole hammer. (Jalloh et al., 2016)

3.4 METHODS OF GROUNDWATER EXPLORATION

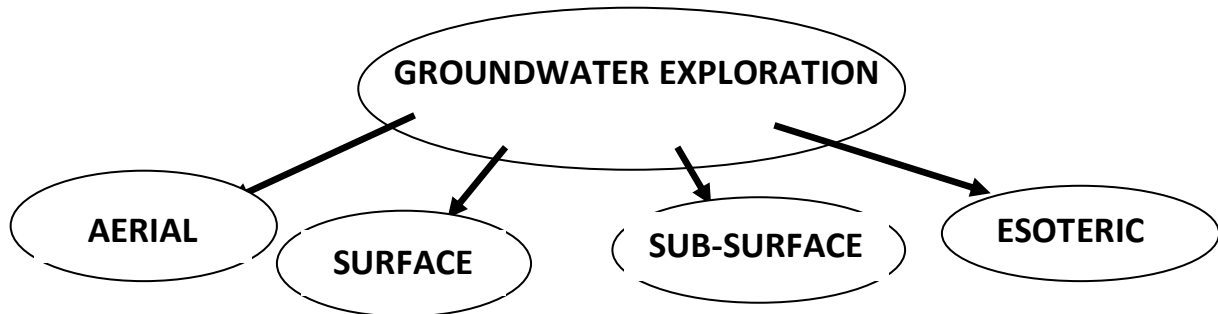


Figure 3.3: Groundwater Exploration Method

3.4.1 Methods and Techniques of Ground Water Exploration

Table 3.2: Techniques of Groundwater Exploration

AERIAL METHODS	SURFACE METHODS	SUB-SURFACE	ESOTERIC
1. Photogeologic	1. Geological	1. Geological.	1. Water divining.
2. Landsat/ IRS	2. Geomorphological methods	2. Hydrogeological	2. Astrological.
3. Infrared imagery	3. Hydrogeological	3. Tracer technique	3. Biophysical.
4. Electro magnetic [EM] techniques.	4. Geophysical Methods.	4. Geophysical Logging technique	
	a). Electrical & EM. b). Seismic. c). Magnetic. d). Gravity		
	5. Geobotanical		
	6. Geochemical		

Groundwater exploration is the investigation of underground formations to understand the hydrologic cycle, know the quality of groundwater, and identify the nature and types of aquifers. Groundwater can be explored using different methods as illustrated above. The four major groundwater exploration methods are the areal method, surface method, subsurface method and esoteric methods. However, this research focuses on the Surface Geophysical and Hydrogeological (Borehole) aspect. One of the surface geophysical methods is the vertical electrical sounding

method. Vertical Electrical Sounding (VES) is one to provide valuable information regarding the vertical successions of subsurface geo-materials in terms of their individual thicknesses and corresponding resistivity values. It is rapid and much effective in estimating aquifer thickness of an area and is cost effective technique for groundwater study.

3.4.2 Desk Study of the Project Area

This research is aimed at the Freetown Basement Complex and the Granite Greenstone Terrain. The Freetown Complex is a moderately well-exposed mafic layered igneous complex forming the mountains on which the city of Freetown is built. It is dated at c. 202 Ma, i.e. end-Triassic. It has been studied in some detail by a number of authors, both for its igneous history (Wells, 1962; (C.L, 2001) and for its potential for platinum-group element resources (Bowels, 1977).

The crystalline basement consists of granitic rocks occupying about 75% of the country. The north-south trending Liberian granite/green-stone complex is one of the oldest of its formations which date back to the Archean (>3 billion years ago). The local geology is consists of rocks typical of the West African Archean greenstone belt. The granite-greenstone terrain contains low-grade supracrustal belt along NNE-SSW trends. The granite/greenstone complex comprises a series of iron and magnesium-rich rocks (Sula Group) over a quartz-rich basement of granitic composition. The stratigraphic sequence is marked by the basic ultramafics followed mafics (metavolcanics) and a metasedimentary unit (quartzite and banded iron formations) in a greenstone belt lying on or beside granitic basement rocks. The basement relationship of the granites to the supracrustals has been obliterated by intrusion of Late-Kinematic granites and by deformation and metamorphism during the Liberian tectonothermal event (=2700 Ma) which produced the dominant N-S to NNE-SSW trend. Past research shows that groundwater is readily available in these areas.

The water output of the boreholes in the area is largely dependent on the surrounding geology. Majority of the population in the district (Makeni) depend on groundwater for domestic use and other purposes. However, in spite of the high potential of groundwater in this region and the number of boreholes drilled by Aid Agencies, past study reveals that there is still a serious problem with adequate availability and quality of groundwater. This is very evident from long queues at local and drilled wells of people scrambling for water (Jalloh et al., 2016).

3.5 Geophysical Survey

3.5.1 Introduction

All ground water investigation requires the service of Geophysical method as it aids in determining the subsurface structure. Exploring groundwater by geophysical method is termed Ground water geophysics.

3.5.2 Electrical Properties of Earth's Materials

Several electrical properties of rocks and minerals are significant in electrical prospecting. These are:

- Electrical potentials

- Electrical conductivity (or the inverse electrical resistivity)
- Dielectric constant

The electrical conductivity is the most important while the others are of minor significance. The electrical properties of most rocks in the upper part of the earth's crust are dependent primarily on the amount of water in the rock and its salinity. Saturated rocks have high conductivities than unsaturated and dry rocks. The higher the porosity of the saturated rocks, the higher its conductivity. The conductivity of rocks increases as the salinity of saturating fluid increases. The presence of clays and conductive minerals also increases the conductivity of the rocks.

3.5.3 Factors Controlling the Resistivity of Earth Materials

The electrical current is carried through the earth material by either:

1. Motion of free electrons or ions in the solid.
2. Motion of ions in the connate water, come from the dissociation of salts such as sodium chloride, magnesium chloride. This is important when dealing with engineering and hydrogeology.
 - For water bearing rocks and earth materials, the resistivity decreases with increasing:
 - a) Fractional volume of the rocks occupied by water (i.e. water content).
 - b) Salinity or free ion content of the connate water (i.e. water quality).
 - c) Interconnection of the pore spaces (i.e. permeability and porosity).
 - d) Temperature.

Conclusively:

- A. Materials which lack pore spaces will show high resistivity such as:
 - I. Massive limestone.
 - II. Most igneous and metamorphic rocks such as granite and basalt.
- B. Materials whose pore spaces lacks water will show high resistivity such as: dry sand or gravel and ice.
- C. Materials whose connate water is clean (free from salinity) will show high resistivity such as clean gravel or sand, even if water saturated.
- D. Most other materials will show medium or low resistivity, especially if clay is present, such as: clay soil and weathered rocks.
- The presence of clay minerals tends to decrease the resistivity because:
 - i. The clay minerals can combine with water.
 - ii. The clay minerals absorb cations in an exchangeable state on the surface.
 - iii. The clay minerals tend to ionize and contribute to the supply of free ions.

As a rough guide, earth materials are roughly divided into:

- a) Low resistivity less than 100 Ωm .
- b) Medium resistivity 100 to 1000 Ωm
- c) High resistivity greater than 1000 Ωm (Shendi, 2008).

3.5.4 Electrical Prospecting Methods

Electrical methods of prospecting include a large group of geophysical techniques employed for investigating the electrical fields of the earth. Such fields are generated in the earth naturally or artificially by generators or batteries. The distribution & intensity of electrical fields depend on the source of excitation as well as upon the electrical properties & geological structures in the region. The different electrical properties that influence electrical fields are primarily the resistivity ρ , the dielectric permeability C & magnetic permeability ϵ . Electrical parameters vary depending upon the lithology & more influenced by the presence, content & quality of water.

3.5.4.1 Direct Current (D.C.) Resistivity Method

The most common used methods for measuring earth resistivity are those in which current is driven through the ground using galvanic contact.

Generally, four – terminal electrode arrays are used since the effect of material near the current contacts can be minimized.

Current is driven through one pair of electrodes (**A & B**) and the potential established in the earth by this current is measured with the second pair of electrodes (**M & N**) connected to a sensitive voltmeter. It is then possible to determine an effective or **apparent resistivity** of the subsurface (Shendi, 2008).

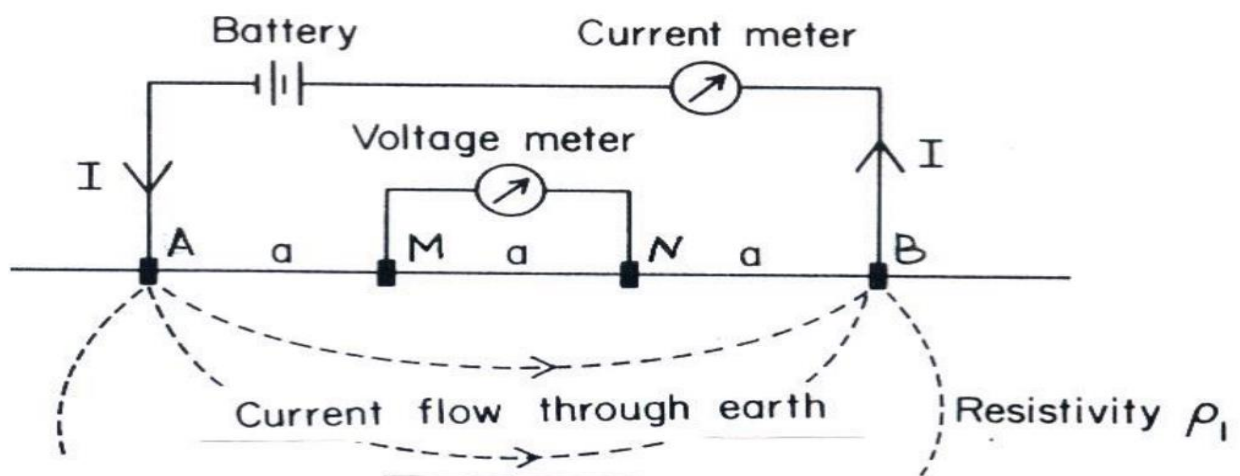


Figure 3.4: Current flow through the earth (Shendi, 2008)

Anomalous conditions or in-homogeneities within the ground, such as electrically better or poorer conducting layers are inferred from the fact that they deflect the current and distort the normal potentials (Shendi, 2008).

3.5.4.1.1 Vertical Sounding Or Electrical Coring

Vertical sounding involves studying the variation of resistivity with depth, as in the case of a layered medium. The spacing between the various electrodes are generally increased with larger spacing, the effect of the material at depth on the measurements becomes more pronounced.

3.5.4.1.2 Horizontal Profiling or Electrical Trenching

Deals with the study of lateral variations such as might be associated with dike like structures or faults, a fixed separation is maintained between the various electrodes and the array is moved as a whole along a traverse line.

3.6 Resistivity Method Field Procedures

There are only two basic procedures in resistivity work. The procedure to be used depends on whether the core interest is in lateral or vertical variations in resistivity.

The first is called horizontal or trenching profiling and the second is called electric drilling or sounding (Shendi, 2008).

3.6.1 Vertical Electrical Sounding (VES or drilling)

Electrical sounding is the process by which the variation of resistivity with depth below a given point on the ground surface is deduced and it can be correlated with the available geological information in order to infer the depths (or thicknesses) and resistivity of the layers (formations) present.

The procedure is based on the fact that the current penetrates continuously deeper with the increasing separation of the current electrodes.

When the electrode separation, $C_1 C_2$, is small compared with the thickness, h , of the upper layer, the apparent resistivity as determined by measuring (ΔV) between the potential electrodes, $P_1 P_2$, would be virtually the same as the resistivity of the upper layer (ρ_1)

As the electrode separation is increased a greater fraction of current will penetrate deeper, the lines of current flow being distorted at the boundary (Shendi, 2008).

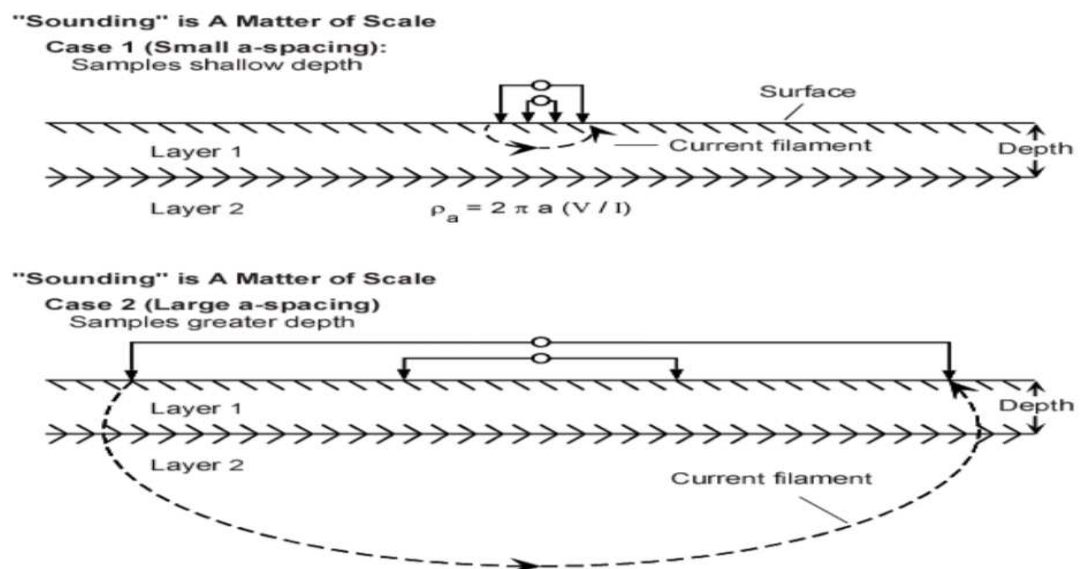


Figure 3.5: Electrode Separation and Current Depth (Shendi, 2008)

In the above figure, when the current electrode separation (A & B) is small compared with the thickness (h) of the upper layer, the apparent resistivity as determined by measuring (ΔV) between the potential electrodes (M & N) would be the same as the resistivity of the upper layer. This is because a very small fraction of the current would penetrate in the substratum below the boundary. At spacings which are very large compared with (h), a greater fraction of current will penetrate deeper and the apparent resistivity approaches (ρ_2) because the fraction of current confined to the surface layer becomes negligible.

In the case of the dipole-dipole array, increased depth penetration is obtained by increasing the inter-dipole separation, not by lengthening the current electrode array.

The position of measurement is taken as the mid-point of the electrode array.

For a depth sounding, measurements of the resistance ($\Delta V/I$) are made at the shortest electrode separation and then at progressively larger spacings.

At each electrode separation a value of apparent resistivity (ρ_a) is calculated using the measured resistance in conjunction with the geometric factor for the electrode configuration and separation being used.

The values of apparent resistivity are plotted on a graph (field curve), the x- and y-axes of which represent the logarithmic values of the current electrode half-separation ($AB/2$) and the apparent resistivity (ρ_a), respectively.

3.6.2 Electrical horizontal profiling (mapping or trenching)

In horizontal profiling, a fixed electrode spacing is chosen (depends on the results of the electrical sounding) and the whole electrode array is moved along a profile after each measurement is made to determine the horizontal variation of resistivity.

It is useful in mineral exploration where the detection of isolated bodies of anomalous resistivity is required.

The value of apparent resistivity is plotted at the geometric center of the electrode array. Maximum apparent resistivity anomalies are obtained by orienting the profiles at right angles to the strike of the geologic structures

3.7 Electrode Configuration

For field practice a number of different surface configurations are used for the current and potential electrodes. Both sets of electrodes are laid out along a line for all of those arrangements. The current electrodes are generally but not always placed on the outside of the potential electrodes. The value of the apparent resistivity depends on the geometry of the electrode array used, as defined by the geometric factor "K".

This research was carried out using the Schlumberger array configuration;

3.7.1 Schlumberger Array

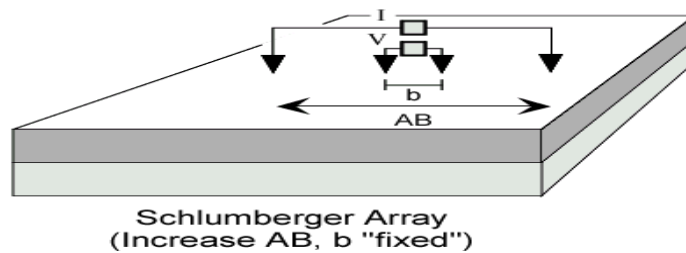


Figure 3.6: Schlumberger Array Configuration

This array is the most widely used in electrical prospecting.

Four electrodes are placed along a straight line on the earth surface with $AB \geq 5 MN$. Two closely spaced measuring electrodes (M & N) are placed midway between two current electrodes (A & B). In lateral exploration with the Schlumberger array, it is permissible to measure potential somewhat off the line between fixed current electrodes.

In addition to the potential associated with current introduced into the earth by the current electrodes, the potential difference as read may include spurious electrochemical potentials between the electrodes and electrolytes in the earth. Often non-polarizing electrodes (such as copper sulfate porous pots) are used to avoid such effects (Shendi, 2008).

3.8 Types of Electrical Sounding Curves Over Horizontally Stratified Media

The form of the curves obtained by sounding over a horizontally stratified medium is a function of the resistivities and thicknesses of the layers as well as of the electrode configuration.

3.8.1 Homogeneous and isotropic medium (One layer medium)

If the ground is composed of a single homogeneous and isotropic layer of infinite thickness and finite resistivity, the apparent resistivity curve will be a straight horizontal line whose ordinate is equal to the true resistivity (ρ_t) of the semi-infinite medium.

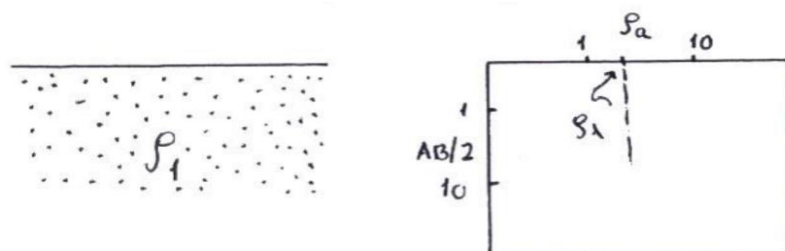


Figure 3. 7 Single layer medium

3.8.2 Two-layer medium

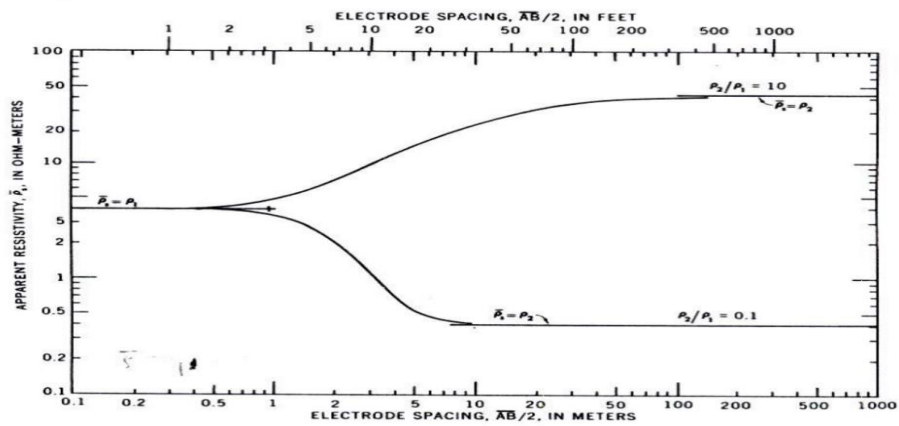


Figure 3. 8 Two-layer Schlumberger curves

If the ground is composed of two layers, a homogeneous and isotropic first layer of thickness (h_1) and resistivity (ρ_1) underlain by an infinitely thick substratum ($h_2 = \infty$) of resistivity (ρ_2) then the sounding curve begins at small electrode spacing with a horizontal segment ($\rho_a = \rho_1$).

3.8.3 Three-layer medium

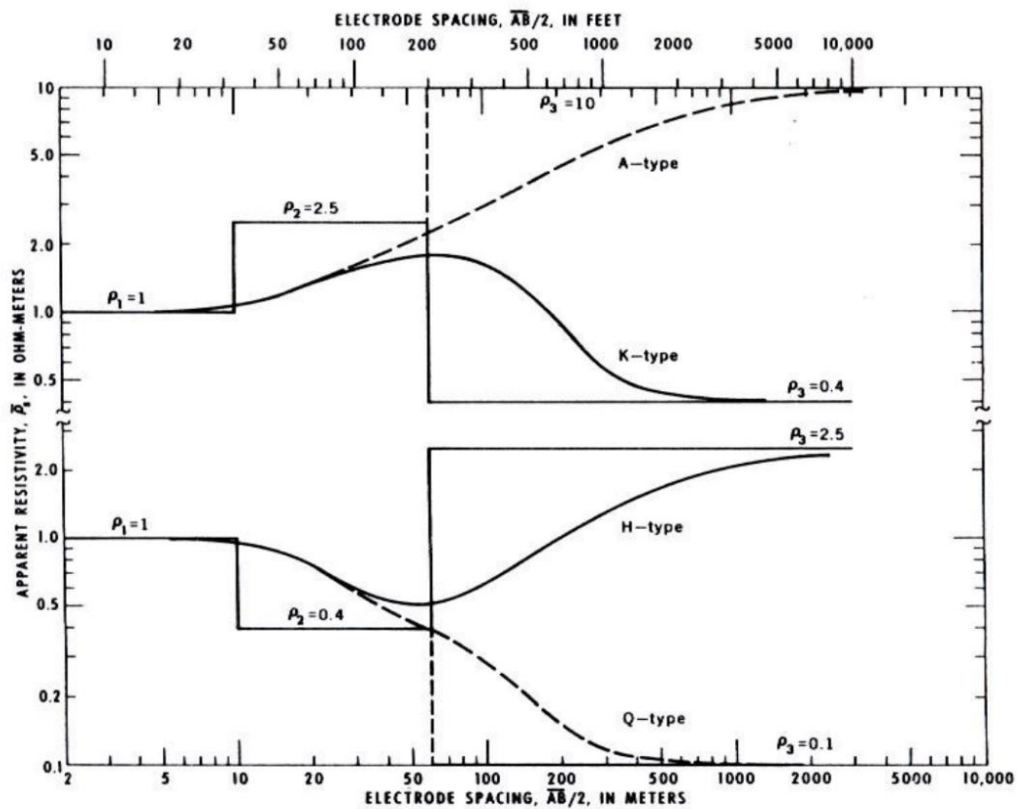


Figure 3. 9 Example of the four types of three-layer Schlumberger sounding curves

If the ground is composed of three layers of resistivities ρ_1 , ρ_2 , ρ_3 and thicknesses h_1 , h_2 , and $h_3 = \infty$, the geoelectric section is described according to the relation between the values of ρ_1 , ρ_2 , ρ_3 . There are four possible combinations between the values of ρ_1 , ρ_2 , ρ_3 . These are:

- I. $\rho_1 > \rho_2 < \rho_3$ H-type curve (minimum type)
- II. $\rho_1 < \rho_2 < \rho_3$ A-type curve (ascending type)
- III. $\rho_1 < \rho_2 > \rho_3$ K-type curve (maximum type)
- IV. $\rho_1 > \rho_2 > \rho_3$ Q-type curve (descending type)

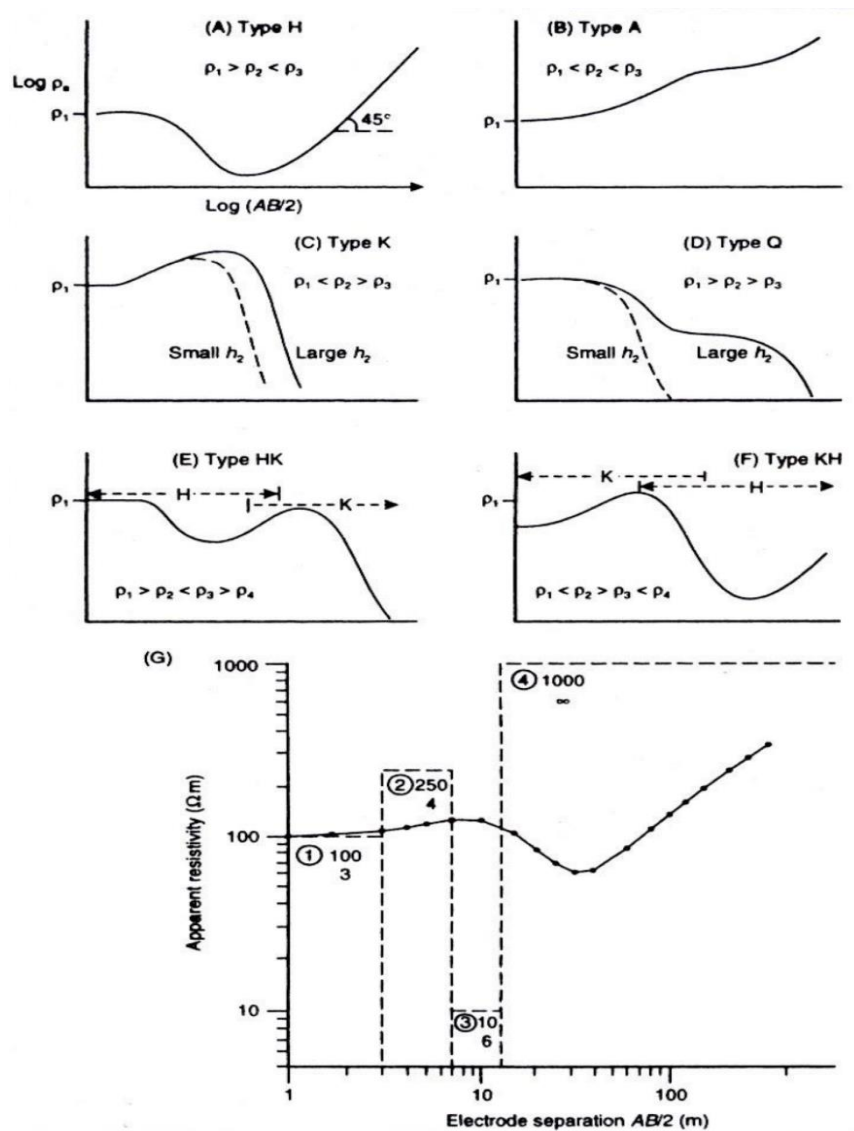


Figure 3. 10 Types of Sounding curves

- Types H and K have a definite minimum and maximum, indicating a bed or beds of anomalously low or high resistivity respectively at intermediate depth.
- Types A and Q shows fairly uniform change in resistivity, the first increasing the second decreasing with depth.



Figure 3. 11 Image of author operating the Syscal Junior Resistivity machine

3.9 Geophysical Data Analysis and Interpretation

3.9.1 Freetown Complex

Table 3.3: Schlumberger Array VES Data for Location A of the Freetown Complex

Client:			Community: St. Ambrose School
Project: Geophysical Survey			Sounding Number: 1
District: Western Area Urban			GPS Coordinate East: 0703735
Date: 1 st August, 2019.			GPS Coordinate North: 0930052
Field Operator:			Elevation: 96m
Schlumberger Array VES Field Data			
No.	AB/2	MN	Apparent Resistivity (ohm-m)
1	1	0.4	613.23
2	2	0.4	775.88
3	3	0.4	826.39
4	4	0.4	780.85
5	4	0.8	764.23
6	5	0.8	713.55
7	7	0.8	545.46
8	10	0.8	378.38
9	10	1.5	345.32
10	15	1.5	227.63
11	20	1.5	330.28
12	30	1.5	221.78
13	40	1.5	247.04
14	40	7.6	165.90
15	50	7.6	147.26
16	70	7.6	978.66

The Vertical Electrical Sounding (VES) data are given above and the corresponding curve is presented below:

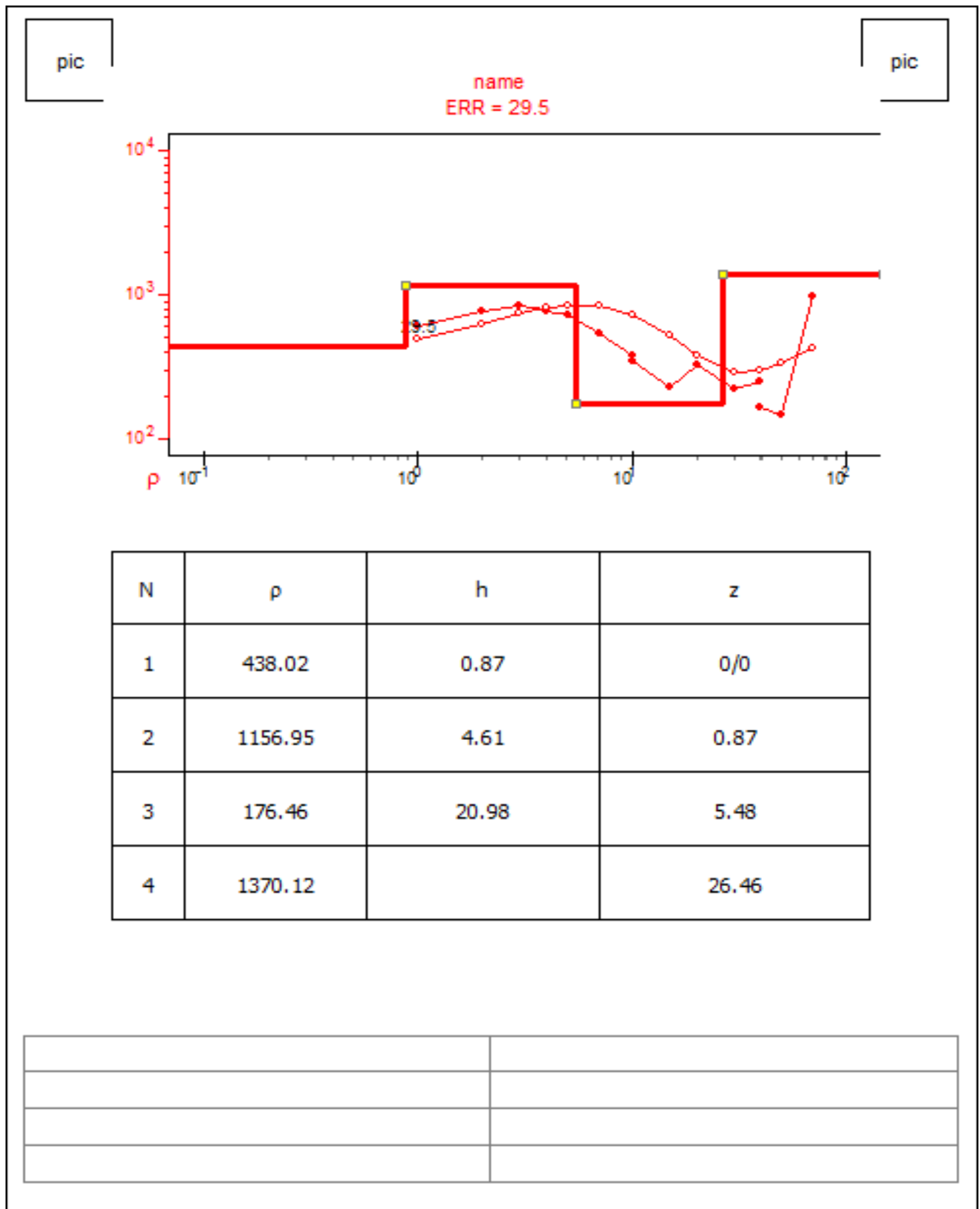


Figure 3.12: Schlumberger Array VES Curve and Model of Location A of the Freetown Complex

The data for Location A of the Freetown Complex (St. Ambrose) shows a four-layer subsurface in which $p_1 < p_2 > p_3 < p_4$. The unusually low apparent resistivity registered in layers 1 and 3 are indicative of the presence of pore electrolyte, possibly groundwater within the regolith top layer and underlying gabbroic rock formations. The equivalent layer thicknesses are 0.87m and 20.98m respectively.

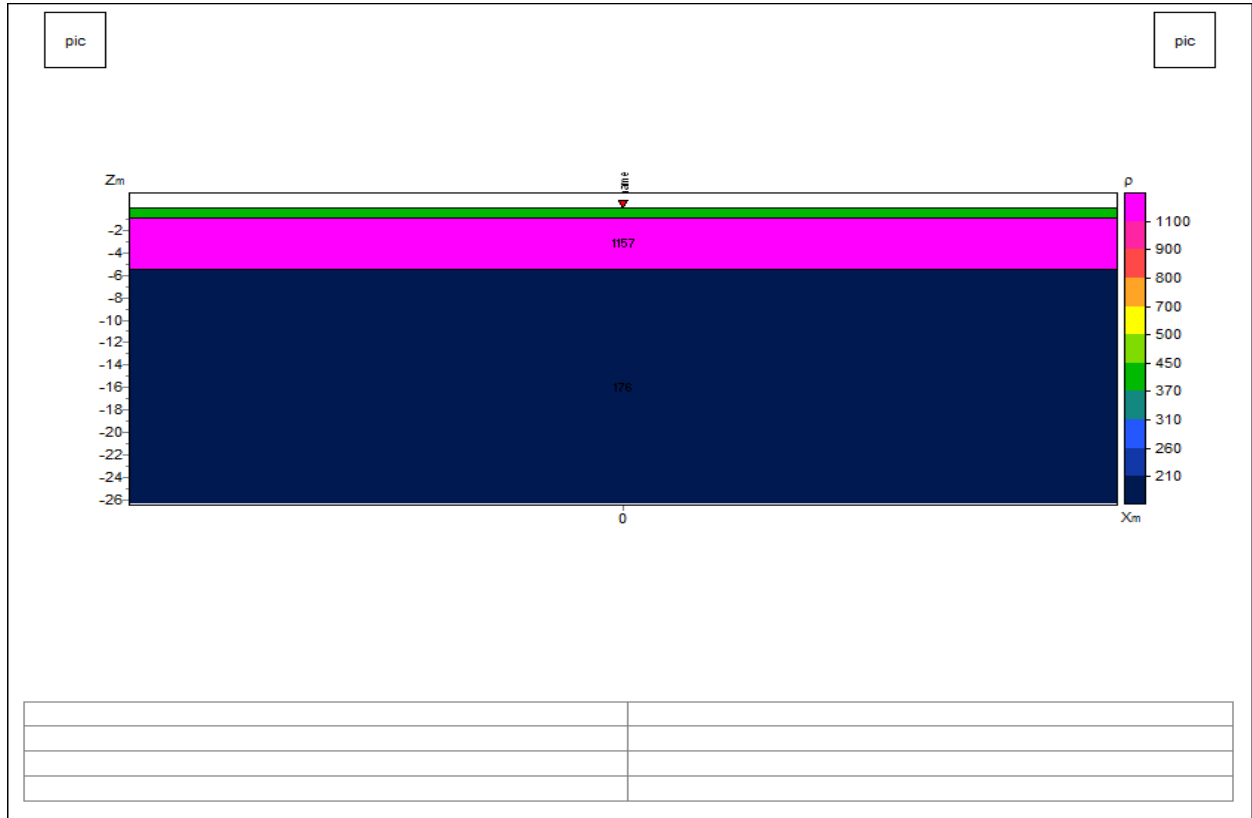


Figure 3.13: Pseudo - section Showing Apparent Resistivities and Layer Thicknesses of Location A of the Freetown Complex

Table 3.4: Selected Promising Points from VES Data

NO.	VES POINT	LAYER	THICK NESS (m)	DEPTH (m)	APPARENT RESISTIVITY (Ohm-m)	POSSIBLE WATER ZONES (m)	MAX DRILLING DEPTH (m)
1	1	1	0.87	0	438.02	5-12	75
2		2	4.61	0.87	1156.95	20-33	
3		3	20.98	5.48	176.46		
4		4		26.46	1370.12		

Table 3.5: Schlumberger Array VES Data for Location B of the Freetown Complex

Client: Lebanese School		Community: Lebanese School	
Project: Geophysical Survey		Sounding Number:1	
District: Western Urban		GPS Coordinate East:	
Date: 18/08/2019		GPS Coordinate North:	
Field Operator:		Elevation: 78M	
Schlumberger Array VES Field Data			
No.	AB/2	MN	Apparent Resistivity (ohm-m)
1	1	0.4	306.4
2	2	0.4	425.6
3	3	0.4	456.9
4	3	0.8	499.6
5	4	0.8	521.6
6	5	0.8	541.9
7	7	0.8	560.1
8	10	0.8	560.6
9	10	1.5	565.5
10	15	1.5	565.5
11	20	1.5	522.7
12	30	1.5	506.1
13	40	1.5	407.7
14	40	7.6	376.1
15	50	7.6	173.4

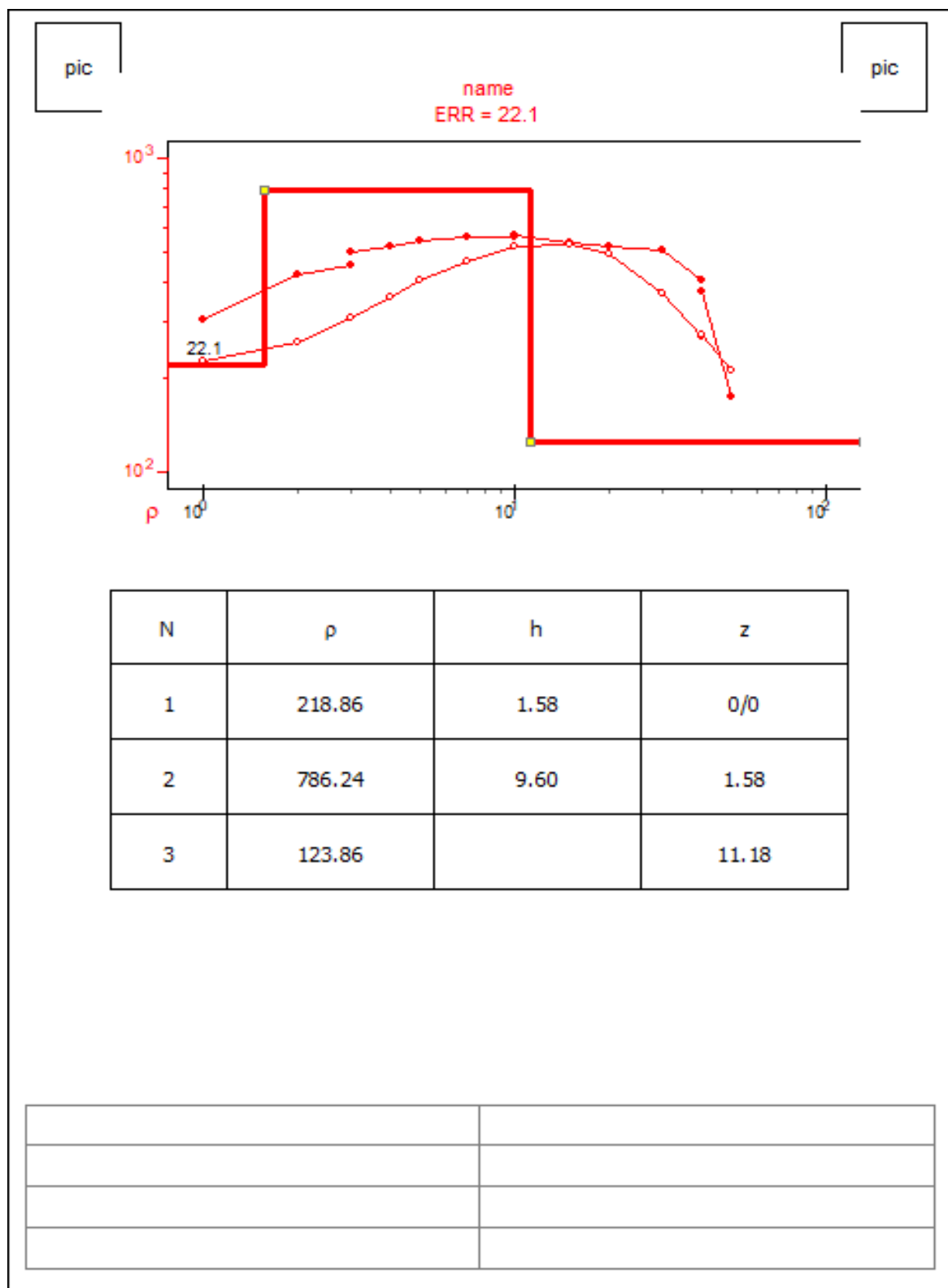


Figure 3.14: Schlumberger Array VES Curve and Model of Location B of the Freetown Complex

The figure displays a 2D cross-sectional plot of a rectangular domain. The vertical axis is labeled Z_m and ranges from -11 to -1. The horizontal axis is labeled X_m and ranges from -10 to 10. A color bar on the right indicates values from 150 to 700. The plot shows a dark blue region at the top (approximately $Z_m = -1$ to -1.5) and a light blue region below it (approximately $Z_m = -1.5$ to -11). A red arrow points to the top boundary at $Z_m = -1.5$. The value 219 is labeled in the dark blue region, and 786 is labeled in the light blue region.

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3.9.2 Granite Greenstone Terrain

Table 3.6: Schlumberger Array VES Data for Location A of the Granite Greenstone Terrain

Client:			Community: Makalie
Project: Geophysical Survey			Sounding Number: 1
District: BOMBALI			GPS Coordinate East: 0727030
Date: 1 st July, 2019			GPS Coordinate North: 0916181
Field Supervisor:			Elevation: 78m
Schlumberger Array VES Field Data			
No.	AB/2	MN	Apparent Resistivity (ohm-m)
1	1	0.4	700.0
2	2	0.4	688.7
3	3	0.4	649.1
4	3	0.8	735.4
5	4	0.8	448.2
6	5	0.8	287.9
7	7	0.8	315.8
8	10	0.8	319.7
9	10	1.5	231.9
10	15	1.5	180.1
11	20	1.5	099.7
12	30	1.5	070.2
13	40	1.5	052.4
14	40	7.6	023.1
15	50	7.6	023.6
16	70	7.6	015.4
17	70	14	017.3
18	80	14	016.7

The VES data is first presented in the form of a table (as shown above) from which a graph of Apparent Resistivity (ρ_a) Vs half the Current Electrode Spacing (AB/2) is plotted.

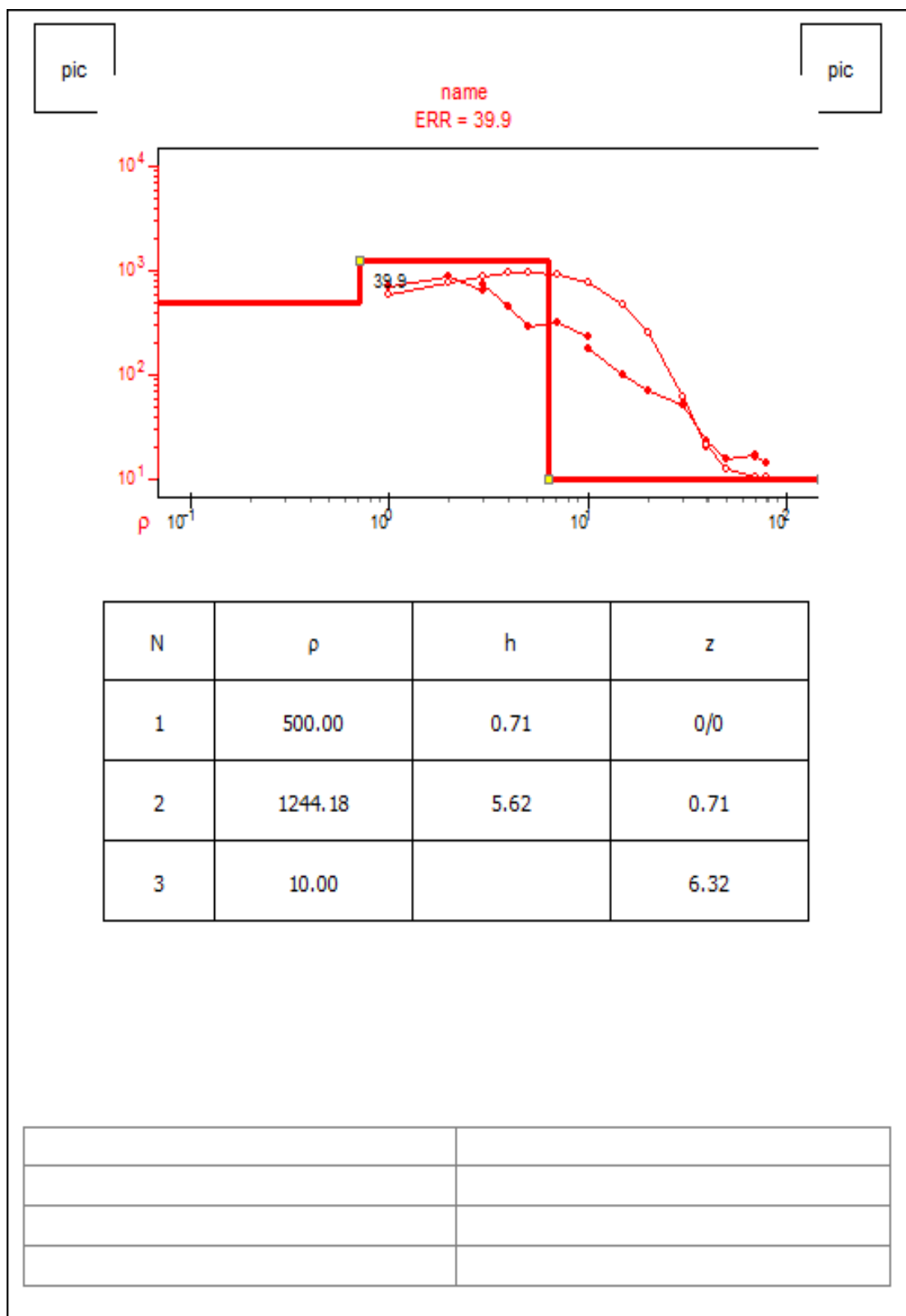


Figure 3.16: Schlumberger Array VES Curve and Model of Location A of the Granite Greenstone Terrain

The data Location A of the Granite Greenstone Terrain (Makalie) shows a three-layer subsurface in which $\rho_1 < \rho_2$ and $\rho_2 > \rho_3$. The unusually low apparent resistivity registered in layers 3 is indicative of the presence of pore electrolyte, possibly groundwater within the fractured bed rock. The equivalent thickness is undefined.

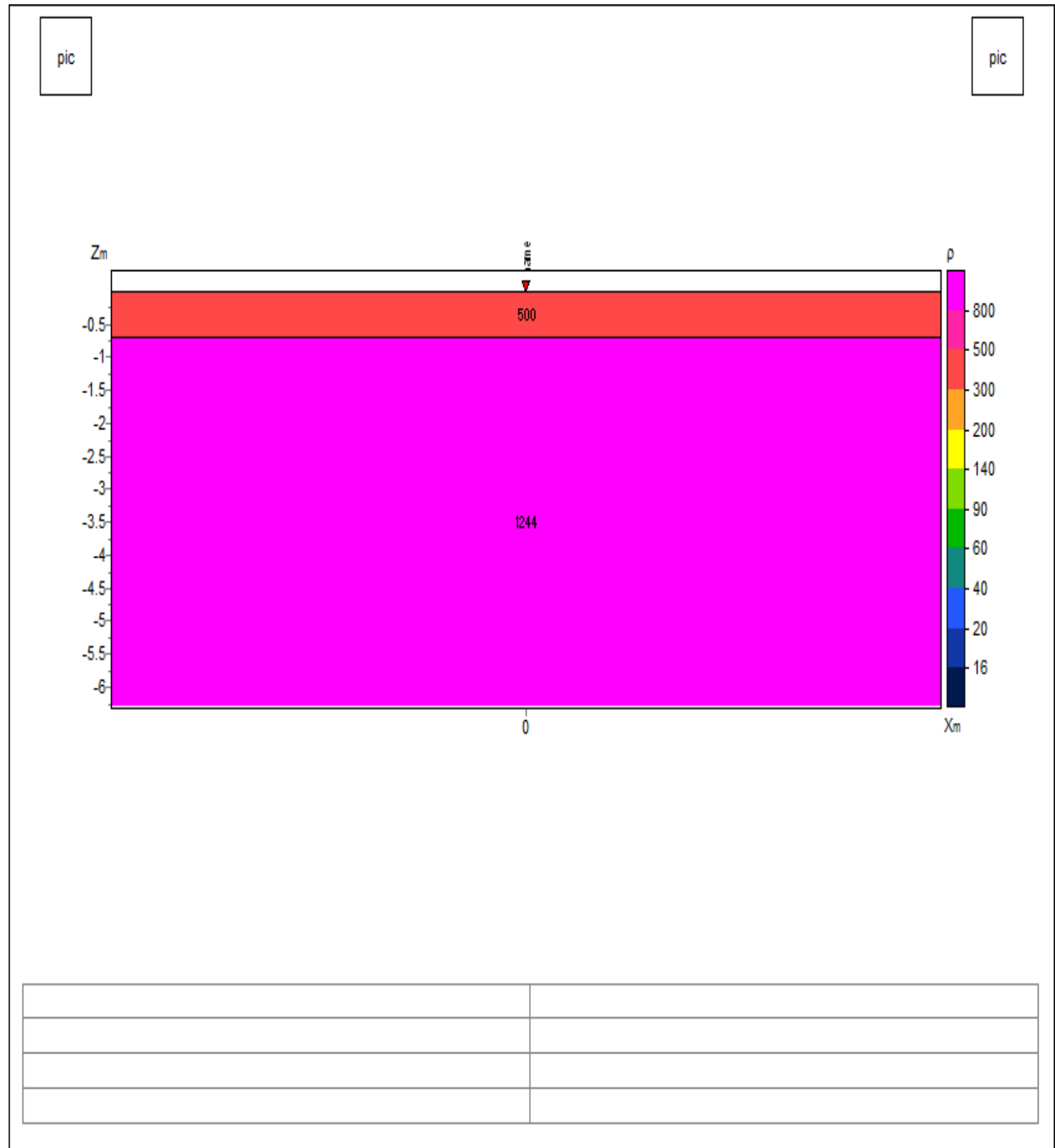


Figure 3.17: Pseudo - Section Showing Apparent Resistivity and Layer Thicknesses of Location A of the Granite Greenstone Terrain

Table 3.7: Schlumberger Array VES Data at Location B of the Granite Greenstone Terrain

Client:			Community: Makeni Government Hospital
Project: Geophysical Survey			Sounding Number: 1
District: BOMBALI			GPS Coordinate East: 0710247
Date: 3 rd July, 2019			GPS Coordinate North: 0913856
Field Operator:			Elevation: 81m
Schlumberger Array VES Field Data			
No.	AB/2	MN	Apparent Resistivity (ohm-m)
1	1	0.4	441.13
2	2	0.4	505.51
3	3	0.4	684.95
4	4	0.4	770.33
5	4	0.8	836.89
6	5	0.8	907.86
7	7	0.8	947.82
8	10	0.8	858.01
9	10	1.5	1056.66
10	15	1.5	1011.08
11	20	1.5	1084.78
12	30	1.5	1217.50
13	40	1.5	1156.33
14	40	7.6	1480.59
15	50	7.6	1297.25
16	70	7.6	1323.02
17	70	14	1578.39
18	100	14	1864.58

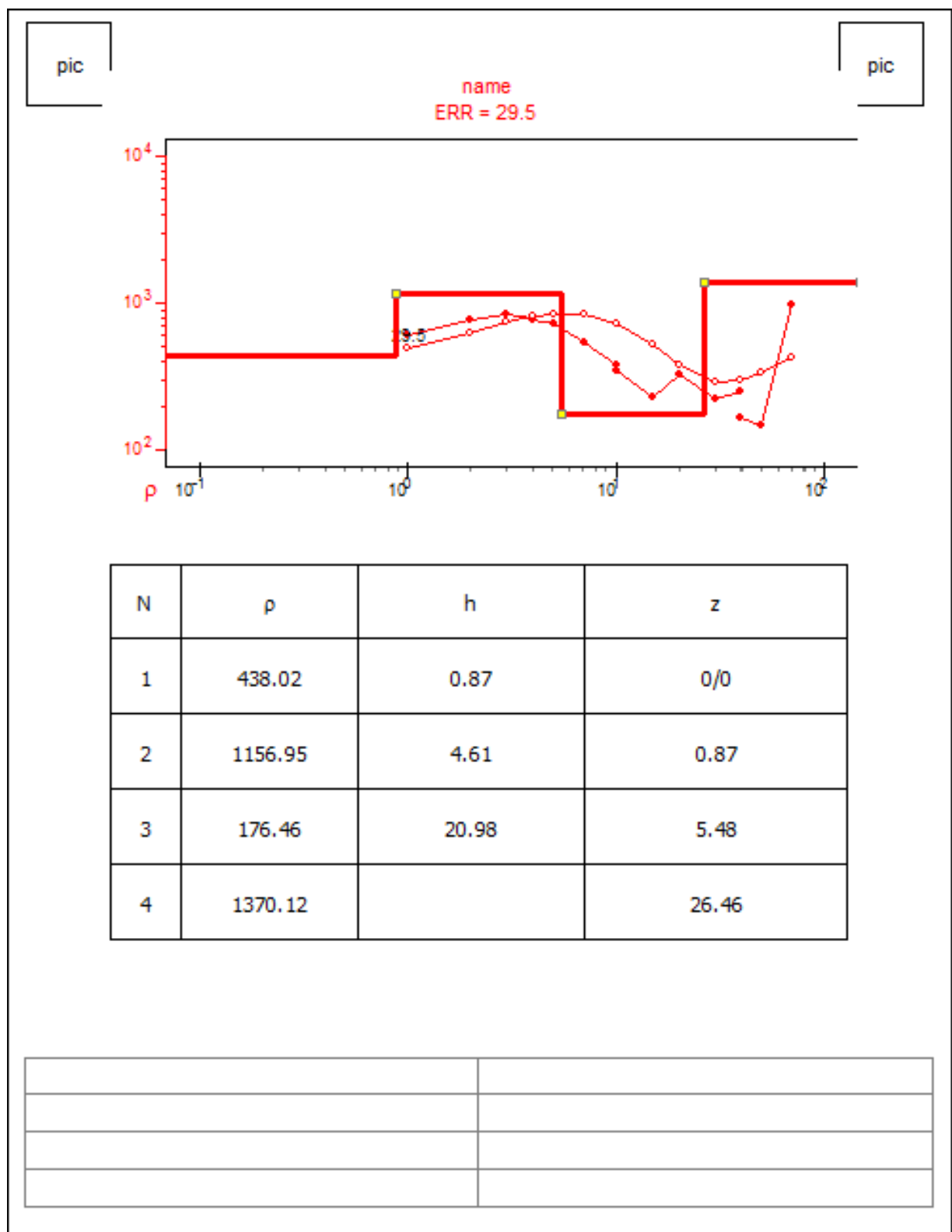


Figure 3.18: Schlumberger Array VES Curve and Model of Location B of the Granite Greenstone Terrain

The data for Makeni Government Hospital shows a four-layer subsurface in which $p_1 < p_2 > p_3 < p_4$. The unusually low apparent resistivity registered in layers 1 and 3 are indicative of the presence of pore electrolyte, possibly groundwater within the regolith top layer and underlying gabbroic rock formations. The equivalent layer thicknesses for layer 1 and layer 3 are 0.87m and 5.48m respectively.

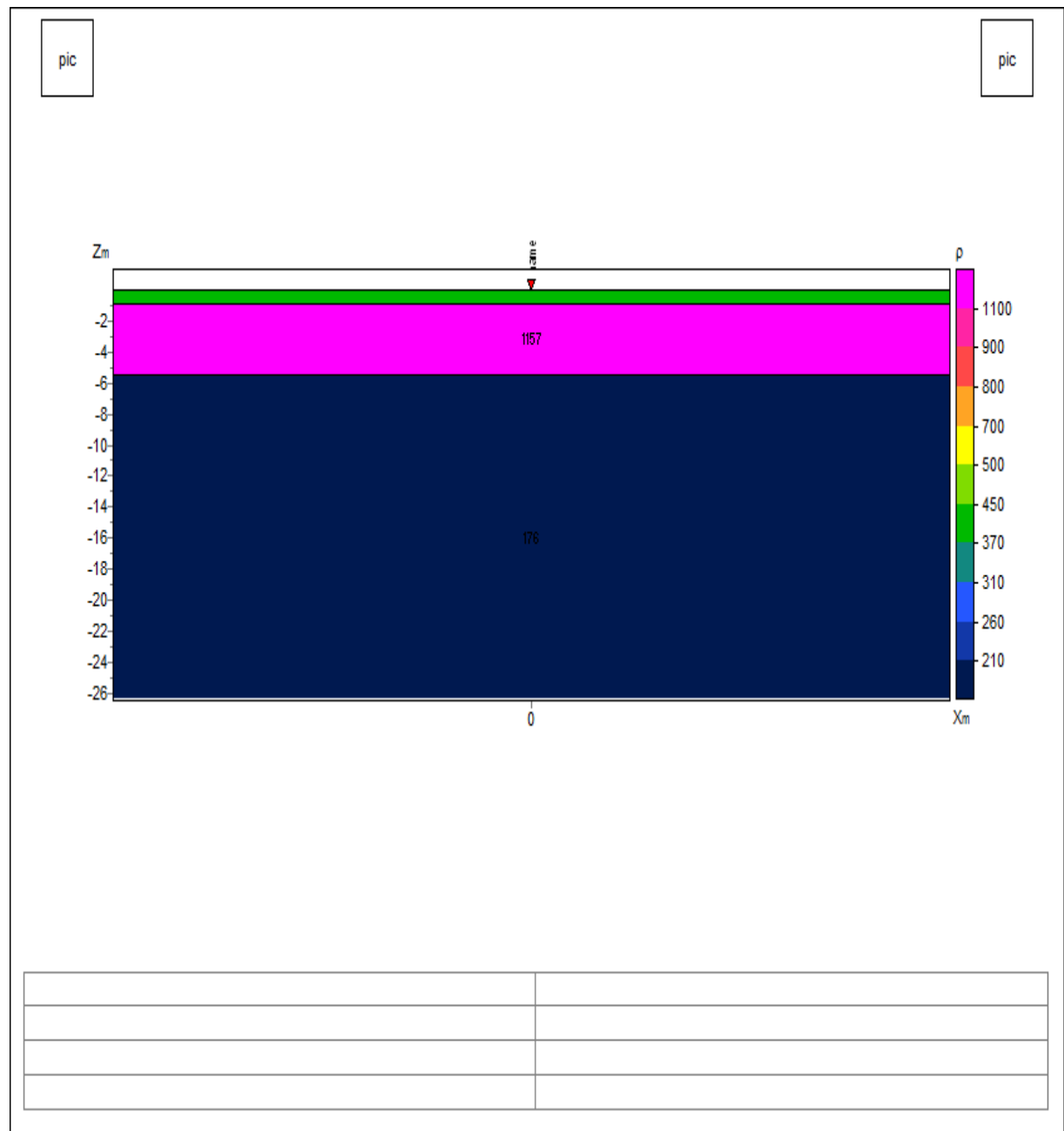


Figure 3.19: Pseudo - Section Showing Apparent Resistivity and Layer Thicknesses of Location B of the Granite Greenstone Terrain

Table 3.8: Selected promising points from VES Data

No.	VES POINT	LAYER	THICK NESS (m)	DEPTH (m)	APPARENT RESISTIVITY (Ohm-m)	POSSIBLE WATER ZONES (M)	MAX DRILLING DEPTH (M)
1	1	1	0.87 4.61 20.98	0	438.02	5-12	70
2		2		0.87	1156.95	20-33	
3		3		5.48	176.46		
4		4		26.46	1370.12		

CHAPTER FOUR

4.1 BOREHOLE DRILLING PROCESSES

There are certain steps involved between the moment you decide to invest in a domestic borehole, and getting water pumped out of the earth. These steps are as follows;

4.1.1 Site Survey

The very first thing that needs to be determined is where the water is, and how to extract it. Before borehole drilling there is need to conduct a Hydro-geological Survey in the proposed site. Generally groundwater is unequally distributed, surveys ascertain suitable sites for exploration of significant quantities of groundwater before carrying out any drilling exercise (Foundation Connect International and WES Consultants, 2004). For all boreholes, the risk of drilling a dry hole should be assessed.

This ensures that the best spot is selected according to the geological data and the preference of the clients. The hydro-geological data, maps, graphs and cross-section profiles obtained from the hydro-geological survey are used in determination of important information such as estimation of drilling depth and Identification of stress areas.

In order to ensure that borehole is hygienic, it is mandatory to site it beyond the minimum distance from existing water points and contaminants (Table 4.1) it must be located up stream of any possible pollutants. It must not be sited where it could be flooded or in depressions with poor drainage. The site must not be liable to erosion and it must not be in an area where pesticides or fertilizers are being used.

Furthermore the nature of shallow aquifers should not be neglected. Host formations having fine or medium grained sized sands normally acts as natural filter for particular pollutants, however, fissured limestone with a high rate of water transmission will carry away pollutants faster and to a distance from source (Wal, 2010).

Table 4.1: Minimum distance of contaminants (m) from borehole (Wal, 2010)

Existing structures	Minimum distance from borehole (m)
Existing public water points (well/borehole)	20
Other existing water wells or boreholes	10
Latrines/Septic tank/soak way	30
Streams, canals, irrigation ditches	20
Buildings	3
Approved or informal solid waste dump, burial ground, lubricant depot	500
Coastline	100

4.1.2 Site Mobilization

Site Mobilization is an important process which follows surveying of site. Mobilization includes the transferring to the job-sites of all equipment, plants, supplies and materials, personnel, and all items necessary for the execution and completion of the work, and shall also include the setting up of all equipment, instruments and all other plants until rendered operable, subject to the confirmation of the Engineer.

4.1.3 Ground Breaking and Drilling

It is only when the rig is completely set up that the workers can begin the operations for the drilling itself. It all begins in the starter hole where a surface hole is drilled down to a specific measurement. Afterwards, the stages of drilling are continued. Once the hydro-geologists have determined the path for borehole drilling, construction of the borehole continues. Different drilling methods are employed based on the geology of the area.

4.1.4 Rock Sampling

The collection of representative subsurface samples is key to the development of relevant and accurate geotechnical evaluations and assessments. As the drilling process continuous, geological rock samples are taken at set intervals. Struck and water rest levels are constantly recorded. This process enables Geologists to estimate the yield of individual aquifers encountered.

4.1.5 Casing

The casing process keeps the well open and protects the earth, similar to the efforts to protect groundwater. The hard metal casing shores up the borehole and extends through both the verticality and the horizontal drilling phases, assuring the long-term integrity of the well from end-to-end. In addition to providing stabilization and keeping the sides of the well from caving in on themselves, casing protects the well stream.

4.1.6 Well Development

Developing a well is the process of removing fine soil particles, drill cuttings, and residual drilling mud from the well screen and borehole annulus in order to establish a good hydraulic connection with the surrounding formation. This development aims at repairing the damage done to the aquifer during the course of drilling by removing additives from the borehole.

4.1.7 Capping And Slab

The final stage of borehole drilling requires the pumping and piping of water from the successful borehole. The end use of the water will largely determine the type of pumping and reticulation system that will be installed (Foundation Connect International and WES Consultants, 2004).

4.2 Drilling Techniques

Several techniques of drilling for water have been developed to suit the type of borehole required and the geological context. Some formations are very hard, such as granite, while others are soft or

unconsolidated such as sand and gravel found in an alluvial setting. Drilling and subsequent well completion should be considered together when deciding which drilling method is most appropriate. Some methods may be faster than others but may result in disturbing the aquifer to the point of reducing yield. For example, if the production zone is completed in unconsolidated sediments, high-pressure drilling fluids may actually cause damage to the aquifer (disturb existing natural packing by suspending and mixing grains). In this case, production wells need to be drilled using a slower, less-disruptive method so that production-zone disturbance is minimized (Wal, 2010).

Some drilling methods for drinking water boreholes are:

4.2.1 Rotary Drilling

Drilling is accomplished by the rotation of a weighted cutting tool. Rotation is achieved through a 'top drive' rotary head travelling down the derrick as drilling proceeds, or by passing a square or hexagonal length of drill pipe (Kelly) through a fixed rotary table. Drilled material is continually flushed to the surface by fluid (e.g. air, water, bentonite clay, polymer, foam or a combination of these) circulating through the hollow drill pipe. The drilling fluids often also help to cool and lubricate the drill bit and pipe, stabilize the borehole formation (prevent collapse) and hold cuttings in suspension when drilling stops. The drilling fluids are re-circulated via settling pits to settle out the cuttings brought to the surface.

4.2.2 Down the Hole Hammer Drilling

This technique allows drilling in hard formations. A cutter with tungsten carbide buttons, fixed directly onto a pneumatic hammer (DTH), is rotated with a hammer action to break and grind the rocks. The hammer works like a pneumatic road drill, using compressed air delivered by a compressor. The air flow raises the cuttings to the surface.

There are two phases, percussion and blowing.

- Percussion: the compressed air operates the piston of the hammer, which strikes the drill bit pressed on the rock; part of the air then escapes into the annular space, carrying the cuttings with it.
- Blowing or removal of the cuttings: the drill bit is withdrawn slightly, so that all the air flow passes around the hammer without operating it, and then escapes into the annular space.

An air operated reciprocating hammer at the bottom of a slowly rotating drill string rapidly strikes the borehole face. The exhaust air immediately removes fractured rock and flushes it to the surface. The hammer face comprises extremely hard inserts that can achieve high drilling rates in hard rock formations (Wal, 2010).

4.2.3 Percussion Drilling

A drill bit at the end of a flexible cable falls down the boreholes to hit the bottom of it by its own weight and is then pulled up, to be left to fall again when the drill bit has been raised high enough to gain sufficient momentum, and so on. In unconsolidated formations the walls of the borehole

have to be stabilized by temporary casing. Cuttings are removed through the bailer system in the drill bit or a separate bailer attached to a separate string (Foundation Connect International and WES Consultants, 2004).

4.2.4 Hand Sludge Drilling

Before the drilling starts, a starter hole is dug. A tank containing mud (a mixture of water and cow dung that has a viscosity large enough to lift up earth particles and simultaneously strengthens the borehole wall, preventing it from collapsing during drilling) is connected to the hole. During drilling the tank supplies the hole with the necessary mud. Moving a lever pipe connected to the drill pipe up and down drives the drill pipe into the ground. A vacuum is created in the drill pipe by closing the top of the pipe with a hand during the upward movement. The top of the pipe is left open during the downward movement, causing earth particles drifting in the mud to enter into the drill pipe. During the upward movement the mud with the earth particles is sucked up in the pipe. The mud flowing out at the top of the drill pipe flows back into the water tank. The earth particles in the mud deposit on the bottom of the tank. The mud flows from the tank back into the borehole in the annular space between borehole wall and drill pipe. The hand sludge method is suitable for soft ground (except for highly cohesive soil, such as heavy clay).

4.2.5 Rotary Sludge Drilling

The principle is similar to that of the hand sludge method with a rotating movement added to the "falling motion" of the drill pipe. This rotating movement is effectuated by an arm attached to the above ground part of the drill pipe. The arm is used to turn the drill pipe 45 degrees at the moment the drill bit hits the bottom of the hole. The drill pipe is then raised, just like in the hand sludge method, by means of a lever. During the upward movement, the arm is used to rotate the drill pipe anti-clockwise returned the pipe to its starting position for the following rotation. The rotation makes the drill bit more effective in cutting the soil in the hole. Therefore this method can be used for harder ground types (especially for medium to heavily compacted soil without stones) than the hand sludge method.

4.2.6 Stone Hammer Drilling

This technique can be locally applied in hard soils without the need of high-tech equipment or highly skilled staff. A galvanized iron pipe is lowered into the borehole, with a cone-shaped drill bit (the hammer head) secured to the bottom of it. The hammer head serves to break the soil layers. To increase the impact of the hammer head, a weight of 80 kg is lowered into the pipe. The weight falls freely from a height of 2 to 3 feet onto an iron floor welded in the pipe at a slight distance from the hammerhead. By allowing the weight to fall repeatedly onto the floor, the hammerhead is hit into the ground. Because the pipe is watertight, the weight falls through an empty pipe, which increases the falling speed and allows the weight to exert a large force. The weight is raised using a lever (bamboo or steel tube) with a counterweight. Apart from crushing hard layers, the cuttings need to be removed as well. This requires the bit to be hollow with steel teeth (the teeth are made

of very hard and durable car-spring steel) welded on the side, so that it can collect the crushed material and soil particles. The pipe and the hammerhead need to be raised repeatedly to remove the material collected in the bit. To minimize the material falling out of the open bit, 2-2.5 feet have to be hammered at a time, so that the soil and stone particles remain firmly compacted in the bit. Just as with a hand auger, the pipe and the head are raised slowly, while turning the pipe. After removal of the pipe, the well is washed with cow dung sludge to plaster the borehole wall and prevent it from collapsing (Foundation Connect International and WES Consultants, 2004).

4.2.7 Hand Drilling

The hole is formed by turning around an auger. The auger consists of a horizontal handle connected to steel pipes that are screwed to each other with at the bottom a drilling bit. Turning around and pressing down the handle causes the drilling bit to turn and be pressed downwards as well. When the drilling bit turns and is pressed downwards, it grabs the soil and takes it. Each time when the drilling bit is full of soil, the auger is removed from the hole. When the drilling bit is outside the hole, the soil is removed from the drilling bit. Then the auger is returned back into the hole. When the hole becomes deeper new steel pipes are added to allow the auger to reach deeper. When the water table is reached a smaller drilling bit is used and a temporary casing is installed. Hand drilling is suitable for soils that are not too hard and where the water table is within the maximum depth that can be reached with hand drilling, which is approximately 25 m.

4.2.8 Jetting

Water is circulated down a hand-held pipe. The water flowing out of the bottom of the pipe fluidises the soil, allowing the pipe to sink. The loosened soil is carried to the surface through the annulus formed between jetting pipe and the wall of the hole. This technique is often used in combination with the use of a mud and temporary casing. Jetting is mainly suitable in soft soils. Holes of up to 40 m can be realized with jetting (Foundation Connect International and WES Consultants, 2004).

4.3 Borehole Logging And Data Interpretation

Borehole Logging: Is the recording of geophysical and geologic data recovered from a borehole. Geophysical borehole logs can be used in conjunction with drill cuttings, sidewall samples, and cores to establish the geologic succession in the well. This information can then be interpreted geologically. The logs can be used to estimate formation porosity, jointing, fluid properties, hydrocarbon saturation, and formation pressures. Water wells are often logged by devices to detect water flows, levels of inflow, and such water properties as temperature and electrical conductivity (Allaby, 2013).

4.3.1 Importance Of Drilling Logs

It is very important to determine the exact location (depth) of permeable layers (aquifers), and the location of any impermeable layers in the borehole.

To do this, simple but accurate drilling logs should be created. A drilling log is a written record of the geological formations (soil layers) drilled, according to depth. Soil samples should be taken at regular depths (e.g. every meter) and described during the drilling process. The soil description is then recorded in the form of a drilling log. The drilling log will help to determine:

1. The right aquifer for installation of the well-screen
2. Depth and length of the well-screen
3. Depth and thickness of the gravel pack
4. Location of the sanitary seal

Database

Besides the direct use of drilling logs in the field, drilling logs are also very important to record the hydro geological information of the drill site. For example, if at a later stage other wells have to be drilled in the same village or area, it is very useful for the drilling team to know the geology, depth of the water table and likely total drilling depth. Previous drilling logs are an essential source of information for these purposes, before the new drilling starts. This information could be important for the choice of the drilling equipment. The drilling logs can be kept together in a file, which is called a database. By taking care to record and preserve good drilling logs, the drilling team will present itself as a professional and skilled team to their clients (Wal, 2010).

4.3.2 Taking Soil Samples

The first step in making a drilling log, is to take representative samples of the soil (geological formations) encountered in drilling. This means: the sample should be a pure piece of the layer that is being drilled at the moment of sampling (avoiding mixing the sample with soil from other layers!). Samples should be taken every meter and/or every time the formation (soil) type changes. The samples should be put on a plastic sheet and write down the depth if the samples are not immediately described during the drilling process.

4.3.3 Drilling Depths

The final drilling depth is reached when at least 4-6 meter has been drilled into a water bearing permeable sand, gravel layer, weathered layer or fractured zone at an appreciable depth. It is then recommended to drill two extra meters for installation of the sump and as a reservoir for particles in the borehole, to settle down in, during the well casing installation process.

4.4 Filling in The Drilling Logs

- Samples should be described during every break in the drilling process and must be written down; the depth, name and characteristics on the drilling log.
- However, for those who cannot write, the formation column should be hatched and the difference between permeable, semi permeable and impermeable layers by different hatching should be shown.
- Now the well-screen length and depth can be determined.
- Once the well-screen and PVC casing are hatched in the first column, the exact depths for the annular backfill (i.e. gravel pack, sanitary seal and cuttings) can be determined by use of the drawings on the drilling log.



Figure 4. 1 Cross-section of Group members on a drilling site

4.5 Borehole Log Data

Table 4.2: Borehole log data for Location A of the Freetown Complex (Saint Ambrose)

CONTRACTOR		WINGIN		CLIENT			
LOCATION		Saint Ambrose School, Allen Town		DEPTH OF BOREHOLE		50m	
				START DATE		6 th August, 2019	
BOREHOLE REFERENCE NO.		1		COMPLETION DATE		9 th August,2019	
DEPTH STRUCK WATER		20m, 25m, 30m		DRILLING METHOD			
DRILLING DEPTH		DRILLING PROGRESS			SAMPLE DESCRIPTION		
DEPTH (m)	INTERVAL	FROM	TO	PENETRATION RATE (m/min)	SAMPLES	DRILLING DIAMETER/CHANGE OF BIT (inches)	
0-5	5	14:00	14:10		Weathered Gabbroic Rocks Literites with high water potential (Water zone)	10''	
5-10	5	14:11	14:20				
10-15	5	14:20	14:30				
15-20	5	14:31	14:50				
20-25	5	15:02	15:10				
25-30	5	15:12	15:15			7''	
30-35	5	15:15	15:40		Gabbroic Rocks with Fractues		
35-40	5	16:26	16:37				
40-45	5	9:37	9:49				
45-50	5	9:50	10:00				

First water strike: 20m

Second Water strike: 25m

Table 4.3: Borehole Log Data for Location A of the Granite Greenstone Terrain (Makalie)

CLIENT							
LOCATION		Makalie Town		DEPTH OF BOREHOLE		50m	
				START DATE		06/07/19	
BOREHOLE REFERENCE NO.		1		COMPLETION DATE		07/07/19	
DEPTH STRUCK WATER		20-30m and 35-40m		DRILLING METHOD		DTH	
DRILLING DEPTH		DRILLING PROGRESS		GEOLOGICAL BOUNDARIES			
DEPTH (m)	INTERVAL	FROM	TO	SAMPLE DESCRIPTION		DRILLING DIAMETER/CHANGE OF BIT (inches)	
0-5	5	13:14	13:17	Brownish-red loose soil		12'' DTH bit	
5-10	5	13:20	13:24	Wet reddish-brown loose + laterite			
10-15	5	13:26	13:30				
15-20	5	13:45	13:49	Greyish black clay		8'' DTH bit	
20-25	5	14:12	14:16				
25-30	5	14:25	14:31	Partially weathered granitic rock			
30-35	5	14:52	14:56				
35-40	5	15:25	15:29	Fractured granitic rock			
40-45	5	15:30	15:37				
45-50	5	15:40	15:45				

4.5 Borehole Construction

4.5.1 Borehole Design

A fundamental step in achieving an efficient well design is to complete a drilling log, during the actual drilling process. The geologist must describe the drilling samples at least every 'break', as

samples can easily get lost or being. From the drilling logs the exact depth and length of the well screen and the depth and thickness of the gravel pack and sanitary seal can be determined.

Borehole diameter

The internal diameter of the PVC well casing is selected to fit the outer diameter of the pump that is going to be installed. The drilled diameter of the borehole in turn depends on the outer diameter of the PVC well casing. For the diameter of the borehole, consideration of the following parameters is vital;

- The drilled diameter of the borehole should be at least 2-inch larger than the outer diameter of the PVC well casing to be able to place the gravel pack and sanitary seal.
- If this rule is not applied and the space between the PVC well casing and the borehole wall is too small, it is almost impossible to place the gravel pack and sanitary seal at the correct depth.
- Moreover the backfill may get 'stuck' on its way down (this is called 'bridging') and end up in the wrong position (Foundation Connect International and WES Consultants, 2004).

Borehole depth

When the final depth for the bottom of the well-screen in the aquifer is reached an additional two meter should be drilled. This is to allow for fine soil particles, suspended (mixed with the water) in the borehole, to settle prior to and during the installation of the well-screen and casing (by doing so, the determined well-screen depth can be maintained), and to accommodate a sump.

Completion of the borehole

Finally, before the drilling pipes are lifted, the fluid-drilled borehole should be flushed with clean water to remove all fine particles that are suspended in the hole. If this is not done, the particles will settle at the bottom of the well (influencing the final installation depth) or enter the well-screen during the installation of the well casing, already filling up the sump.

Measuring tools

Before the actual well construction starts, it is important to double-check the final depth of the borehole with a measuring tape. Sometimes the length of drill pipes (which are used during the drilling process for measuring) can vary, or there is confusion among the drilling team members about the number of drill pipes already in the ground. For the latter it is important to count all your drill pipes beforehand. Depth measurements should be done with a measuring tape or specially made measuring tool.

A cheap and accurate measuring tool is easily made. A 1 meter length of reinforcement bar, bent into a loop, is attached to a long piece of a 4mm thick rope. At exact 1 meter intervals knots are tied

in the rope. The final depth of the borehole or depth of backfilling can be measured by counting the knots (Wal, 2010).

4.5.2 Steps in Borehole Construction

1. Preparations

All materials needed for the installation and backfilling should be prepared. Measure out the effective length of the PVC pipes and cut the last pipe to a length, allowing 1 meter to be left above ground level after installation.

Centralization of the well screen

To prevent the slots from becoming blocked with clay due to scraping of the well screen against the borehole wall during installation, the well-screen should be self-made spacer rings attached to centralize. Centralizing the well-screen in the borehole also allows the gravel, the filter screen pack to settle equally around the screen, leaving at least 1-inch of gravel all around the well-screen.

Centralization can be achieved by attaching spacer rings or centralizers with an interval of every 3 meter around the well-screen.

The spacer rings can be made of PVC rings, which can be attached on 4 sides around the well screen.

2. Installation of the PVC pipes

A practical method of lowering the PVC pipes into the borehole is to use a rope. One end of the rope is attached to the drill rig and the other end is wrapped three times around the pipe to form a self-closing loop. The rope is used to prevent the casing and screen slipping into the borehole while adding a new length of pipe. Install all the prepared pipes, and leave 1m of pipe above ground level so that the well-screen is placed at the correct depth.

3. Cleaning and flushing the well-screen

When the well-screen has been installed at the correct depth, the pipes and screen should be flushed in the case of fluid drilled boreholes. Pour water into the PVC pipes and allow the dirty water to overflow out of the borehole. If the added water only enters the well slowly (or not at all), this could indicate blockage of the well-screen slots by clay or fine material from the borehole wall. Extra water pressure in the casing and well-screen should then be created by adding a plunger or surge block (or simply a plug of cloth), which is then moved up and down in the casing. The process will be repeated until the water directly flows away when added. Continue flushing with clean water until the water which is coming out of the borehole is clean. Only then the gravel pack should be installed.

4. Insertion of permanent casings, screens and gravel pack

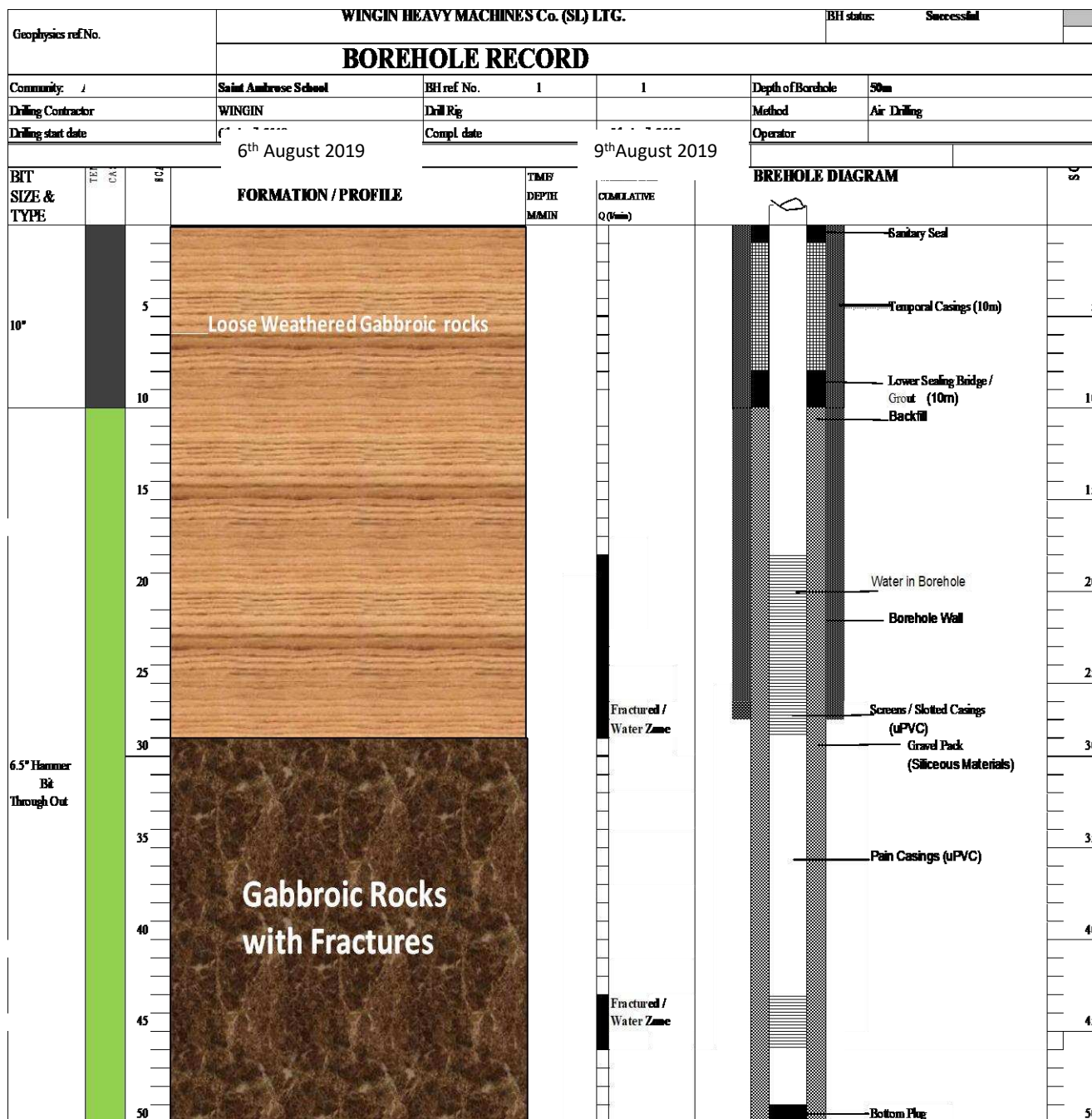
Large aggregates need to be inserted in the annular space, between the casing and the borehole wall in order to fix the bottom of the casing.

Unstable casing may be necessary to grout the bottom of the borehole casing. The grouting at the bottom of the casing is called the bottom seal. Grouting involves injecting cement slurry into the annulus between the casings and the wall of the hole. This can be done either manually or with the tremmie pipe. A tremmie pipe is a hose through which the cement can travel down to the desired depth. The use of a tremmie pipe is a must when the lining has screens to avoid the danger of the cement clogging up the slots. The cement slurry should be mixed in a clean and empty container, be prepared by mixing 24 litres of water per 50 kg of cement, and mixing should be done vigorously to obtain a uniform slurry. Grouting should be done immediately after installing the permanent casing lining and be allowed to set overnight. The bottom seal should have a minimal thickness of 1 m.

When the casing does fully reach the desired depth or the casing is possibly unstable, a minimum of 2 m is advised. The required annulus for grouting is minimal 50 mm, or 2 inch. For grouting also, Bentonite (thick clay) can be used instead of cement. It is more durable, but also much more expensive. In practice it is therefore hardly used. When there is temporary casing, grouting of the permanent casing should be alternated with partial pulling out of the temporary casing. This is to avoid cementing the temporary casing. If grouting is to be done the drilling team should measure the exact depth of the borehole before grouting starts. For the measurements of the depth of the borehole a tape measure with a weight can be used (Wal, 2010).

Table 4.4: Problems and solutions regarding permanent casings, screens and gravel pack

Problem	Solution
After the permanent casing has been installed, a soft, collapsing formation is encountered at greater depth.	Probably the hard rock had not been reached when the casing was installed, or a strongly weathered fracture was encountered. There are two solutions: 1. Sufficient water had been trapped in the overburden. The hole can then be backfilled up to the competent rock or the casing (in which case a seal is needed). 2. The hole is drilled further and the entire hole is cased down to the bottom. This will probably be with a 4 inch casing. The water strike section needs to be screened.
The casing does not reach the desired depth.	When the difference is considerable (more than 0.5 meter) try blowing out the obstacle, using a hammer that fits within the casing. If this fails, take out the casing and go down with the same hammer used previously to crush the obstacle. When the difference is moderate (less than 0.5 m) fine sand (possibly mixed with gravel) should be inserted down the annulus space to make a base on which the cement seal can be made. This avoids cement leaking through and blocking the aquifer. In addition, the grouting should be two meters to ensure proper stability.
The permanent casings break during installation	When recovery is not possible, install casing with a smaller diameter (probably all the way down the hole) and fill the space between the two linings with gravel.
One or more pieces of casing fell into the hole	Sometimes the Driller has special equipment to fish out objects out of the hole. If these are not available, often it is tried to screw the casing to other casing in the hole. An alternative is to attach a bag with cement to the hammer and push it through and past the piece of casing. The cement will swell due to the contact with water. The casing can then be pulled out as it is stuck behind the cement bag.



Gravel for gravel pack Cement for grouting Bentonite for grouting Installation of grout seal Cleaning & development Centralisers fitted Safety cap fitted Backfill aband. BH Disinfection date Platform construct. date Platform transport adjust. Cut access to site			M	Remarks: We stop at 50m because of sufficient and sustainable water Prepared by: WINGIN HEAVY DUTY MACHINES Co. (SI) LTD. Certified: MORLAIKANU Approved: Approved:
	50		KG	
			M	
	10m		M	
	1:03		HRS	
			x	
Yes		No		(Contractor)
Yes	x	No		
Yes		No		
				Approved:
				Approved:
				KM
				KM

Figure 4.2: Saint Ambrose School Borehole diagram – Freetown Complex Location A

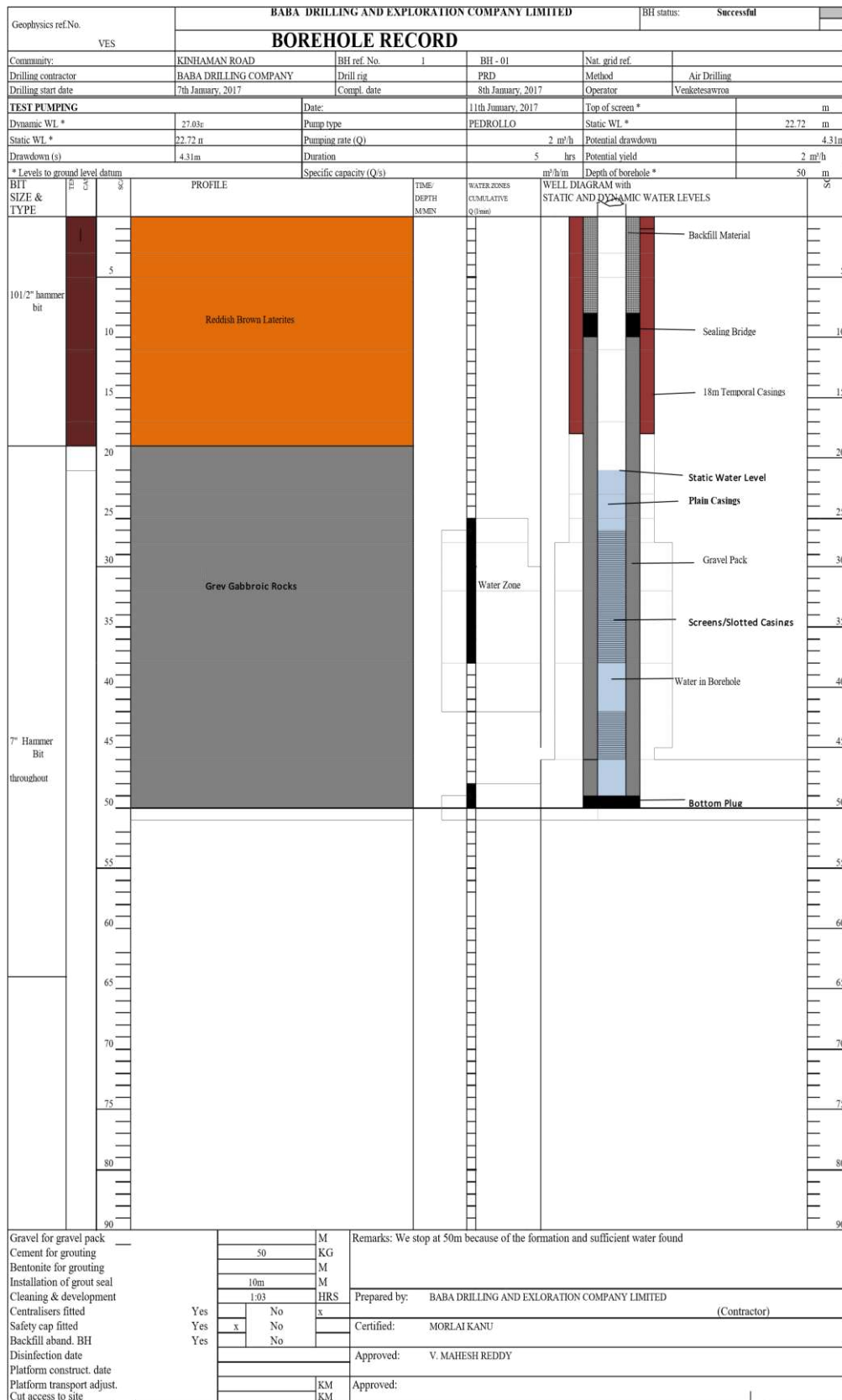


Figure 4. 3 Lebanese School Borehole diagram-Freetown Complex Location B

Table 4.5: Installation of Casings and Borehole Completion of Location B of the Granite Greenstone Terrain

Casing Material: Poly-Vinyl Chloride (PVC)						
Diameter			6 Inches			
INSTALLATION			SEE BOREHOLE DIAGRAM (Not to scale)			
SCREENS AND PLAIN CASINGS						
	From	To				
Plain	0.72	30				
Screens	30	33				
Plain casings	33	36				
Screens	36	42				
Plains	42	50				
Screens	50	56				
Plain	56	59				
Screen	59	62				
Plain + Bottom Plug	62	65				

4.6 Borehole Development

4.6.1 Introduction

After casings and screens and the gravel pack have been installed, the borehole needs to be cleaned. Often it is full with dirt resulting from the drilling. This cleaning of the water is called well development. This is often done by lowering the drilling pipes with hammer to the depth of water strike. Air is compressed down through the pipes. The air will blow the dirt, together with water out of the hole. This is the time when the airlift yield is determined. This is the amount of water that is blown out of the hole. It is an indication for the yield used for the pumping-test. Before the Drillers leave the site, the hole has to be properly sealed off and capped.

The main objective of well development is to remove finer materials like silt, clay, sand and drilling fluid residues from the borehole and immediate surroundings (gravel pack and aquifer). The gravel pack and the aquifer are cleaned and opened up so that water can flow into the well more easily and the water is not murky (filled with sediments)

Well development should take place after the gravel packing but before the hole is back filled.

Several techniques are available for well development and sometimes a combination of these techniques is used to get the best development results. Useful techniques are:

- Surge block or plunger
- Discontinuous pumping (start-stop cycle pumping)
- Continuous pumping with large flows

If development is done properly it can increase the yield of the borehole by 20-30 %.

4.6.2 Depth of Borehole Development

The first criterion influencing the decision of the depth of well development, is the depth and type of the aquifer. Each development step needs to last at least until the water is cleared.

If the aquifer is in the hard rock the following sequence is proposed:

1. Development (just above) the bottom of the hole
2. Development at the fracture
3. Development at the bottom of the hole

If the aquifer is in the overburden and screens have been placed the following sequence is proposed:

1. Development (just above) the bottom of the hole
2. Development 2 m above the screens

4.6.3 Pressure of Borehole Development

It is very difficult to decide on the right power. As a rule of thumb, the initial power needed to overcome the pressure of the water column 97 kPa (970 mbar) per 10 m, is usable during well development.

IMPORTANT: Development with too much power can disturb the aquifer and clog it up. Additionally, when developing with a powerful compressor, the pressure can build up too fast within the hole and the PVC screens and even the plain casings can break, making the borehole unusable.

A hole can in theory, be blown dry during air development. This should be avoided at all times as the aquifer can be badly damaged.

To gain time on drilling and gain money on diesel consumption a small type compressor can be used for development. It does take 2 to 3 times longer, but the drilling rig can continue to the next site and less (and less qualified) personnel are needed.

4.6.4 Re-development

After a well has been in use for several years and the yield decreases (becomes less), re-development of the well can be considered. Re-developing a well is easily performed using surge block and discontinuous pumping.

4.7 Pumping Test

Borehole pumping tests are usually used to determine aquifer parameters. By pumping out water at specified rates, stress is applied to the borehole and the response from the aquifer is used to estimate aquifer parameters (Tonder, et al., 2002). The estimated parameters are then taken as representative values for the aquifer system (Freeze & Cherry, 1979). Typically three types of such tests exist; namely, constant discharge test, stepped discharge test and recovery test. From these tests, Theis and Cooper-Jacob formulas can be applied to estimate aquifer parameters. Factors affecting the choice of pumping test are provided in Table 4.6 The choice of formula to be used depends on the type of aquifer, whether confined or unconfined (Freeze and Cherry, 1979).

4.7.1 Stepped discharge test

Stepped discharge tests are used to estimate borehole efficiency and optimum yield. The borehole is subjected to pumping in equal time steps. After every time step, which is usually 1 or 2 hours, the pumping rate is increased by a fixed increment. The stepped test is good for determining the short-term relationship between yield and drawdown of a borehole. The test is limited to determine borehole and not aquifer characteristics. Hence the stepped test usually foreruns and provides estimation data for the constant discharge test (ICRC, 2010).

4.7.2 Constant discharge test

Constant discharge tests are carried out in order to estimate aquifer parameters, nature and boundaries (Hiscock, 2005). These are the pumping tests used in aquifer analysis. The borehole is subjected to prolonged pumping, for 12 to even 72 hours, at a constant sustainable rate. For both tests, a plot of time vs. drawdown is made, which is then matched with the (Theis, 1935) type curve or the Cooper-Jacob (1946) straight line solution. From the curve matching, T and S can be determined.

$$s = \frac{2.3Q}{4\pi T} \log \frac{t_2}{t_1} \quad (4.1)$$

Where s is the drawdown, T is transmissivity, t is time and Q is discharge of the well.

But when $\log \frac{t_2}{t_1} = 1$, Δs is drawdown difference per log cycle, then the equation rearranges to

$$\sim 69 \sim$$

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (4.2)$$

Storativity (S) is given by;

$$S = \frac{2.25Tt_0}{r^2} \quad (4.3)$$

Where t_0 is the value of t at the intercept and r is the distance from the discharging well

4.7.3 Recovery test

After pumping is stopped, the water levels in the borehole and aquifer start to rise again which is called recovery or residual drawdown (Freeze and Cherry, 1979). Aquifer parameters can be estimated from the rate and pattern of recovery (Hiscock, 2005). The recovery test is more reliable than the other two because recovery takes place at a constant rate while on the other hand, it is very difficult to maintain a constant pumping rate in the real field. The recovery test is also usually used to verify the aquifer parameters estimated in the constant rate test (ICRC, 2011). The Theis (1935) equation used to estimate transmissivity (T) is as follows

$$T = \frac{2.3Q}{4\pi\Delta s'} \quad (4.4)$$

Where, Q is the rate of discharge in m^3/day and $\Delta s'$ is the residual drawdown difference per log cycle of t/t' (t is time from beginning of pumping and t' is time from the end of pumping in m).

Constant Discharge Pumping Test Data for Location A of the Freetown Complex (Saint Ambrose)

Community: SAINT AMBROSE SCHOOL

Date: 20/08/2019

Client:

Duration Of Test: 3hrs

Time: Start: 13:45

Test Conducted by: WINGIN

Borehole Ref. No. 1

Depth of Borehole: 50m

Static water level: 17.28m

Pump setting: 48m

Table 4. 6: Constant discharge pumping test data for Saint Ambrose

Time (Minute)	Water level (m)	Drawdown (m)	Cumulative Drawdown (m)	Discharge (m ³ /h)	Recovery (m)	Observation
0	17.28	0	0	Constant discharge of 3.17m ³ /h	47.52	Clean H ₂ O Pump out
1	19.61	2.33	2.33		47.06	
2	23.33	3.72	6.05		46.81	
3	23.73	0.4	6.45		46.53	
4	24.75	1.02	7.47		46.27	Brownish water pump out
5	25.56	0.81	8.28		46.10	
10	35.97	10.41	18.69		45.28	
15	39.73	3.76	22.45		44.29	
20	47.52	7.79	30.24		43.30	
25					42.65	
30					41.54	
35					41.40	Purely clean and cool water pump out
40					40.80	
45					40.24	
50					39.45	
55					38.96	
60					38.34	
70					37.39	
80					36.33	
90					34.98	
100					33.60	
110					32.79	
120					31.27	
140					29.49	

Calculations Of Discharge (Q) / Yield

Discharge (Q) in Litres /Hour

$$Q = \frac{\text{liters} \times 3,600}{\text{time (sec)}}$$

Where:

- litres = 22
- Average time = 25 secs.

$$\text{Therefore } Q = \frac{22 \times 3,600}{25} = 3,168 \text{ lit./hr}$$

$$Q = 3.2 \text{ m}^3/\text{hr}$$

Or
0.88lit./sec

Constant Discharge Pumping Test Data

Community: MAKENI GOVERNMENT HOSPITAL

Date: 23/07/19

Client: WINGIN HEAVY DUTY MACHINE COMPANY (SL) LTD

Time: Start: 10:45

Depth of BH: 65m

End: 14:45

Pump Setting: 50m

Borehole Ref No. 1

Static Water Level: 3.42m

Table 4. 7 Constant discharge pumping test data for Makeni Government Hospital

Time (Minute)	Water level Below Datum(m)	Discharge Rate (m ³ /h)	Recovery (m)	Observation
0	3.42	Discharge rate 4,500lts/hr.	13.34	Clean water pumped out
1	4.54		13.10	
2	5.27		12.85	
3	6.25		12.45	
4	7.09		12.10	
5	8.75		11.83	
10	9.06		11.30	
15	9.25		10.85	
20	9.50		10.55	
25	9.99		9.87	
30	10.70	Discharge rate 4,200lts/hr.	8.79	Purely clean and Pure water pump out
35	10.87		8.50	
40	11.65		7.91	
45	12.13		6.59	
50	12.37		5.74	
60	12.37		4.61	
70	12.48		4.50	
80	12.50			
90	12.78			
100	12.88			
110	13.02			
120	13.11	Constant Discharge rate of 4,200lts/hr.		
140	13.18			
160	13.25			
180	13.34			
210				
240				
270				
300				
330				
360				

Calculations Of Discharge (Q) / Yield

Discharge (Q) in Litres /Hour

$$Q = \frac{\text{liters} \times 3,600}{\text{time (sec)}}$$

Where:

- litres = 21
- Average time = 20 secs.

$$\text{Therefore } Q = \frac{21 \times 3,600}{20} = 3,780 \text{ lit./hr}$$

$$Q = 3.78 \text{ m}^3/\text{hr}$$

Or

$$1.05 \text{ lit./sec}$$

4.8 Borehole Characteristics

Borehole Recharge

This is the ability of a borehole to produce water to a static water level after pumping. It is greatly dependent on season. Recharge rate is normally high during the rainy season but low during the dry season.

Borehole Yield

Borehole yield is the quantity of water that can be abstracted from a borehole. It is the maximum rate of abstraction from the borehole and can be expressed as l/s, m³/hr, m³/d or m³/a.

In order not to over pump the Borehole which may result to saline intrusion, encrustation, and excess lowering of the water table it is vital to carefully note the recharge rate of the borehole.

Static Water Level (Swl)

This is the level of water in the well under normal, undisturbed conditions. It is best determined when the well has not been pumped for several hours for several hours before measuring. There are many ways to measure static water level, these include: an electric sounder or electric depth gauge, wetted tape or airline.

Dynamic Water Level (Dwl)/ Drawdown

Drawdown is referred to as the change in hydraulic head observed at a well in an aquifer, generally due to pumping a well as part of an aquifer test or well test. Dynamic water level is the difference between the Static water level (SWL) and the pumping water level (Allaby, 2013).

4.9 Comparison Of The Factors That Influenced The Groundwater Potential Of The Project Areas

From the study carried out, it is evident that Groundwater do exists in both the basement rocks, this resource is confined to the fault zones that are permeable, the fractured regions, weathered zones, around basic dykes and other relevant structures.

In chapter three, several factors are highlighted that influence the groundwater potential of the project area. Slope is one of them, high slope favors greater runoff thereby preventing adequate retention of the water on the ground surface and significantly reduces the groundwater recharge potential as opposed to lower slope. However, the topography of the project areas (Freetown Complex and the Granite Green Stone Terrain) are similar, but the Complex has relatively prominent slope thereby inhibiting its potential as percolation and infiltrations are limited. The Basement Complex (Granite Green Stone Terrain) has component of medium- to coarse-grained granite typical of the older Achaean formation. Exposures of grey and pink granites are dominant in the Basement Complex. These rocks have less porosity and are classified into low groundwater potential zones. However, intense weathering and tectonic activities have resulted to porosity and permeability in area of overburden and fractures at depth. On the contrary, the Basic Complex is younger and thus has limited fractures and thin weathered layers (Overburden) with thicknesses ranging from less than a meter to 15m as the case may be. Hard rocks lack primary porosity but secondary porosity which occurs after their crystallization allows groundwater occurrence, they occur in the form of fractures due to the action of weathering. The Vertical Electrical Sounding carried out shows a magnitude of weathering of about 40m depth in the Granite Greenstone Terrain but the Freetown Complex is relatively shallower as evident in the borehole logs and their respective diagrams (Table 4.2 and 4.3 and Figure 4.1 and 4.2). The Basement Granites which has high amount of porosity is considered to be of high groundwater potential. Another significant factor is drainage density. The higher the drainage density, the higher the run-off will be, and infiltration of water into the subsurface is affected. The Freetown Basic Complex is almost bounded by the Atlantic Ocean and has steep slopes as opposed to the vast area of the Granite Greenstone Terrain which only has Rivers traversing it. Areas having less density are distinguished as higher rank as they facilitate recharge and this is a characteristic of the **Granite Green Stone Terrain** and areas with high density designated with lower rank as they facilitate less infiltration and recharge as evident in the **Basic Complex**.

4.10 Comparison Of Collected Data From The Project Area

Vertical electrical sounding (VES) were carried out at different locations of the study area to understand the geology and also to verify the extent of weathering, fractures and other features like joints, dykes etc. These locations are; Saint Ambrose School and Lebanese School (Table 3.3 and 3.5) for the Freetown Complex and Makalie Town and Makeni Government Hospital (Table 3.6 and 3.7) for the Granite Greenstone Terrain.

Generally, resistivity values for unaltered Granitic rocks are higher than unaltered Gabbroic and Basaltic Rocks. However, the tables above in chapter three (Table 3.3-3.8) present different resistivity data with their respective curves and the corresponding borehole logs and diagrams. In actual sense, it is clear that resistivity and conductivity have inverse proportionality.

Vertical variation in formation properties is visible from the Borehole logs in chapter four; (i.e. the extent of weathered layers, fractures in bed rock and unaltered crystalline basement rocks). From the borehole logs and borehole diagrams, it is very clear that the thicknesses of weathered zones are greater in the Granite Greenstone Terrain extending up to 40m and above as compared to the thin layers weathered zones with the Basic Complex. Groundwater could only exist in the weathered and fractured zones in these crystalline basement rocks.

Pumping tests data were also attached to some of the existing data collected to determine the yield of wells to validate the groundwater potential zones and compare the sustainability rate of those boreholes (Table 4.6 and 4.7).

The groundwater potentials were also compared in terms of borehole depths; areas with higher potentials are characterized by shallower boreholes, unlike areas of lower potentials with characteristic deep boreholes or wells.

4.11 Groundwater Potential Zonation and Validation

Though several features are used to identify the groundwater prospects of an area, this study was limited to evaluate the groundwater prospects through Geophysical survey (Electrical resistivity) to delineate the various distinct characteristics and sub-surface features in each of the locations in question and analyses geological and hydrogeological parameters.

However, some of the areas are classified as high groundwater potential areas, while some parts can be classified as moderate or low groundwater prospects area within the same geological formation. This is clearly shown in the variation of resistivity values within the same formation (Table 3.3).

High groundwater potential areas are present in the areas with low slope, intense weathering, and highly fractured areas. These are highly promising area for groundwater development. The complex geology, geomorphology and land use result in varied groundwater potential zones of an area.

CHAPTER FIVE

THE ECONOMIC IMPORTANCE OF THE PROJECT AREA

5.1 Mineral Potential

5.1.1 The Freetown Complex

The Freetown igneous complex is a basic layered complex that forms an intrusive body on the coast. It is composed of gabbro, norite, troctolite and anorthosite. Platinum occurs in the gravels of the streams that drain the complex.

The relationship of this complex with other units is obscured by the coastal veneer of tertiary sediments.

5.1.1.1 Platinum-Group Minerals (Pgm) In The Freetown Complex, Sierra Leone

PGM have been located in situ in the rocks of the Freetown Layered Gabbroic Complex for the first time occurring in this stratiform layer of pyroxene troctolite. Cooperite (PtS) is the main PGM. Some PGE arsenides and antimonides occur in lower horizons but are rare. Pd-Cu alloys are to be found within another unique horizon.

The PGM are frequently associated with sulfides, mainly chalcopyrite and minor pentlandite. Many of the PGM grains are less than 1 micron in size with a few in the 2–4 micron range and one example of Pt-Fe alloy is 9 by 6 microns. The PGM occur in a late magmatic, high Ca amphibole which has formed interstitially to plagioclase or plagioclase and olivine (Dixey, 1925). Some droplet-shaped cooperite can be found attached to droplet-shaped magnetite within the amphibole. The most common PGM occurrence is near the margin of the sulfides. The PGM-sulfide assemblage is found at the edge of the amphibole or in interstitial sites associated with the amphibole, mica or quartz. Cooperite located at the edge of the amphibole or in the interstitial locations has later been altered to Pt-Fe alloy. In one case part of the PGM grain hosted by amphibole remains as cooperite whilst the part of the same grain projecting from the amphibole boundary into altered silicate has been altered to Pt-Fe alloy (Pollett, 1951).

The PGM in the rocks are considered to have formed following an event - a reduction in pressure caused by tension early in the opening of the Atlantic perhaps accompanied by an injection of fresh magma - which caused the silicates to form at more primitive compositions. As crystallization proceeded at these PGE-enriched horizons, the residual interstitial magma became supersaturated in metals, volatiles and sulfur. This led to the formation of an immiscible PGE-rich sulfide liquid followed by sulfide saturation. Sulfide saturation led to sulfide crystallization which acted as a collector for the PGE. Droplets formed from the immiscible PGE-rich liquid were enclosed in the core of the late magmatic amphibole. The slightly later PGE-sulfide assemblages were trapped at the rim of the late magmatic amphibole or formed interstitially in association with the amphibole, mica or, occasionally, quartz.

PGM have been known in eluvial and alluvial deposits derived from the Freetown Complex for more than 70 years. 0.5 to 10 mm grains were extracted from streams draining westwards into the Atlantic (Pollett, 1951). Platinum-iron alloy (with a composition close to Pt₃Fe), laurite, erlichmanite and Ir-Os alloys are the most abundant PGM in these deposits with minor tulameenite (Bowels, 1977). The PGM assemblage within the rocks is substantially different from those found within the weathered profile. Weathering of the intrusion since the Eocene has been under tropical rainforest for at least part of that time and has created a deep laterite with local hard pan. The weathering has also affected those rocks now exposed at the surface leading to alteration of the primary magmatic PGM assemblage predominantly PtS to Pt-Fe alloy (Briden, Henthorn, & Rex, 1977).

5.1.2 The Granite Greenstone Belt

5.1.2.1 Mineral Deposits

Deposits of chromite and asbestos are exclusively associated with the ultramafic units of the Kambui-Gori zone in the east and of the central Sula-Kangari belt, respectively (Pollett, 1951). Copper, nickel and cobalt mineralization of sub-commercial quantities occur in both the ultramafic and basaltic components, whereas gold is found throughout the volcano-sedimentary piles. Iron ore deposit is restricted to the upper sedimentary sequences of northern part of Sula-Kangari belt in the west. There is, therefore, a close genetic relationship existing between various lithological units and mineralization. Chromite bodies have been located from the southern tip of the Kambui belt onto the central part of the Gori belt, a stretch of about 100 km and up to 20 km wide (Williams, The Archaean geology of Sierra Leone, 1978). Within this zone, bands of chromite ore-body varying in thickness from a millimetre to six metres interband with and grade into olivine serpentinite. Such a chromiferous belt about 100 km is followed by hornblendic and then feldspathic bands. All dip steeply westwards in conformity with the rest of the greenstone belt. Euhedral chrome-spinel crystals reach 1.5 cm but normally range from 0.5 to 2.5 mm across. The chromite of Kambui belt is unlike the Alpine podiform deposits which, according to (Thayer, 1960), lack euhedral chromite crystals. Lump ore from massive chromite deposits and disseminated ore, the 'leopard skin' horizon, are other varieties all of which constitute a large reserve.

Chromite was mined in the vicinity of Hangha between 1938 and 1963 when it was stopped partly because labour drifted to the diamond mining and partly because of the high costs of transportation some 250 km to the port. The recovery of the ore is difficult because of the steep dips and impersistence of the ore bands.

Moreover the grade of ore which averages 42% Cr₂O₃ is low. The analysis of Hangha ores given by (Dunham et al., 1958) is reproduced: Cr₂O₃ 45%, FeO 13%, Al₂O₃ 20% and MgO 16%. Asbestos deposits though not of commercial value occur along the southeastern side of the Sula-Kangari belt where the main zone of anthophyllite asbestos and anthophyllite rocks covering an area 8 km long with a maximum of 1 km was mapped by (Marmo, 1962). But the asbestos which is present in varying amounts is mostly hard and brittle and when flexible it is always accompanied by talc.

Asbestiform anthophyllite occurs in lenses and in association with serpentines. The latter displays a gradation westwards from olivine serpentinite to olivine-tremolite serpentinite and thence to tremolite serpentinite. It is thought that the primary dunite with some orthopyroxene was secondarily altered to anthophyllite, talc, actinolite-tremolite and serpentinite $\pm$ chlorite $\pm$ carbonates.

Geochemical and geophysical investigations carried out by various workers (e.g. (Garrett & Nichol, 1967) show higher concentration of nickel, copper and cobalt within the volcanic units. It has also been found that nickel, copper and cobalt and sometimes molybdenite, sphalerite and galena are associated with gold. No ore deposit of any of these sulphides worth mining has been located but their anomalies especially those of arsenic and molybdenum have been used as tracers to locate gold.

Gold is carried by nearly all streams and rivers draining the volcanic terrain and many of these are valuable deposits of alluvial gold. The alluvial deposits have also served as a guide in tracing gold ore-bodies back to the source rock. In the Kangari Hills auriferous rocks outcrop in two localities namely Baomahun and Makong. In the former, mineralization is in garnetiferous magnetitecummingtonite schist (=banded iron formation) which is close to the contact with cordierite schist. Strips of auriferous quartzite in this area suggest that it is a fault zone. In the vicinity of Makong, gold is mineralized in quartz veins, granular quartz pegmatite and in granite porphyry. Gold ore-bodies have also been located near Komahum in the central part of Nimini belt. In this locality the mineralization is at various horizons including the magnetite quartzite and magnetite-amphibole quartzite (=banded iron formations), amphibole and quartz veins. All these are in the volcanic/sedimentary contact zone. Assays of between 6 g tonne⁻¹ and 70 g tonne⁻¹ have been reported by the Geological Survey Department. Trenching and bore hole data reveal that several zones from less than a metre to 4 m wide parallel each other and that gold and arsenopyrite are mineralized beyond a depth of 30 m. Shear or fault zones are thought to have provided the main channel way for the mineralizing fluids.

Iron ore deposits occur as banded iron formation which is characteristic of the transitional zone between the volcanic and the sedimentary units. As would be expected this iron ore-bearing rock is present in each of the greenstone belts under review but it is only in the Sula-Kangari belt that iron ore deposits attained an economic stature. The iron ore-rich zone extends for about 65 km from Darakuru (9° 11' N: 11°32'W) to Sangbari (8°40'N: 11°47'W). The ore grade is above 55% and the reserve is estimated at over 120 million tonnes by Marmo (1962).

The ferruginous rocks are banded and/or laminated and consist of magnetite quartzite, magnetite-biotitequartz schist, magnetite-quartz-hornblende schist, garnet-tremolite-magnetite schist, or magnetite-talc schist. In fresh rocks magnetite is the iron-bearing ore mineral.

Outcrops of weathered materials may carry massive ores of haematite, goethite and martite which are pseudomorphs of magnetite.

5.2 Rocks

Rock as a natural substance, a solid aggregate of one or more minerals or mineraloids was characteristic of both the Freetown Igneous Complex and the Granite-Greenstone Terrain. The occurrence of rocks across the area favors quarrying by local dwellers and company of interest for various constructional purposes as rocks play a great role in reinforcing human structures and our environment. This makes the complex to yield good number of open quarries as point source of income for companies for example Leocem. Quarries are places where rocks are separated from their natural in-situ position and which are then processed for use as follows;

- Ornaments (Beautiful rocks within the project areas can be polished as an ornament for decorating floors, walls of buildings, Churches and tombstones.
- Aggregates for buildings and road construction

5.3 Water Resources

Water is perhaps the most important commodity on earth. There can be no life on earth without water. Therefore water plays a very crucial role in the existence of human beings and other animals, as well as in their activities. In the studied area, water occurs in various forms such as surface (streams, rivers) and groundwater (in boreholes). The economic importance of this resource is very vast. Water provides goods (e.g. drinking-water, irrigation water) and services (e.g. hydroelectricity generation, recreation and amenity) that are utilized by agriculture, industry and households.

Water is used to clean clothes and other fabrics in homes. On commercial basis, it is used by dry cleaners, capital washing firms and domestic and office cleaning companies.

In manufacturing industries, water is used for various purposes. These include washing raw materials, washing containers and machines, diluting chemicals or ingredients as well as a raw material in industries such as in beverages industries e.g Coca cola

Water is a key component of the electricity generation process. It may be directly used to turn turbines that generate electricity or it may be heated to produce steam which is then used to power machines that produced electricity.

Water is used for recreational purposes such as swimming. People pay to use facilities such as swimming pools, thus generating income for those who run the facilities.

Water facilitates the growth and development of the fishing industry. This is because water supports the existence of fish in rivers, lakes, oceans or in fish ponds.

People who sell water in the project area earn income from this activity. Water provision also generates money for supplying water to homes, offices and industries.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This project was aimed at determining the groundwater potential of the Freetown Complex and the Granite Greenstone Terrain in Sierra Leone, using geophysics and borehole data. Four locations were considered, two each for both the Freetown Complex and the Granite Greenstone Terrain, these locations are; Saint Ambrose and Lebanese School for former and Makalie and Makeni Government Hospital for the later. Electrical Resistivity Geophysical survey i.e. Vertical Electrical Sounding (VES) using the Syscal Junior Iris Instrument (Resistivity Meter), was primarily utilized for the above locations of the project area.

Rocks within the Granite Green Stone Terrain are greatly weathered and fractured with depth of regolith extending to tens of meters as opposed to the younger Freetown Complex with relatively low weathered layers and less fractures as clearly indicated by the resistivity and borehole log data. Resistivity values are lower in weathered and fractured zones with corresponding higher groundwater potentials and higher in unaltered layers with lower potential (I.e. the lower the resistivity, the higher the conductivity and the higher the potential, the reverse is also true) although there are some exceptional cases.

Notwithstanding, it was observed that borehole depths and yield depends on the geology and the aquifer characteristics of a particular area. Areas with intense weathering and fractures will have shallower boreholes with high yield; unlike areas with less weathering and fractures which are characterized by deeper well with sometimes lower yield as deduced from borehole logs and pumping test data from various locations.

Borehole logs gives is a clear representation of the vertical compositional variation of geological materials as analysis are done at specific intervals. A stratigraphic section is presented indicating clearly the layer differences as shown in the borehole diagrams. The upper layers consists mainly of weathered laterites overlying the crystalline rocks which are sometimes fractured.

Borehole construction or design is determined from the analysis of borehole logs. Screens casings are place within fractured and weathered zone with water and plain casings in unaltered and dry zones.

It was also recognized that, pumping test are conducted to determine the productivity of a borehole and to assess the hydraulic performance of a borehole (aquifer transmissivity and storativity); usually in terms of its yield-drawdown characteristics. To locate borehole positions especially within the crystalline basement aquifers systems require the correct procedures and right equipment for sustainable productivity.

Mapping and identifying the groundwater potential zones in an area help to plan for sustainable groundwater exploitation and management.

However, with all the parameters used; the Granite Greenstone Terrain has higher groundwater potentials compared to the Freetown Complex.

Favorable groundwater potential zones identified from this study would serve as a tool to various organizations and decision makers in planning for groundwater resource exploration and development in these areas which will result in high yield.

6.2 Recommendations

During the course of this field work, resistivity profiling could not be carried out at multiple VES stations prior to selection of the most suitable one for the vertical electrical sounding due to the lack of enough space, upon subsequent investigations, a vital recommendation is that multiple resistivity profiling be carried out before choosing the most suitable one for the more detailed vertical electrical sounding, in order to increase the potential of water discovery during drilling.

A special attention must be given when conducting resistivity surveys to attain a consistent straight horizontal line on the surface because this corresponds to the vertical depth of investigation, which in turn gives information about the various layers of the subsurface. Great concern should also be administered to the readings as they are recorded, to prevent loss of data and also to visualise any sharp decrease in the resistivity values that may be caused by as a result of anomalies (buried metal objects such as electric pipes etc. and take note of them).

There are several factors that enhance the groundwater potential of the project area, however, human activities tend to greatly affect these influencing factors. These activities include the different use of land; Agriculture. Catchment areas should be preserved to sustain this resource.

For the Freetown igneous complex it is recommended that drilling should target a greater depth relative to the granite-greenstone terrain, 70m depth is appreciable to penetrate the bedrock into the fractured zone where aquifers can produce sustainable yields.

Borehole development is a fundamental aspect and should be exercised satisfactorily as it greatly determines the yield of the borehole. A properly developed borehole will produce optimum and sustainable yield, but if the screen and plain casings are not installed properly and at the right depths, the yield of the borehole will be greatly impaired.

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