Comprehensive Mapping Analysis for Underground Water Resources Evaluation using Engineering Survey and GIS-Assessment in Northern Region of Sierra Leone-

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Comprehensive Mapping Analysis for Underground Water Resources Evaluation using Engineering Survey and GIS
─Assessment in Northern Region of Sierra Leone─

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Comprehensive Mapping Analysis for Underground Water Resources Evaluation using Engineering Survey and GIS
―Assessment in Northern Region of Sierra Leone―

A Doctoral Dissertation

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In

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By

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ABSTRACT

Groundwater is used for drinking water to support daily life in rural areas where surface water is inadequate. Particularly in West Africa, securing drinking water is an urgent matter with the increase in population. In Tonkolili and Pepel districts in northern region of Sierra Leone, majority of the population depend on groundwater for domestic and other purposes. The iron ore is mined from Tonkolili and the iron concentrate is stockpiled in Pepel for shipping. Even though there is high, potential of groundwater and many boreholes drilled in the areas by aid agencies, there is still a serious problem with adequate availability and quality of groundwater, because both the quantity and quality of water in the boreholes are not properly maintained and managed. This is evident from long queues of people scrambling for water at drilled wells and the high amount of water related diseases reported at health centers in the project areas.

The objectives of this research is to determine how the mining activity from Tonkolili to Pepel affect the underground water resources and the groundwater quality of those areas, which could be used as basis for future guide that might help government agencies and various stakeholders to properly manage the water resources. The research focused on the hydro geologic framework of the areas, especially how different combinations of geologic, topographic, and hydrologic conditions control the abundance, chemistry and movement of groundwater beneath different geologic terrains based on groundwater investigation of 75 boreholes from the two districts.

This dissertation consists of six chapters, which are heighted below:

Chapter 1 is the introduction to groundwater. This chapter outlines the reason for groundwater investigation and assessment; it justifies the objectives and scope of the research. This chapter also reviews previous work and methods of geographic information system (GIS) and engineering survey related to the investigation.

Chapter 2 describes a method of engineering survey and GIS fitting for field investigations of water resources. Engineering survey was used for field measurements and the survey points are processed using GIS to produce the topographic map, geological map and drainage system map. GPS data points collected from the field may also be used to establish ground control points for aerial triangulation in photogrammetry. Each of these methods plays an important role in groundwater investigation.

Chapter 3 describes groundwater system of the project area and hydrological formations with the definition of certain important terms used in groundwater. It also discusses the data collection methods like the earth resistivity survey, pumping test and groundwater quality analysis. Specific aquifer properties (e.g. hydraulic conductivity, transmissivity or water table levels) are also explained on national and regional scale because groundwater storage hinge on aquifer parameters, rate of water movement and recharge of the aquifers. The project areas revealed confine aquifer system. 1) Tonkolili district: granitic terrain with fracture aquifer system and 2) Pepel district: sediments with sand porous aquifer system.

Chapter 4 details the methodologies used in groundwater investigation and water quality analyses. The softwares, Zond Vesip for resistivity analysis, Aquifer Test Pro for pumping test and Arc Map for GIS, were used to model the aquifer depths, which range from 5 to16 m below surface level in Pepel depending on the elevation. The research involved 74 boreholes where 35 boreholes were drilled in the sedimentary sequence in Pepel and 39 in the fractured basement aquifer in Tonkolili. The resistivity values from Pepel were plotted to describe the sub-surface layers, and the pumping tests were done in all the boreholes. The geophysical survey results of the five boreholes revealed the presence of four lithological formations with groundwater being sourced from the third and fourth layers. However, the fourth layer consisting of sand/gravel is considered more prolific than the third layer. The apparent resistivity values form the sedimentary sequence range from low of 103Ωm to high of 11700Ωm. The transmissivity increases with decrease in resistivity through the layers. This has a tendency to find suitable place to drill a new borehole.

Chapter 5 discusses and analyzes the results. Whilst the granitic terrain comprises of fractured aquifer system and a clay layer (aquitard), the sediments comprises of sand aquifer system that exhibit high yield potential. Their analyses give a clear understanding of the aquifer system in the fracture basement with average borehole yield of 1.90m^3/hr. and that of the sedimentary sequence with average borehole yield potential of 2.04m^3/hr. The water quality test showed that pH values of 74% of boreholes in Tonkolili district and 54% of boreholes in Pepel districts were less than the WHO recommendation of 6.5-8.5. This shows that groundwater in those areas are mostly acidic. The study revealed that the turbidity of the sampled waters from 3 boreholes (7% of total) in Tonkolili were above the maximum concentration limits of 5 NTU recommended by WHO, while the waters sampled from 10 boreholes (29% of total) in Pepel were above the limit. The fecal coliforms were found in sampled water from 25% and 20% of the boreholes in Tonkolili and Pepel, respectively.

It was found that in Pepel, pH has a negative correlation with Fe^{2+} and Mn^{2+}. It implies that decrease in pH is related to increases in Fe^{2+} and Mn^{2+}, which results in increase of turbidity in both districts. The reason is that as the acid waters interact with the iron concentrate on the surface in Pepel and waste rocks of iron ore in Tonkolili, Fe^{2+} and Mn^{2+} are dissolved because of low pH. This may leach through the ground slowly to contaminate the underground water resources. Fecal-coliform showed no correlation with pH in both districts. The presence of fecal coliforms in most of the wells may be due to movement of pollutants from closely located pit latrines and leaking septic tanks as well as indiscriminate defecation by people around the wells. The pH value has no relationship with transmissivity and resistivity.

Chapter 6 is a summary and conclusion of the findings and a recommendation for future studies on groundwater investigation and water quality analyses.

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Alhamdulillah! All praises and thanks are due to God Almighty Allah for seeing me through and for His abundant mercies, guidance and protection on me.

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A dissertation work has never been the work of a single individual; it is the product of a close collaboration between the student and his academic supervisor. My case is not an exception. From the initial conception of my research ideas, through implementation and culling obstacles all the way into polishing the final text of this dissertation, Professor Kyuro Sasaki has been a tireless guide, passionate and energetic professor and a diligent proofreader. His insistence on simplicity, clarity, strictness and inflexibility has paved my way of thinking and made me the Water Resources Engineer I always wanted to be. I am grateful to express my profound gratitude to Sasaki sensei's nurturing my training at Kyushu University.

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Special thanks to my wife Isatu Barrie and children, Ibrahim Jalloh and Abubakarr Jalloh this thesis is dedicated to you. You are the bedrock of my success. I love you both more than you can imagine and thank you for the love and unconditional support you have always shown me. To my elder brother and mentor, Ibrahim Jalloh, thank you for giving us your unwavering support. You made sure that everyone in the family has an equal opportunity to achieve by Allah's permission. Thank you to all my friends especially Ramie Saad and S.M. Koroma.

Finally, this dissertation would not have been possible without the support of my entire family members especially Dr, Abu Bakaarr Jalloh, I am forever grateful to all my brothers and sisters for the love and unconditional support. Words cannot describe how much I love my mother and late father. I am deeply indebted to them for all their love. I pray to Allah to grant my father Janatul-Firdaus, Ameen.

LIST OF FIGURES

LIST OF TABLES

CONTENTS

CHAPTER 1

INTRODUCTION

1.1. Introduction

This chapter review the importance of water both surface and groundwater to human existence human life. It outlines the reason for groundwater investigation and assessment and justifies the objectives and scope of the research. It also, reviews previous work related to groundwater investigation.

1.2. Literature Review

Groundwater is used for drinking water to support daily life in rural areas where surface water is inadequate. Particularly in West Africa, securing drinking water is an urgent matter with the increase in population. In Tonkolili and Pepel districts in northern region of Sierra Leone, majority of the population depend on groundwater for domestic and other purposes. Even though there is high potential of groundwater and many boreholes drilled in the areas by aid agencies, there is still a serious problem with adequate availability and quality of groundwater, because both the quantity and quality of the water in the boreholes are not properly maintained and managed.

Water is an important natural resource that requires proper management to ensure its quality, quantity and sustainability (Ibemenuga et al, 2014). From hydrological statistics, the volume of water worldwide amounts to some 1.4 x 109 Km3 (Hassan et al., 2008). Water is an indispensable resource needed for the socio-economic development of any country. Globally, 1.1 billion people do not have access to safe water and 2.4 billion people are without adequate sanitation (Garba et al., 2008). This number keeps on increasing especially in developing countries like Sierra Leone. Access to safe drinking water in villages, towns and cities are becoming evident. Sierra Leone is one of the countries that experience high amount of rainfall but still access to safe drinking water is a major problem. Evidently, all the rainfall goes into storage (groundwater). Its exploration, exploitation and distribution to the communities is lacking.

Groundwater comprises of water that exists beneath the land surface, held within openings or pores of soils and geological formations. According to most classical definitions, this term refers exclusively to water occurring at or beneath a surface, known as the water table. Below the water table is a region known as saturated zone, in which pores are completely filled with water. Trimmer (2000) defines groundwater as water that naturally occurs in porous rock materials underground. Groundwater potential means having a latent possibility or likelihood of occurrence of groundwater in an area. Areas or zones of abundant groundwater available for use are referred to as areas of good groundwater potential. Productive water bearing zones referred to as good groundwater potential aquifers.

1) Resistivity Survey

Among the various geophysical methods of groundwater investigation, the Electrical Resistivity Method has the widest adoption in groundwater exploration. (Afolayan et al., 2004). Oyedele E. A. A., Olayinka A. I (2012) did statistical evaluation of groundwater potential in Southwest Nigeria using resistivity survey on the basement complex and related resistivity with overburden thickness and depth to bed rock but he did not do water quality analyses. He did not explain the relationship between resistivity and transmissivity or depth to aquifer, which has the potential for borehole selection. However, he determined that clay formations have low resistivity values with little or nr groundwater potential.

A recent study by Ali S, and Deyassa G. (2017) also, on groundwater investigation using resistivity only highlighted the subsurface geo-electric layers and the resistivity values through the VES soundings but failed to explain the relationship between resistivity and transmissivity in groundwater investigation. He used the resistivity values in table 1-1 below to describe the subsurface layers. According, his research the resistivity value decreases in fractured sandstone bedrock. Fractured sandstone bedrock has relative increment of resistivity value to about 255Ωm of thickness nearly 37m. The 4th layer with significantly reduced resistivity value of 48 Ωm, is interpreted to be variably fractured and loosely bedded sandstone saturated with water. Whereas my research suggest that resistivity increases with depth, except in clay formations.

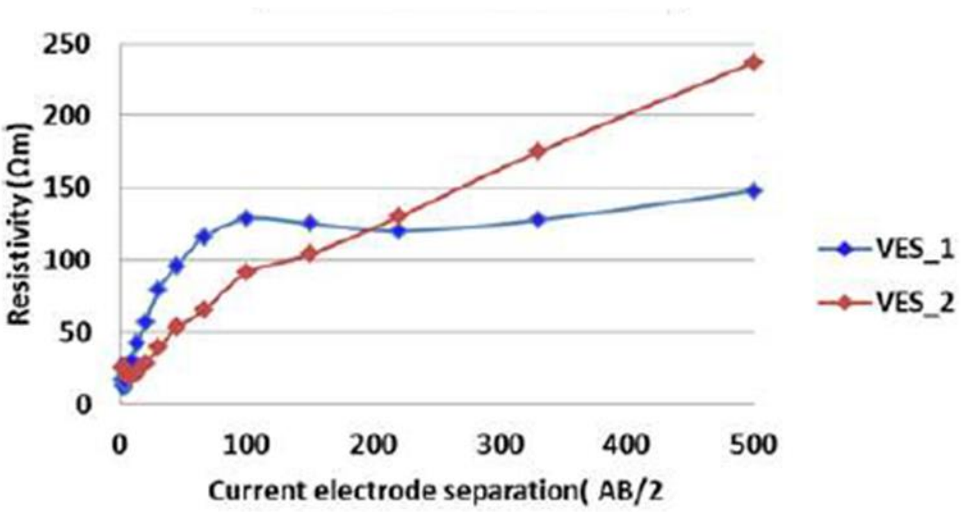


Figure 1-1: Results by Ali S. and Deyassa G., (2017) on resistivity survey

Their results show that, the resistivity increases with the current electrode at shallow depth then it reduces at deeper soil formations.

My research shows that there is a linear relationship between resistivity, transmissivity and depth through sandy soil formations (porous aquifer) which means increase in resistivity is associated with transmissivity and depth in the studied area. This will serve as a baseline for future groundwater investigation.

2) Water Quality

According to (WHO 2014) exposure to microbial pathogens that contaminates water supplies is responsible for a significant number of public health issues in developing countries like Sierra Leone. About 1.3 billion people in developing world are compelled to use contaminated water for drinking and cooking and over six million children are believed to die every year from water related illnesses (Mkandawire, 2008). This is very evident from long queues of people scrambling for water around drilled wells and the high amount of water related diseases reported at health centers in the project areas. Unsafe drinking water is a major cause of diarrhea, which is responsible for an estimated 10% of the global mortality among children under the age of five (WHO 2104). Viral and parasitic infections, environmental enteropathy, and undernutrition are other health concerns associated with unsafe water. Consequently, information about drinking water quality is essential for guiding efforts to reduce waterborne diseases.

However, it is important to determine the quality and portability of water. Amfo-Otu et al. (2014), in their study of correlation analysis of groundwater colorations from Mountainous Areas, Ghana, determined that pH has a negative correlation with turbidity, conductivity and colour as seen from the figures below.

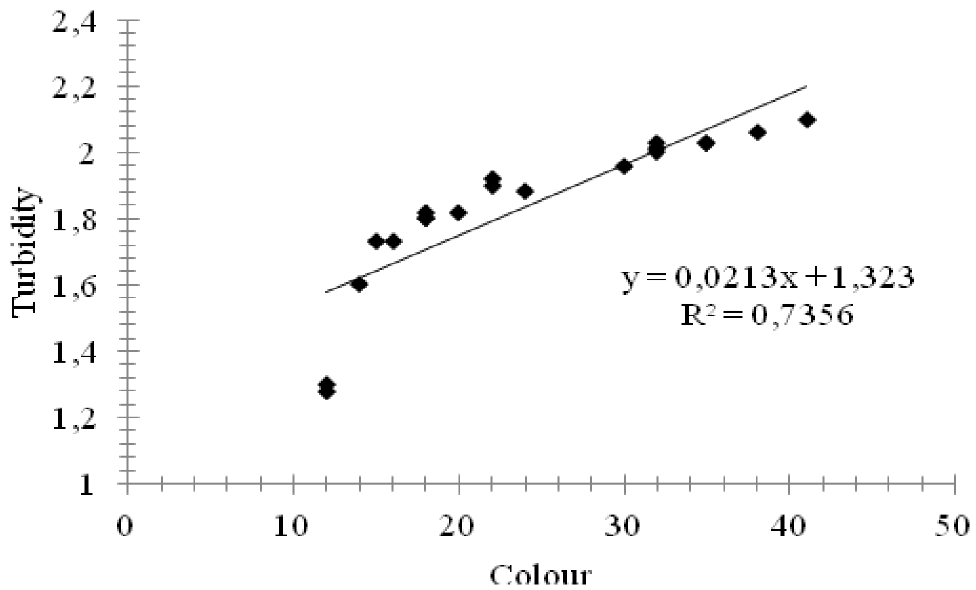


Figure 1-2: Results by Amfo-Out et al., (2014) on turbidity and colour

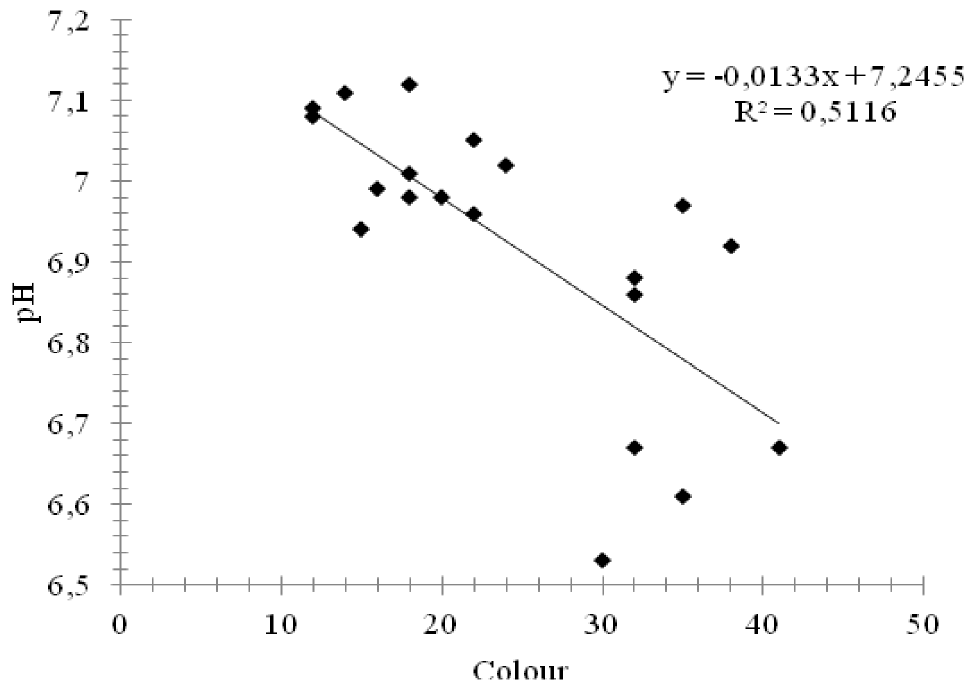


Figure 1-3: Results by Amfo-Out et al., (2014) on pH and colour

However, in this study, my research analyzed the relationship between pH, Fe, Mn, turbidity, conductivity sulphate and fecal coliforms to determine the cause of water quality deterioration.

The influence of iron ore mining activity to water quality parameters cannot be underestimated. Pepel and Tonkolili normally experience a high amount of rainfall in the rainy season. This rainfall goes to rebuilding the ground water through effective infiltration, if soluble minerals are present on the surface, it will dissolve easy and infiltrate the underground water resources. Water quality analyses also suggest that the acidity of the water (low pH) is associated with the presence of H^+, which dissolve Fe and Mn in both districts.

1.2 Background of the Study

Hydrogeology is the study of groundwater and its interaction with the geologic framework, landscape, surface-water bodies, and the human environment. It is both a qualitative and quantitative science having many applications to the modern environment. The identification of the geologic characteristics of groundwater resources beneath any given point in the landscape and quantitatively and qualitatively determine how much groundwater is available for different kinds of end uses without compromising the resources is the bases for this research.

Sierra Leone has an abundance of surface water; hence, ground water has so far received little attention. A national study in 1980 used geophysical soundings, identifying five geological units whose resistivity can be considered as reference for many areas of the country (UNDP/FAO, 1080).

Table 1-2: Geological units identified through geophysical soundings (UNDP/FAO, 1980)

Layer Type	Resistivity (Ωm)
Lateritic Crust	1200 - 1700
Clay and Sand (regolith)	20 - 30
Hard Clay	80 - 400
Clay	20 -30
Basement Rock	> 900

The results of the VES above provided a clear information about the lithology of the Bullom group, the Bolilands and the fractured basement of the granite formations. The Bullom formation consist mainly of sandy clay with sand aquifer 30 – 40 m thick inwards. The soundings reveal that the fractured Precambrian basement rock is about 250 m deep. Two soundings in the Bolilands penetrated thick clay strata in the first 30 - 40m. Similarly, the electrical soundings made in granite areas seem to indicate that the fractured and altered rock may be 30 - 40 m thick along the main faults. These and other applications broadly highlight the concept of hydro geologic framework — how different combinations of geologic, topographic, and hydrologic conditions control the occurrence, abundance, chemistry, and movement of groundwater beneath different geologic terrains.

The research focuses on some parts of the Northern region of Sierra Leone, Tonkolili and Port Loko districts. Surface water is readily available in these areas but lack of proper water management system has made it unsafe for human consumption. The Sierra Leone water Company (SALWACO) has the mandate of supplying water to residents of the project areas i.e. Tonkolili and Port Loko Districts, but surface water management scheme is lacking. There are many rivers but water is not trapped from them and treated for human consumption.

Because of this, SALWACO embarks on a project sponsored by World Bank to drill boreholes for the Communities in the said Districts hence; residents of Tonkolili and Port Loko Districts depend on groundwater supply for safe drinking purpose. A major mining company (African Minerals) has its operations going on in both districts; they too in compliance with their corporate social responsibility have dug few boreholes around its concession for the residents.

Majority of the population in the districts depend on groundwater for domestic and other purposes. However, in spite of the high potential of groundwater in this region and the number of boreholes drilled by Aid Agencies, study reveals that there is still a serious problem with adequate availability and quality of groundwater supply. This is very evident from long queues at local and drilled wells of people scrambling for water and the high amount of water related diseases reported at health centers in the project areas.

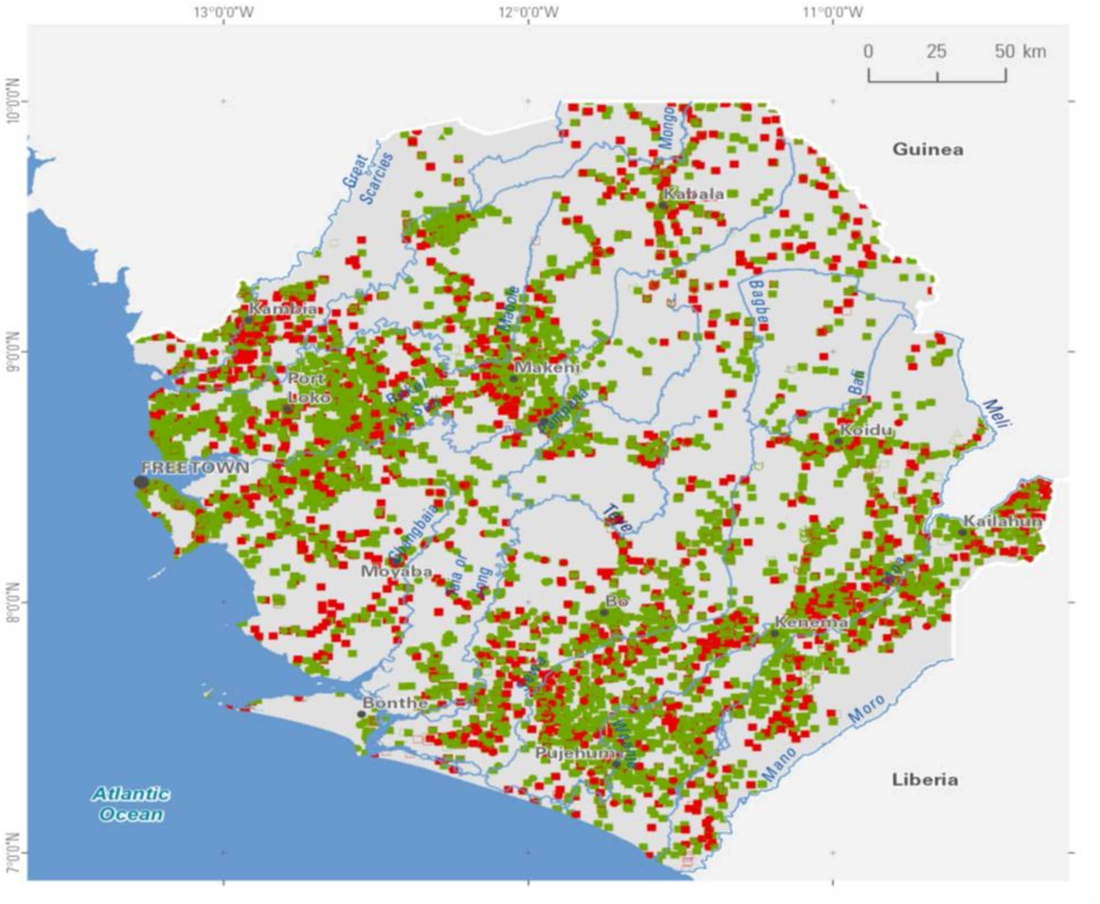
The northern region is blessed with many rivers, swamps and lakes which show that water is readily available in those areas but poorly managed. The few hand dug wells and boreholes that are available are not properly maintained. Latrines located close to them are polluting the water bodies in the project area and environmental impacts of construction work by either the local people or Mining Companies.

This research is going to focus on exploration, exploitation and Groundwater water quality assessment of some boreholes from the two districts (Tonkolili and Port Loko) in the Norther region. At present residents of both districts, utilize groundwater and surface water for portable and domestic uses.

1.3 Problem Statement

Sierra Leone is blessed with abundant surface water, groundwater and rainfall. However, lack of proper management of the water resources has led to water shortages within the country. Presently, many boreholes and shallow hand-dug wells are being constructed across the country by local people with no prior knowledge of the local geology, national hydrogeology and without access to in-depth information leading to a host of issues such as poor construction practices, unsuccessful siting, and water quality deterioration.

In this research, comprehensive mapping of 74 boreholes, investigation of underground water using resistivity survey and water quality analyses to determine the cause of water quality deterioration in relation to low pH, turbidity and feacal-coliform will be done which will lead to the bases of this research. The Inventory of Groundwater Points in Sierra Leone map (Figure 1) shows the wealth of the nation's known groundwater abstraction points. The map was based on information modified from the water points inventory of 2016 published by the Salone Water Security Project (Ministry of water Resources Inventory, 2016).



Type	Category	Functionality status	Legend
Spring	*Protected*	*Yes*	▲
		No	▲
	Unprotected	*Yes*	△
		No	△
Borehole	*Tube Well or Borehole*	*Yes*	●
		No	●
	Unequipped	*Yes*	○
		No	○
Hand-dug Well	*Protected*	*Yes*	■
		No	■
	Unprotected	*Yes*	□
		No	□
Sub-surface Dam		*Yes*	
		No	

Figure 1-4: Groundwater points of Sierra Leone, extracted from Ministry of water Resources Inventory (2016).

1.4 Research Aims and Objectives

The aim and objectives of this research is to:

a) Investigate underground water resources-Using Earth Resistivity survey
b) Identify areas with high borehole yield potential-Pumping test
c) Evaluate ground water quality of those areas in relation to iron ore mining activities.

This would form bases for future guide/information that might help government agencies and various stakeholders to properly manage the water resources. My research will serve as a baseline for future groundwater investigation and water quality analyses for government and agencies alike. The iron ore mining area of Tonkoli and the shippement port of Pepel are choosen for this research. Tonkolili district that comprises predominantly of granite basement and Pepel Island, Port Loko district that is predominantly the Bullom group of sediments.

1.5 Research Methodology

The research methodology outlines the process from data collection through processing and analyses. This involves the selection of the project area, collection of drill holes information, data processing and analyses. Figure 1-4, below outlines the process.

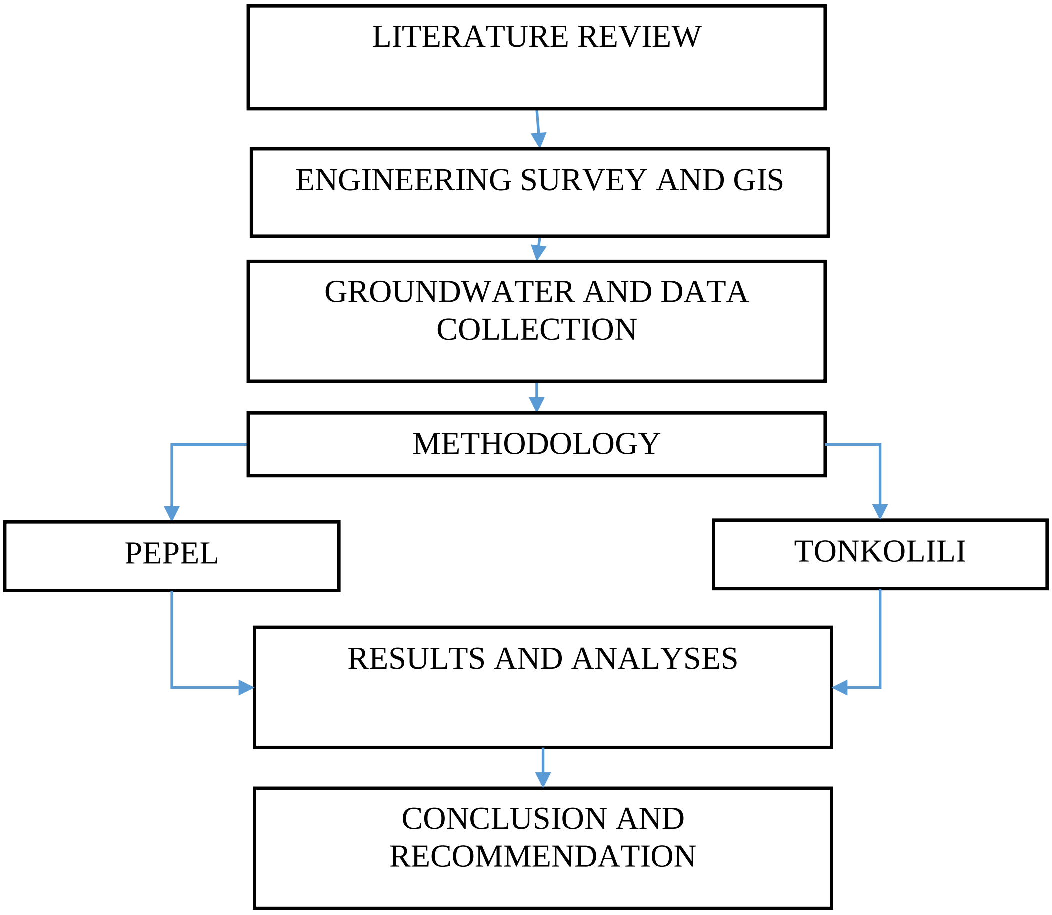


Figure 1-5: Research Flow Chart

1.6 Research Justification

The supply of water in the rural areas of Sierra Leone depends mainly on rivers, streams boreholes and shallow hand dug wells that are either contaminated or dries up quickly.

Majority of the boreholes or hand-dug wells are constructed by local contractors with no prior knowledge or investigation of the hydrogeology of the areas. With the increase of the number of population, agricultural expansion and mining companies in the rural areas, the scarcity and contamination of surface water become inevitable. Hence, the need for groundwater exploration.

Groundwater prospecting using GIS in complement with geophysical survey method will be important in solving water shortage and surface water contamination. It also provides useful information for borehole drilling and well sites selection. The study of the hydrogeological investigation, groundwater potential and water quality of the northern districts of Sierra Leone provide a useful information for future water resources development, planning and management.

1.7 Research Scope

The research focuses on hydrogeological investigation of groundwater potential and water quality in the northern region of Sierra Leone. The studied area covered the following localities of Kunike Sanda, Barina Chiefdoms in Tonkolili district and Pepel, Port Loko district.

Thirty-Five boreholes were sampled from Pepe, Port Loko districts and thirty-nine boreholes were sampled from Tonkolili district. It involves collection of boreholes location coordinates, geophysical data, pumping tests data, vertical resistivity data and water quality data. The variables considered from the VES survey are resistivity values, apparent resistivity layers.

The research also investigates the average aquifer depth of the areas, which is important for cost analysis in boreholes planning and execution. For nature of hydrogeology of the study area, drainage and slope were considered. Aquifer and aquifer parameters such as porosity, water content, hydraulic head, hydraulic conductivity, specific yield and specific storage were considered.

Drawdown and discharge were also investigated using pumping test. GIS was used to delineate the Geology, Hydrogeology, soil and vegetation of the project area.

1.8 Thesis outline

This thesis comprises of six chapters that is summarised as follows:

Chapter 1 is the introduction to groundwater. This chapter reviews previous work and outlines the reason for groundwater investigation and assessment; it justifies the objectives and scope of the research. It also, highlights methods of geographic information system (GIS) and engineering survey related to the investigation

Chapter 2 describes a method of engineering survey and GIS fitting for field investigations of water resources. Engineering survey was used for field measurements and the survey points are processed using GIS to produce the topographic map, geological map and drainage system map. GPS data points collected from the field may also be used to establish ground control points for aerial triangulation in photogrammetry. Each of these methods plays an important role in groundwater investigation.

Chapter 3 describes groundwater system of the project area and hydrological formations with the definition of certain important terms used in groundwater. It also discusses the data collection methods like the earth resistivity survey, pumping test and groundwater quality analysis. Specific aquifer properties (e.g. hydraulic conductivity, transmissivity or water table levels) are also explained on national and regional scale because groundwater storage hinge on aquifer parameters, rate of water movement and recharge of the aquifers. The project areas revealed confine aquifer system. 1) Tonkolili district: granitic terrain with fracture aquifer system and 2) Pepel district: sediments with sand aquifer system.

Chapter 4 details the methodologies used in groundwater investigation and water quality analyses. The softwares, ZOND VESIP for resistivity analysis, Aquifer Test Pro for pumping test and Arc Map for GIS, were used to model the aquifer depths, which range from 5m to16m below surface level in Pepel depending on the elevation. The research involved 74 boreholes where 35 boreholes were drilled in the sedimentary sequence in Pepel and 39 in the fractured basement aquifer in Tonkolili. The geophysical survey results of the five boreholes revealed the presence of four lithological formations with groundwater being sourced from the third and fourth layers. However, the fourth layer consisting of sand/gravel which is considered more prolific than the third layer. The transmissivity increases with decrease in resistivity through the layers. This has a tendency to find suitable place to drill a new borehole.

Chapter 5 discusses and analyzes the results. Whilst the granitic terrain comprises of fractured aquifer system and a clay layer (aquitard), the Bullom Group of sediments comprises of sand aquifer system that exhibit high yield potential. The final analysis gives a clear understanding of the aquifer system in the fracture basement with average borehole yield of 1.90 m^3/hr and that of the sedimentary sequence with average borehole yield potential of 2.04 m^3/hr. Finally, water quality tests in the boreholes showed that pH values of 46% of boreholes in Tonkolili district and 54% of boreholes in Pepel, Port Loko districts were outside WHO recommended value of 6.5-8.5. In Tonkolili, 23% of the sampled boreholes have fecal coliforms and in Pepel 34% of the sampled boreholes have fecal coliforms. It was found that in Pepel, pH has a negative correlation with Fe^{3+} and Mn^{2+}. It implies that decrease in pH is related to increase in Fe^{3+} and $Mn^{2+,}$ which results in increase of turbidity in both districts.

Chapter 6 is a WHO standard discussion, conclusion and recommendation.

CHAPTER 2

ENGINEERING SURVEY AND GIS IN GROUNDWATER INVESTIGATION

2.1 Introduction

This chapter describes the study area in relation to topography, drainage system, climate and soil condition using engineering survey and GIS. It also discusses the data collection methods like the earth resistivity survey, pumping test and groundwater quality analysis. Each of these methods plays an important role in groundwater investigation.

2.2 Field Reconnaissance and Data Collection

Reconnaissance survey of the study areas was conducted in May 2016 and September 2017. This reconnaissance visit enabled the researcher to be familiar with the study areas in terms of extent, scope and location. During this visit, the researcher was able to plan the actual fieldwork; sampling and methods adopted during fieldwork in terms of boreholes distribution and physical characteristics such as soil, vegetation geology. The available information of the areas was used as basis for data collection. The co-ordinates of sample positions that had been pre-determined and generated on the electronic versions of respective Field Sheets were uploaded onto GARMIN HCF GPS, which was then used to navigate to the designated sampling locations. GPS coordinates of borehole location were collected. Dip and strike measurements were made by a clinometer compass and rocks were chipped with a hammer. Brief descriptions of rock samples were carried out in the field and photographs were taken to show some of the features and structures of the different lithology.

2.3 Engineering Survey and Photogrammetric Techniques

Several types of surveys exist each with different accuracy and purpose. Even though their accuracies differ depending on the type of survey done, but they are closely interrelated in modern practice. Engineering surveys and Photogrammetry are widely used throughout the world by most counties for the production of topographic maps.

However, the digital era has changed things in that; many countries uses Leica Helava DPW770 digital photogrammetric workstation and Zeiss Intergraph imaging to produce topographic map and orthophoto for big cities. The digital photogrammetric system has been upgraded to 'total station' (i.e comprise of three different fields, which include photogrammetry, remote sensing and geographical information system (GIS). The upgraded version is known as Leica Photogrammetric System (LPS), which uses ERDAS as the engine (Anuar Ahmad, 2006).

Even though surveying forms an integral component of a nation or community development, it also plays a crucial role in terms of the accuracies of the different methods employed. In order to avoid the dispute over land parcels and poor judgement over state land developmental planning issues, the need to test the accuracies of the different methods, each with its own digital developmental era and suggest which method is more suitable for a particular purpose may arise.

For the purpose of this research, engineering survey and GIS are used to produce the topographic map of the project areas. In engineering survey, Total station and GPS could be used as standalone techniques in topographic mapping. Here GPS was used for data collection and GIS used data processing to produce the topographic map.

2.3.1 Difference between Topographic map and Plan

To perform any survey for any purpose, we need to know the difference between a topographic map and a plan. For the purpose of this research, we are using topographic map.

1) Topographic map

Topographic map portrays the shape, features and elevation of the land. . Topo map as it is sometimes called depict the three-dimensional ups and downs of the terrain on a two-dimensional surface. These maps use "contour lines" (lines of equal elevation) to show elevation. Lines that are close together indicate steep terrain, while lines far apart indicate flat terrain. Maps are used for several functions:

a) By geologists for exploration of natural resources, like groundwater etc.
b) By engineers and planners for road, highway, canal and pipeline construction,
c) By architects in housing and landscape design,
d) By agriculturists in soil conservation work,
e) By archaeologists, geographer and scientists in various fields

2) **A Plan**

Where are as a Plan is a set of two-dimensional diagrams or drawings used to describe a place or object, or to communicate building or fabrication instructions. Usually plans are drawn or printed on paper, but they can take the form of a digital file. Plans are usually scale drawings, meaning that plans are drawn at specific ratio relative to the actual size of the place or object. Various scales may be used for different drawings in a set. The projections of land features on a horizontal plane are depicted on a plan. It contains North-line with respect to which the relative directions of the different land features may be ascertained. It has a scale that helps to determine the actual horizontal distance between any two-land features, which can be read from the drawing. However, it contains no information from which geographical location of the area may be determined (De, A. 2007).

3) Map scale

Conceptually, map scale is the ratio between the distances of any two points on the map compared to the actual ground distance represented. Maps are rarely drawn at the same scale as depicted in the real world. Most maps are made at a scale that is much smaller than the area of the actual surface being depicted. The amount of reduction that has taken place is normally identified somewhere on the map. This measurement is commonly referred to as the map scale. On most maps, the map scale is represented by a simple fraction or ratio. This type of description of a map's scale is called a representative fraction. For example, a map where one unit (centimeter, meter, inch, kilometer, etc.) on the map represents 1,000,000, will have the same units on the actual surface of the Earth which would have a representative fraction of 1/1,000,000 (fraction) or 1:1,000,000 (ratio). Of these mathematical representations of scale, the ratio form is most commonly used on maps. Scale can also be described on a map by a verbal statement. For example, 1:1,000,000 described as "1 centimeter on the map equals 10 kilometers on the Earth's surface" or "1 inch represents approximately 16 miles".

Most maps also use graphic scale to describe the distance relationships between the map and the real world. In a graphic scale, an illustration is used to depict distances on the map in common units of measurement. Graphic scales are quite useful because they can be used to measure distances on a map quickly. A large-scale map shows great detail in small features and has a large representative fraction, example a map with a scale of 1:10,000. A small-scale map shows large features and small representative fraction, example a map with a scale of 1: 250,000.

4) Map Projection

The shape of the Earth's surface can be described as an ellipsoid, which is a three-dimensional shape that departs slightly from a purely spherical form. The Earth takes this form because rotation causes the region near the equator to bulge outward to space. To represent the true shape of the Earth's surface on a map creates some problems, especially when this depiction is illustrated on a two-dimensional surface., To overcome these problems, cartographers have developed a number of standardized transformation processes for the creation of two-dimensional maps. All of these transformation processes create some type of distortion artefact. The nature of this distortion is related to how the transformation process modifies specific geographic properties of the map. Some of the geographic properties affected by projection distortion include distance; area; straight-line direction between points on the Earth; and the bearing of cardinal points from locations on our planet.

An estimate of the earth's surface based on an ellipsoid provides a determination of the elevation of every point on the earth's surface, including sea level, and is often called a datum. Over time, many datums have been developed in different countries and are presently used. With more accurate means of measurement today (i.e. satellite and GPS), recent datums are referenced from the centre of the earth rather than a theoretical surface. The resulting North American Datum of 1983 (NAD83) and the slightly refined World Geodetic System (WGS84), from the U.S. Military in 1984, are internationally accepted as the geodetic reference system (GRS 80) which is used for the purpose of this project.

2.4 Geographic Information System (GIS)

A geographic information system (GIS) is a framework for gathering, managing and analyzing data. GIS integrate many types of data for various purposes. It analyses spatial location and organizes layers of information into visualization using maps.

GIS is a powerful tool for developing solutions for water resources, such as assessing water quality and managing water resources on a local or regional scale. Hydrogeologists use GIS technology to integrate various data and application into one, manageable system. For this research GIS is used to produce the topographic map of the study areas, geological and to assess the water quality. However, GIS is a tool that is widely used for different purposes.

For this project, the mapping was done on a regional mapping scale using the 1:50.000 topographic sheets. Pumping test analyses of 10 borehole water samples from 74 selected wells were collected in the two districts from May – September 2017 was done. Samples were collected from each well for physical-chemical and bacteriological analysis in new plastic bottles with their caps tightly secured. The samples are placed in iced coolers and transported to the laboratory, where they were stored in a refrigerator for analyses. The coordinates from field mapping of soils, rocks and borehole were download, using GIS software; a map of the location was produced. See figure 2.1 below

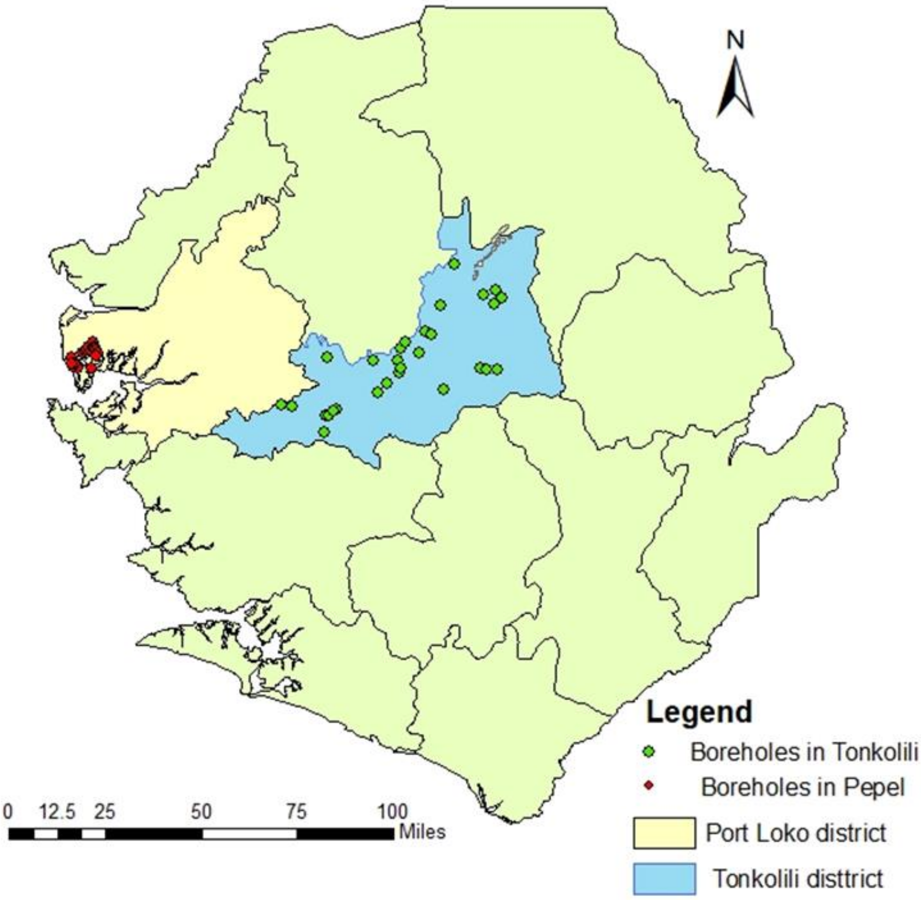


Figure 2-1: Borehole Location Map

2.5 The Geography of the Studied Areas

The Study area comprises of two districts in the Northern region of Sierra Leone. The first area is Kunike Sanda, Tonkolili district and the second area is Pepel, Port Loko district. However, both districts have many things in common such as topography, drainage system, vegetation, climate, soil conditions and mining activities.

1) Tonkolili District

It lies between longitude 11º 42^1 and 11º 27^1 west of Greenwich and latitude 8º 42^1 and 8º 33^1 north. It lies within sheet 56 and 57 of the 1:50.000 contoured plain metric map of Sierra Leone. Figure 1 shows the topographic map of Sierra Leone. The studied area covered the following localities of Makali, Mathonkara, Makoni Line, Petifu Line, Masingbi, Masaba, Machain, Magbasia, Bumbe and a host of other villages.

2) Pepel, port Loko District

The historic village of Pepel serves as a shipment port for Shandong Steel's iron ore, mined in Tonkolili District, northern region of Sierra Leone. Pepel village with a population of 1000 is relatively low-lying and one of several islands occurring on the Coastal Creek of Sierra Leone. It is located between latitudes 8° 35' 47" N and longitudes 13° 03' 53" W.

Although fishing is the main occupation of the people, the commencement of operations of Shandong Steel's Rail and Port facility has necessitated an influx of job seekers from other parts of the country.

The major land use is small-scale gardening, which is practiced by older women. There are no surface water sources on the Island and groundwater appears to be the principal source of drinking water. Figure2-2: below shows the location of the two districts within the topographic map of Sierra Leone.

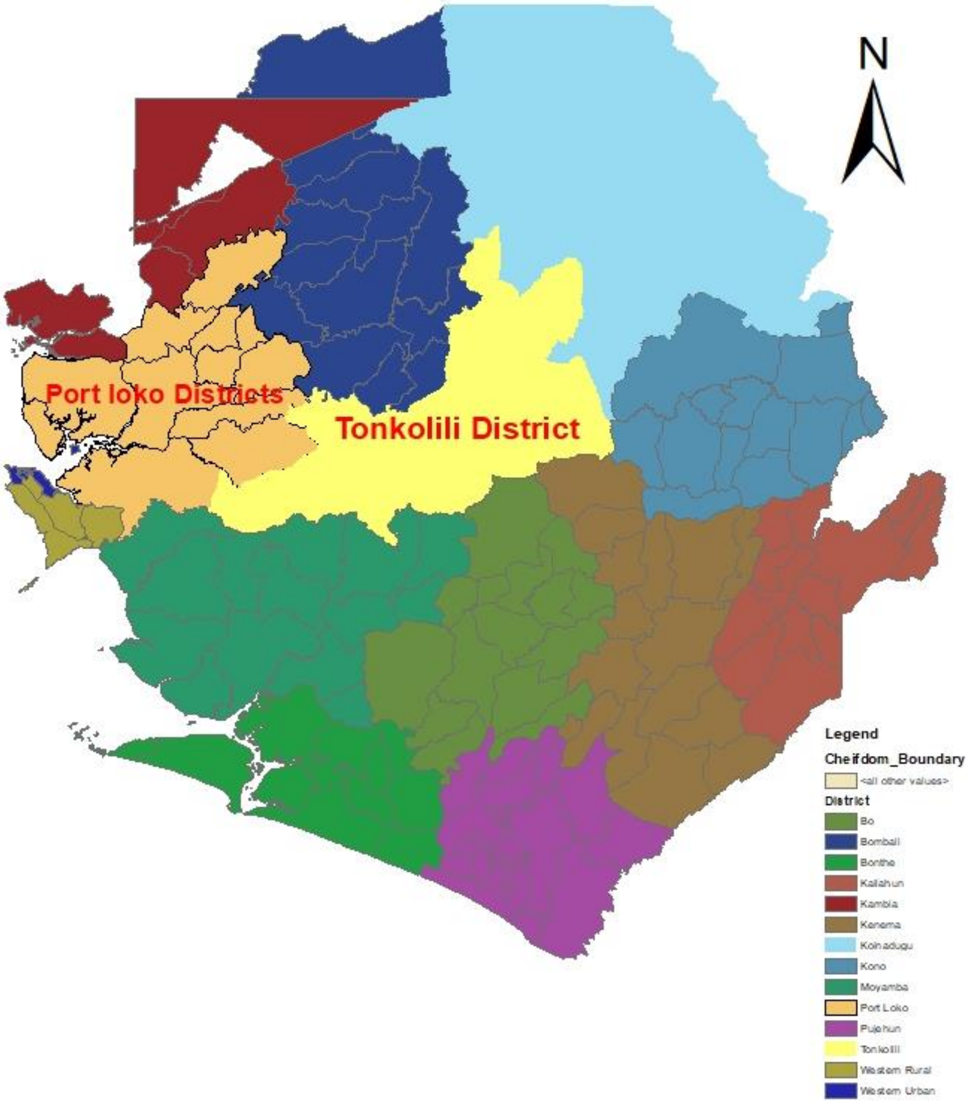


Figure 2-2: Topographic map showing project Areas

2.5.1 Topography

1) Tonkolili District:

Tonkolili is a hilly terrain with the hills rising over several meters above sea – level. The Sula Mountains occur in the northern – most part of the area and are separated from the Kangari hills by the Panpana River running roughly in the east-west direction. The hills in the area form a continuous strip and are concentrated in the middle of the area.

The Kangari hill forms a prominent ridge south of Makali and rise to height of over 600m. Apart from the Kangari hills there are other smaller hills found within the project area. These hills include the Bonke hill located in the North-West (NW) and the Bumbe hill in the North-East (NE) of the project area. The Kangari hill is the highest topographic feature in the area. The arrangement of the hills with the surrounding flat to gently undulating country reflects the geology. The schist belt occupies the central hilly area and is enclosed in a sea of gently undulating granitic rocks.

2) Port Loko District

Pepel is a relatively low-lying land with mangrove swamps that eventually empty into the sea. Geographically, the area can be characterized as a coastal, tropical landscape with a limited range of uniform landforms.

2.5.2 Drainage System

These areas are drained by several streams and rivers. The individual mountains are separated from each other by sharp, deep valleys. The prominent rivers in the area are – the Kabankefera and Tebenko.The Kabakefera river flows across the area in a roughly North – South direction and is fed by several tributaries including Masuntak, Makrugbali, Kantegbe, Kalange, Matong etc – and it marks the boundary between the two chiefdoms i.e. Kunike Sanda and Barina. The Tebenko River flows in the same direction as the Kabakefera but bends prominently around the Makali area to flow almost at right angles to the original direction and eventually empties in to the Pampana River.

The small tributaries and streamlets take their directions from secondary topographic features and eventually drained into the sea. Unlike the rivers, some of the streams are perennial while others are only seasonal. However, these streams and rivers transport wastes, which are dump into them and finally empty their contents into the Pampana River and the sea. Hence, a good mechanism of drainage system is found within the area. Figure 2-3: below shows streams, rivers and surface water monitoring points within the project areas. This affirms the good drainage system within the region. Generally, the region experiences high rainfall, which increases from North to south.

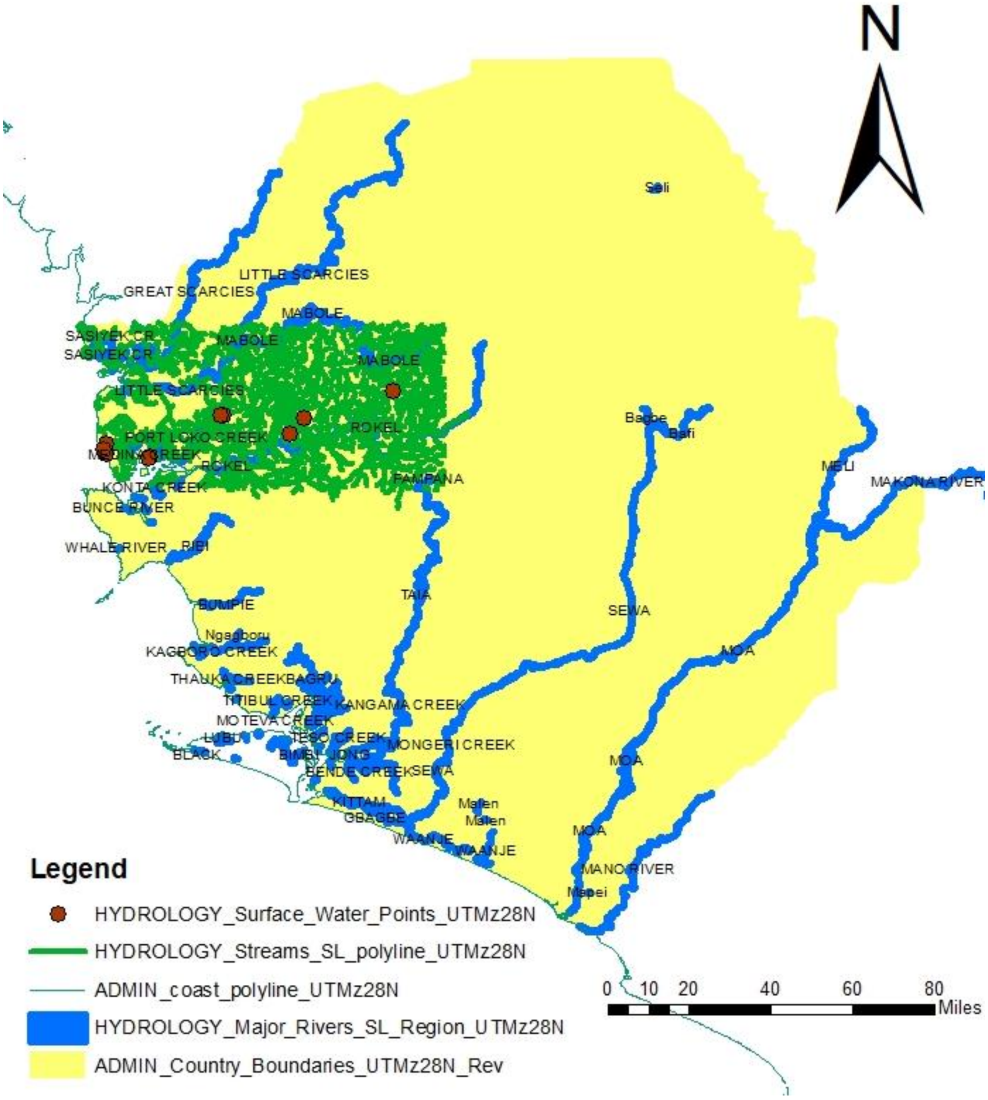


Figure 2-3: Rivers, Streams and Surface water Monitoring Points

2.5.3 Vegetation

Most of the area is covered by thick vegetation especially along streams and very close to villages where relics of the virgin forest are still preserved. Some of these thick forests have been cleared for farming, thus exposing a lot of out crops for investigation.

Lateritisation is very extensive in some areas and is generally less widespread within the Kangari hills than it is within other parts of the project area. However, fresh outcrops are present in many areas.

The area is covered by thick shrubs, variety of grasses, swampy land which occur particularly in valleys as a result of prolong annual flooding and soils mostly of residual origin. Nonetheless, the area has a network of secondary roads, footpaths and cut lines made by farmers. These provide access to most of the area, thus facilitating the mapping.

2.5.4 Soil Condition

The project areas are covered by lateritic soils mostly of residual origin. In most areas there are thin silty clays overlying the laterites. These brown silty soils appear to be the result of cultivation over a long period and turning of the soils by ants and earthworms during the fallow period of the land.

These silty soils are absent from areas of high elevation where the soil contain irregular laterite pebbles in a dark brown loamy matrix. The gently sloping areas surrounding some hills and in places where the soil covers have been stripped off by erosion, the exposing lateritic duricrust have much thinner soils

2.6 General Geology of Sierra Leone

Sierra Leone forms parts of the West African Craton. About 70% of the outcrops are older than 2.1 G. a. These rocks have been affected by many tectonic events and the structures produced have been used to unravel the geological history of the country. The country consists mainly of an Archaean granite greenstone terrain bounded in the West by a Westward dipping zone of intense high-grade rocks which forms the Kasila group and it has been interpreted as suture. East wards the granite – greenstone terrain is bounded by low-grade metamorphic rocks of the Marampa group. The geology of Sierra Leone like other parts in West Africa consist of:

1) The Basement complex

2) The Supracrustal rocks

3) The Intrusive granites

2.6.1 The Basement Complex

The rocks in the basement complex range in composition from migmatised meta-sediments, gneissose-quartz-diorite or granodiorite and foliated or massive granites to medium-grained homogenous biotite granites. The rocks in the basement complex is metamorphosed and outcropped as irregular linear supracrustal with a NS to NE-SW trend. The basement can be sub-divided into infracrustal rocks, Kambui Supracrustal rocks and basic and ultrabasic rocks (Macfarlene et al., 1980). The basement is mainly Leonean in age.

At least two major episodes of deformation, metamorphism and granitisation are recognized within the basement complex

a. The Liberian event which is the youngest i.e. $\leq$ 2.7 Ga.
b. The Leonean event which is the oldest i.e. $\geq$ 2.7 Ga.

A third major event of deformation, metamorphism and granitisation are the Rockelide event, which is about 550 Ma. The Leonean episode resulted in the formation of folds and fabrics trending in the E – W direction, but structures formed in the Leonean event have been obliterated by the younger Liberian episode thus leaving little or no evidence of the Leonean event.

Figure 2-4: Rocks of the Basement Complex in the Granite Terrain (Jalloh et al. 2013)

2.6.2 The Supracrustal Rocks

The greenstones of the Liberian event have been considered as the supracrustal suit to the Leonean basement (granitic basement); this is because the structures on the rocks during the Leonean event were obliterated by the younger Liberian event. The supracrustals are mainly referred to in Sierra Leone as the Kambui super group (comprising the Sula and Marampa group) which forms the bulk of the granite – greenstone terrain overlying the Eastern part of the country with the Leonean as the basement. The supracrustals in Sierra Leone have been divided into several groups which consist of large variety of metamorphic rocks of both igneous and sedimentary parentage. These supracrustal rocks include schist, serpentinite, amphibolites and ironstones as seen in figure 2-5 below.

Figure 2-5: Amphibolite rocks of the supracrustal

2.6.3 The Intrusive Granites

In Sierra Leone they form the syntectonic to late tectonic plutonic intrusions (Marmo, 1955). The intrusions range in size from large masses having gradational contact with the basement to smaller cross-cutting stocks and plutons down to pegmatite and aplites. They are mainly of granites to granodiorite in composition and include smaller masses of diorite, gabbro, syenite and other related rocks as seen in figure 2-6 below. The granites intrude both the basement and supracrustals and are therefore younger than the two. They are proposed to have been emplaced during the last of the reactivation events of the basement. The granitic intrusions vary in size from large elongate batholiths to small circular stocks. The larger bodies tend to be foliated and many of them are porphyritic with feldspars reaching several centimeters in size. The smaller intrusions are unfoliated and generally fine grained. The larger granites are syntectonic i.e. they were emplaced during the climax and metamorphism of the basement. The smaller granites are late – tectonic i.e. they were emplaced during the warning stage of deformation and metamorphism.

Figure 2-6: Gabbroic rock of the intrusive granites.

Geological map below depicts 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. 28 geologic formations have been mapped, ranging from Archean (3.5 billion years ago) to Quaternary (2 million years ago). Hydrogeology of Sierra Leone (Ministry of Water Resources of Sierra Leone (2017).

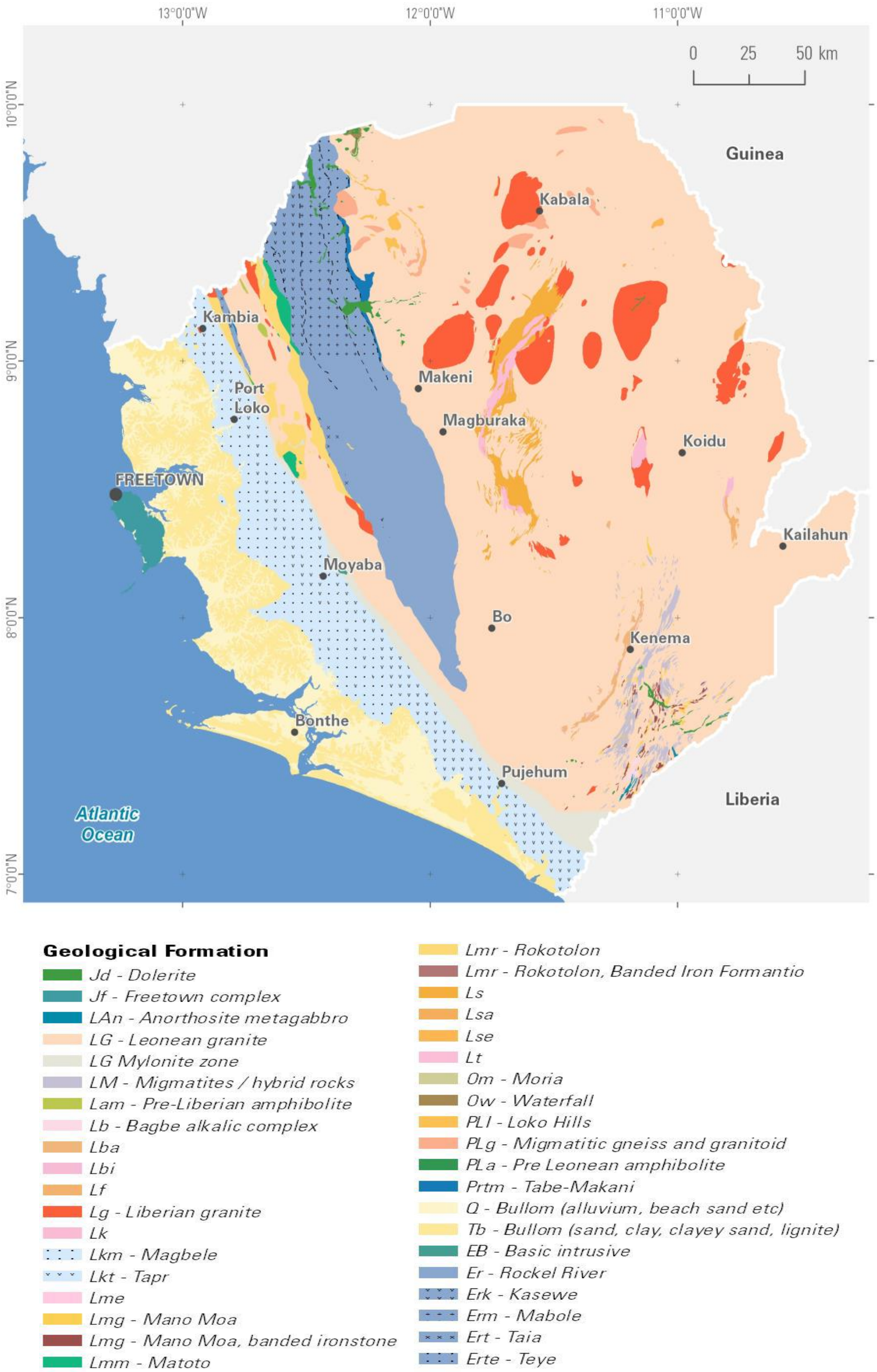


Figure 2-7: Generalized geology of Sierra Leone (2017) base map from Keyser and Mansaray (2004).

2.7 Geologic and Hydrogeologic Setting of the Project Areas

In Sierra Leone, the weathered basement form the most widespread and important aquifer across. The weathered zone is derived from the underlying parent rock formations, under intense rainfall and large seasonal groundwater table variations. The resulting thick tropical soils form an important part of both the unsaturated zone and shallow aquifers (Akiwumi, 1987; UN, 1988).

There are open fractures at depth below the weathered zone, which are associated with fault zones. The flow of groundwater is faster at the fracture zone with high porosity and permeability than the weathered zone as depicted in the project areas. See figue x below. In weathered crystalline basement as it is found in Tonkolili, most sustainable groundwater sources tend to exploit groundwater in fractures at the base of the weathered zone at average depth of 15 – 40 m in basement, depending on the thickness of the weathered zone. In the porous aquifer formation as it is found in Pepel, groundwater sources to tend to exploit groundwater in wet sand layer just below the weathered zone.

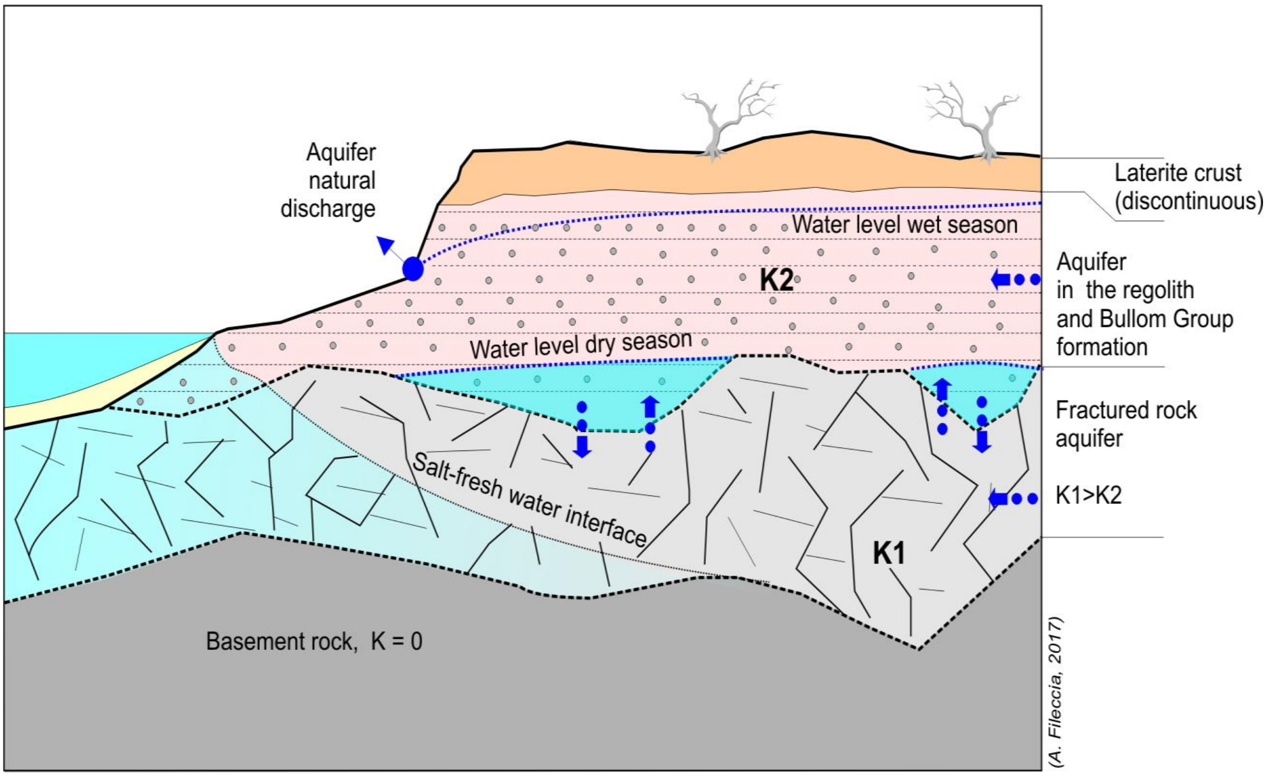


Figure 2-8: Simplified aquifer structure in the coastal zone and fracture basement of Sierra Leone (Ministry of water Resources, 2017)

2.7.1 The Geologic Setting of Tonkolili District

The geology of Tonkolili forms the syntectonic to late tectonic plutonic intrusive granites. The rocks in this region vary in dimension from great elongate batholiths aligned parallel to the structural grain, to small sub-circular rocks.

Figure 2-9: Geologic map of project area in Tonkolili.

The larger bodies tend to be foliated and many of them are porphyritic with feldspars whereas, the smaller intrusions are unfoliated and generally fine-grained. Most of the landform in the Bullom group of sediments is formed by erosion of these granitic masses, with their characteristics exfoliation weathering patterns.

The smaller granite bodies generally have sharp boundaries that cut across the basement structures. The larger granites also have sharp cross- cutting boundaries where they are emplaced into the supracrustal. The intrusion of granites within the supracrustal led to contact metamorphism of the schists and phyllites. The unfoliated nature of the smaller crosscutting (discordant) granites indicates that they were emplaced later, after the main climax of deformation and metamorphism.

2.7.2 The Hydro-geologic Setting of Tonkolili District

Tonkolili District belongs to the consolidated metamorphic hydrogeologic units of the Sayonia Scarp and Rokel River formations. There is a near-surface weathered (regolith) layer that is often dominated by clay. Below this are ancient consolidated meta-sedimentary rocks, with very limited inter-granular porosity.

Groundwater storage and flow occurs within fractures in the basement rocks (secondary porosity), which are often along old bedding plains, although there is limited information on potential borehole yields in the formation due to lack of investigation prior to borehole construction by inexperience local contractors. However, this research provides adequate information on the potential borehole yields for this area. The average monthly and annual rainfall in the area is high, which is the source for groundwater replenishment.

2.7.3 The Geologic Setting of Pepel in Port Loko District

The Island is part of the Coastal Plain, which is underlain by the Bullom Group (Figure 2-10) comprising of unconsolidated to poorly consolidated fluvial, estuarine, and marine sediments. The deposits extend up to 50 km inland and are found at heights of up to 40 m above present sea level.

Although outcrops of the Bullom Group are poorly exposed on the Island, field observations supported by published data (Culver and Williams, 1979a) suggests a laterally variable sequence of poorly consolidated, near horizontal, often iron-stained gravels, sands, and clays with occasional intraformational laterites.

The sands are generally poorly sorted, sometimes graded, but rarely cross-bedded. Occasional grit beds, stringers of rounded quartz pebbles, and horizons of kaolinitic clay clasts are found in association with the sands. Also, within the sands are intraformational laterites, which often form puddingstone horizons (Culver and Williams, 1979a). The clays are red, purple and white in color and are almost invariably kaolinitic.

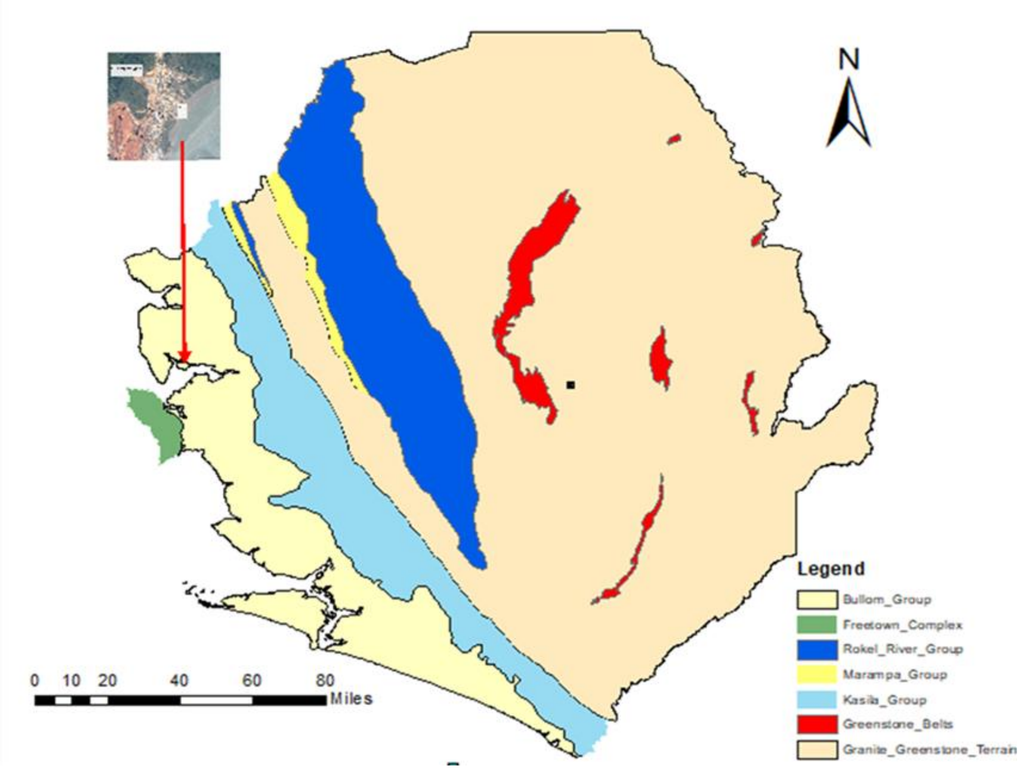


Figure 2-10: Geological map of Sierra Leone showing Pepel (Jalloh et al., 2017)

2.7.4 The Hydro-geologic Setting of Port Loko District

Pepel forms the unconsolidated sediments deposits. This hydrogeologic unit can be subdivided into alluvial (valley fill) and coastal deposits of the Bullom Group formation. There is a dearth of published data on the hydrogeology of the Bullom Group. However, recent drilling campaigns in areas underlain by these sediments have provided new evidence of its potential as a reliable source of water for drinking and other domestic use.

Field observations on the Island corroborated by information from other sources suggest that the topmost layer in the sequence consists of medium to coarse iron-stained sandstone, which overlies a clay layer of variable thickness that serves as an aquitard.

The sediments are part of the Sand and Gravel Aquifer, which is perhaps the highest yielding of all the established aquifers in Sierra Leone.

A vertical section of a cliff face at Konakridee, a small fishing village west of the island suggests a multilayered sequence comprising both unconfined and confined aquifers. Groundwater occurs within poorly consolidated sands outcropping on the surface and between intervening layers of clay. Thus, semi-confined and confined conditions are likely in some places. Static water level measured in five boreholes drilled into the sand aquifer in the late dry season give a mean value of 10.6m. This value is expected to rise significantly at the end of the rainy season in October. Flow within the sand aquifer is intergranular attributable to poor consolidation of the sands.

A Transmissivity of 3.34 m^2/day was determined in a borehole pumping at a rate of 130 m^3/day, for a maximum drawdown of 6.13 m. (Sierra Leone Water Company, SALWACO, 2017).

The area experiences high rainfall and moderate evapotranspiration, with a theoretical annual net surplus of water. The absence of legitimate surface water sources clearly indicates that most of the rainfall goes into storage in the subsurface. By virtue of its location, groundwater on the Island may be influenced by saline intrusion. Wells must therefore be located some reasonable distance from the sea and groundwater withdrawals should be well managed.

Water quality data obtained from pumped boreholes suggest that the ground waters are fresh with total dissolved solids content ranging between 41.3 mg/l and 94 mg/l (African Minerals Limited, 2011). The waters are relatively acidic with pH values ranging from 4.9 to 7.2, with a mean of 5.9. Nitrate concentrations are slightly higher than the global standard (WHO, 2011), with a maximum concentration of 18 mg/l.

CHAPTER 3

GROUNDWATER AND DATA COLLECTION

3.1 Introduction

This chapter describes groundwater system of the project area and hydrological formations with the definition of certain important terms used in groundwater. It also discusses the data collection methods like the earth resistivity survey, pumping test and groundwater quality analysis. Specific aquifer properties are also explained on national and regional scale because groundwater storage hinge on aquifer parameters, rate of water movement and recharge of the aquifers. The project areas revealed confine aquifer system. 1) Tonkolili district: granitic terrain with fracture aquifer system and 2) Pepel district: sediments with sand porous aquifer system.

3.2 Groundwater

Groundwater is water that exists in the pore spaces and fractures in rocks and sediments beneath the Earth’s surface. It originates as rainfall or snow, and then moves through the soil and rock into the groundwater system, where it eventually makes its way back to the surface streams, lakes, or oceans. It makes up about 1% of the water on the Earth (most water is in oceans).

Groundwater occurs everywhere beneath the Earth’s surface but is usually restricted to depth less than about 750 meters. Groundwater originates primarily from either meteoric water, connate water or fossil water.

The subsurface occurrence of groundwater may be divided into zones of aeration and saturation. The zone of aeration consists of pores occupied partially by water and partially by air. In the zone of saturation, all pores are filled with water, under hydrostatic pressure. Groundwater flow in soils and rocks takes place through void spaces, such as pores and cracks. The hydraulic properties of soils and rocks therefore depend on the sizes and shapes of the void spaces. These vary over very short distances (e.g.

micrometers or millimeters). The geological units through which groundwater are stored and transmitted are called aquifers.

The map below shows the main hydro-geologic units and water-table elevation contours, for two particular timeframes December 2016 and April 2017 –and are representative of the general flow conditions for a large area of the country (Fileccia et al., 2017). The groundwater map below depicts the distribution of the three hydro-geologic units at a national scale.

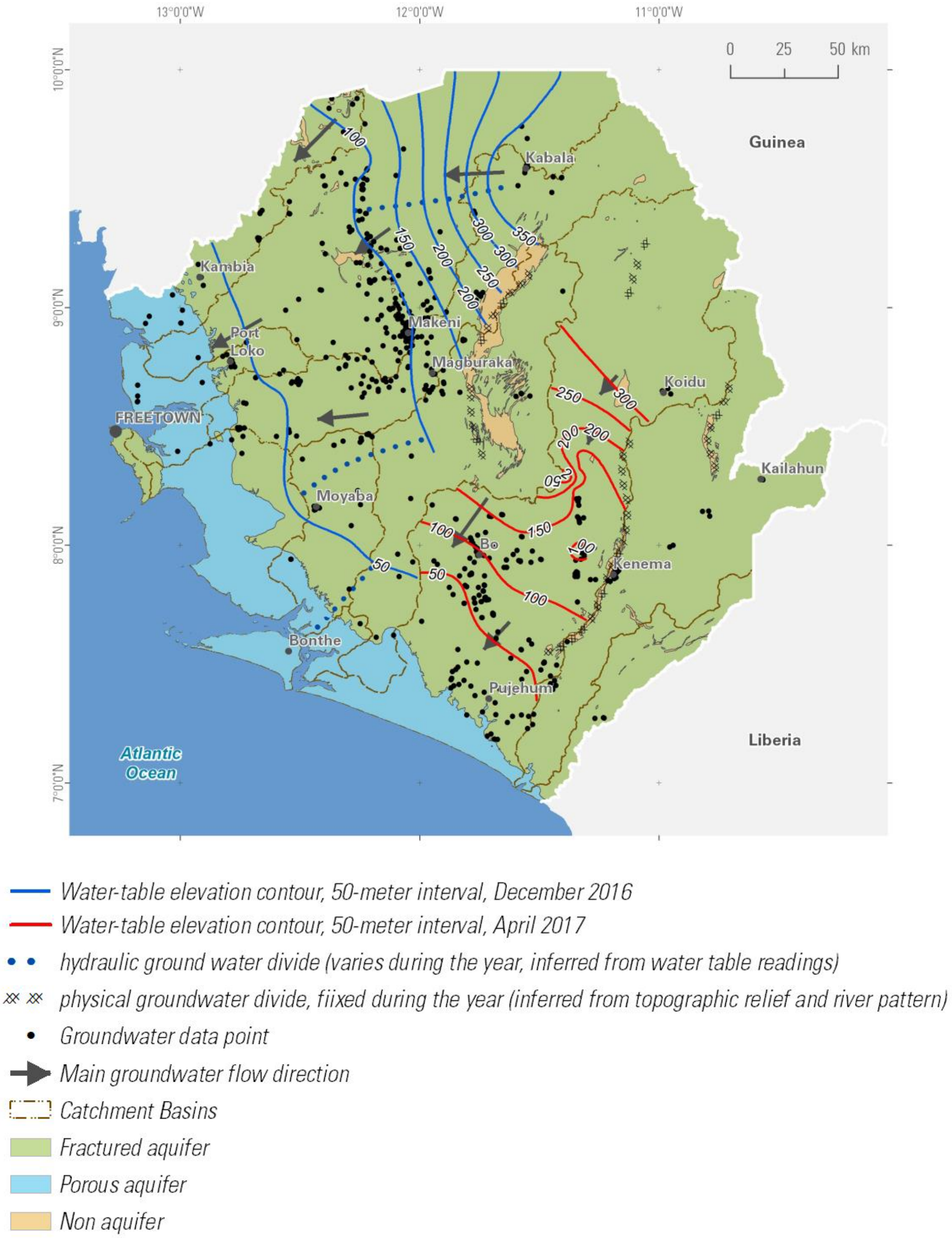


Figure 3-1: Groundwater map of Sierra Leone (Ministry of water Resources, 2017)

The BIF are characterised by alternating thin layers of magnetite-silica bands contained within fine grained, fresh and unaltered pelitic sediments and mica quartz schist beds. The magnetite silica bands are layered parallel to the bedding. Thin beds of non-mineralised to weakly magnetic granite and light to dark grey mafic tuffs appear to be conformably interbedded with the pelitic and mica schist beds. The lateritic duricrust covers the weathered and primary BIF mineralisation and varies up to 65 m in thickness. Between the laterite and the underlying magnetite, the weathered oxidised BIF retains the primary textural fabrics and the mineral assemblage is characterised as being hematite-magnetite-goethite-limonite-silica plus clay minerals.

3.3 Groundwater Situation in the projects areas

Tonkolili and Port Loko as a district and the surrounding villages are dependent on groundwater for safe drinking water supply even though surface water is available but hugely contaminated. Most of the people in these areas and villages are using hand dug wells or boreholes. At present, the water situation is not encouraging as found out during the investigation. The boreholes that were constructed to ease the water problem are not meeting the demand of the community because of the increase in population. Influx of job seekers are putting pressure on the few available boreholes.

3.4 Hydrogeological Formation

There are basically, four hydrogeological formations classified as either aquifers or non-aquifers depending primarily on their permeability.

3.4.1 Aquifers

An aquifer is a ground-water reservoir composed of geologic units that are saturated with water and sufficiently permeable to yield water in a usable quantity to wells and springs. Sand and gravel deposits, sandstone, limestone, and fractured, crystalline rocks are examples of geological units that form aquifers. Aquifers provide two important functions:

a) They transmit ground water from areas of recharge to areas of discharge, and
b) They provide a storage medium for useable quantities of ground water. The amount of water a material can hold depends upon its porosity. The size and degree of interconnection of those openings (permeability) determine the materials' ability to transmit fluid.

Aquifers may be classed as unconfined or confined depending on the presence or absence of a water table, while a leaky aquifer represents a combination of both. Either of them may exist in the project area.

1) Unconfined Aquifers

An unconfined aquifer is one in which a water table varies in undulating form and in slope, depending on areas of recharge and discharge, pumping from wells, and permeability. Rises and falls in the water table correspond to changes in the volume of water in storage within an aquifer.

An unconfined aquifer involves perched water bodies that occurs wherever a groundwater body is separated from the main groundwater by a relatively impermeable stratum of small extent.

2) Confined Aquifers

Confined aquifers, also known as artesian or pressure aquifers, occur where groundwater is confined under pressure greater than atmospheric pressure by overlying relatively impermeable strata. A region supplying water to a confined area is known as a recharge area; water may also enter by leakage through a confining bed. Rises and falls of water in wells penetrating confined aquifers result primarily from changes in pressure rather than changes in storage volumes.

3) Leaky Aquifers

Aquifers that are completely confined or unconfined occur less frequently than do leaky, or semi-confined, aquifers. Leaky aquifers are a common feature in alluvial valleys, plains, or former lake basins where a permeable stratum is overlain or underlain by a semi-pervious aquitard or semi-confining layer. Pumping from a well in a leaky aquifer removes water in two ways: by horizontal flow within the aquifer and by vertical flow through the aquitard into the aquifer. Figure 3-2, below is a Schematic illustration of the various aquifer scenarios described above.

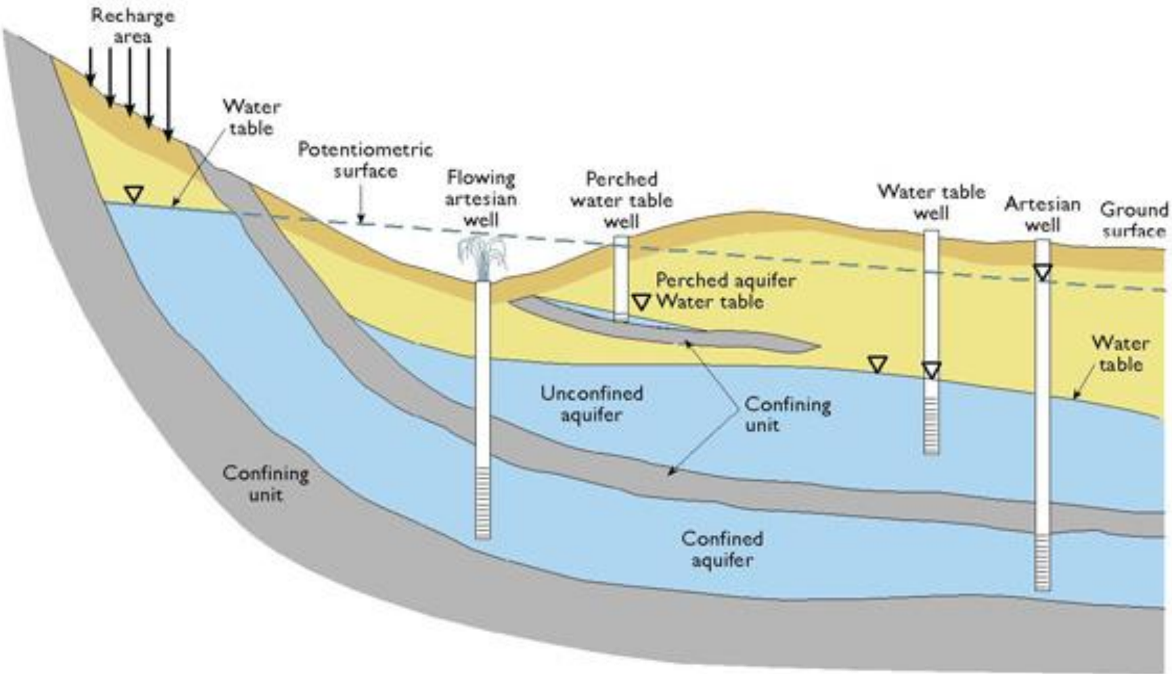


Figure 3-2: Schematic cross section of Aquifer Types (Ministry of Water Resources, 2017)

3.4.2 Aquitard

An aquitard is a partly permeable geologic formation. It transmits water at such a slow rate that the yield is insufficient. Pumping by wells is not possible. For example, sand lenses in a clay formation will form an aquitard.

3.4.3 Aquiclude

An aquiclude is composed of rock or sediment that acts as a barrier to groundwater flow. Aquicludes are made up of low porosity and low permeability rock/sediment such as shale or clay. Aquicludes have normally good storage capacity but low transmitting capacity.

3.4.4 Aquifuge

An aquifuge is a geologic formation that does not have interconnected pores. It is neither porous nor permeable. Thus, it can neither store water nor transmit it. Examples of aquifuge are rocks like basalt, granite, etc. without fissures.

3.5 Aquifer Properties in Sierra Leone

Sierra Leone has very few published records of aquifer properties and no national scale research on the distribution of specific parameters (e.g. hydraulic conductivity, transmissivity or water table levels).

Existing reports from local contractors normally record field data without processing. Well yield in liters/second (L/s) is the most common registered parameter. When drawdown is available, Specific Capacity (SC) can be calculated as an indication of transmissivity.

Other properties such as storage or specific yield values are usually derived from estimates of effective porosity based on an assessment of rock composition, even though this approximation could only be acceptable for porous formations and not for fractured rock aquifers. The above applies for the boreholes in the study area. Several abandoned boreholes and hand-dug wells are found without any record of aquifer parameters or water quality data.

3.5.1 Rain Fall

The project areas lie within the tropical monsoon zone with a pronounced wet season extending from June to October and a dry season from November to May. The areas receive high amount of rain fall not less than 250mm of rain 70% of which falls during the wet season, the remainder occurring during the early and late stages of the dry season. Average daytime temperatures may reach over 35ºc whilst during the night 10 ºC is normal (Macfarlene et al). Rainfall data from April 2013 to April 2015 for Tonkolili and April 2014 to January 2016 for Pepel was obtained and presented below. However, the distribution of rainfall recording stations in Sierra Leone are not homogenous partly because they are not many.

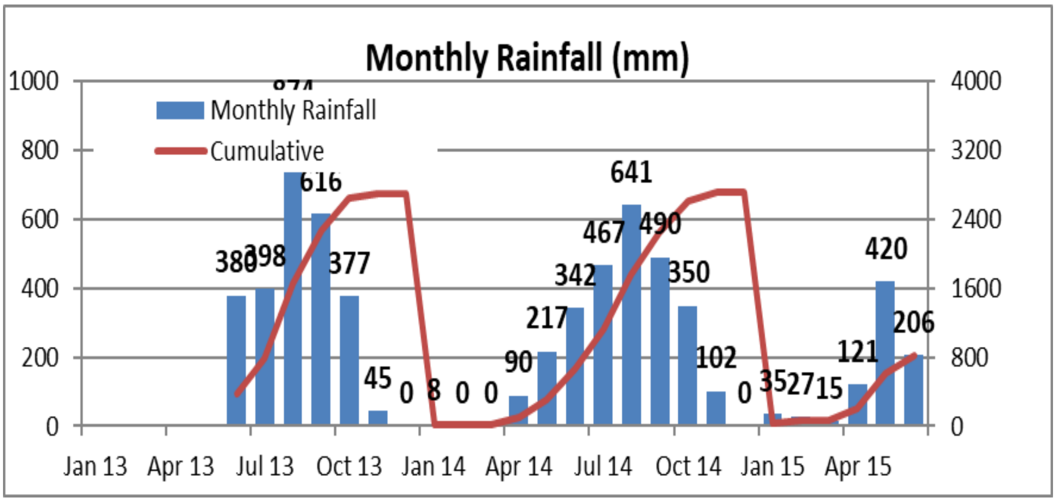


Figure 3-3: Monthly rainfall for from April 2013 to April 2015 for Tonkolili

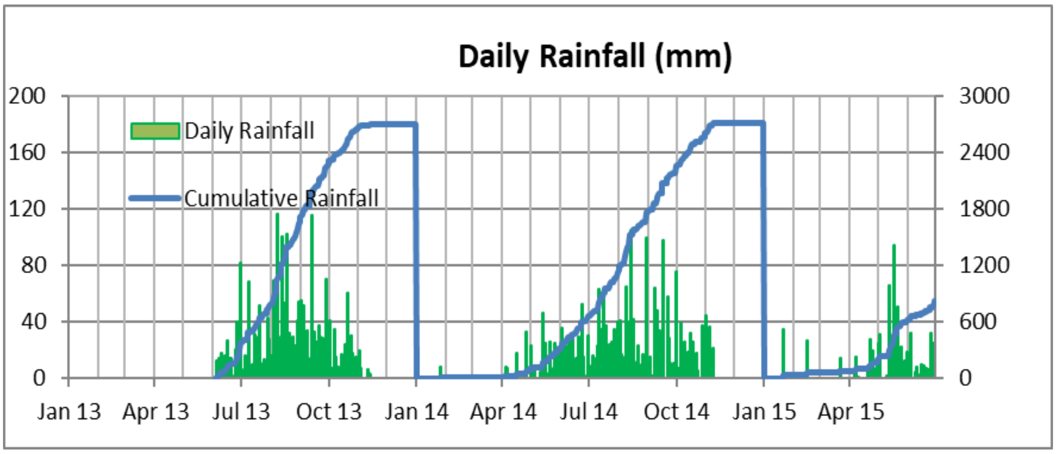


Figure 3-4: Daily rainfall for from April 2013 to April 2015 for Tonkolili

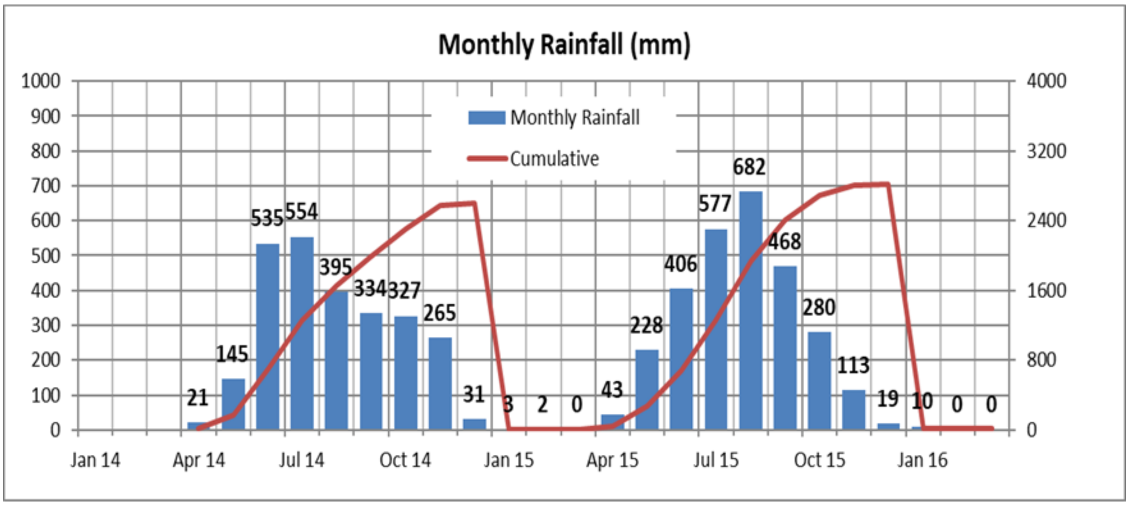


Figure 3-5: Monthly rainfall for from April 2014 to January 2016 for Pepel

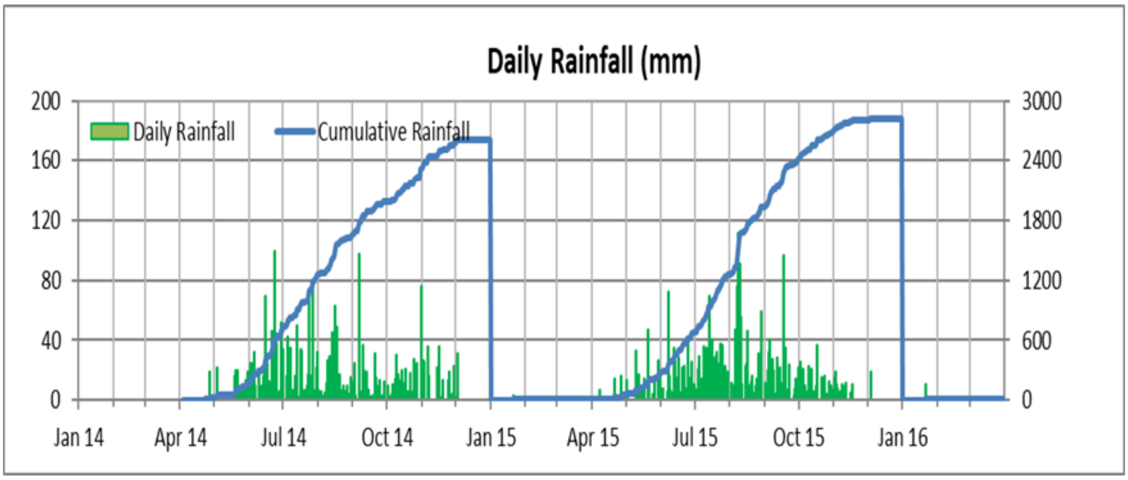


Figure 3-6: Daily rainfall for from April 2014 to January 2016 for Pepel

3.6 Data Type Collected in Tonkolili and Port Loko Districts

3.6.1 Aquifer System

The geometry of the aquifer or aquifer system and possible interlayered aquitards, are determined by the extent and thickness of the aquifer. These geometrical parameters are derived from the study of the geology of the area, borehole drilling data and geophysical well logs. Any geological material that is sufficiently permeable to yield significant amount of water to pumping wells is called an aquifer. For a geological material to be an aquifer, it should be porous and permeable.

During geological field investigation, three major rock formations are found in the project area that have greater potential of groundwater storage: -

a) The weathered layer formation – Nearly all dug wells in the area penetrate this aquifer but recharge is generally low due to low transmissivity
b) The zone between overburden and hard rock – This aquifer is very difficult to penetrate, but with favorable climatic conditions, weathering of the hard rock gives high prospects of exploiting this aquifer. Wells that penetrate this aquifer give water of good quality since water is filtered as it passes through the rocks.
c) The Hard Rock – This aquifer is very reliable but drilling through this aquifer requires special drilling techniques and for this reason, drilling through these aquifers is done by hammer drilling method.

3.6.2 Pumping Test Data

Pumping tests are carried out for the following reasons: -

a) To determine the behavior of the aquifer during pumping in the borehole and for different yields to fix the maximum yield for exploitation compatible with the conditions of the aquifer.
b) To determine particularly the hydraulic characteristics of the aquifer around the borehole (i.e. transmissivity)
c) To determine that the water table of the reservoir do not over exploit the aquifer and to limit the yield according to the condition of the aquifer.

This method, (pumping test) can be used for the determination of Transmissivity and Storativity.

Two boreholes are needed in pumping test. The first one is the production well and the other is an observation well. Essentially water is pumped out of the production well, during this process the piezometric surface will fall and this is called a drawdown. However, in the project area only one borehole, i.e. the production well was used during the pumping and as such, certain assumptions needs to be made, as it is only transmissivity is measured. No radius of influence, hence storativity cannot be estimated.

In an ideal aquifer, the following assumptions are made in carrying out the pumping test as in the project area:

1) There is only a single pumping well in the aquifer.
2) The pumping rate is constant.
3) The well fully penetrate the aquifer
4) The hydraulic head (h) prior to pumping is uniform.

3.6.3 Earth Resistivity Survey Data

In addition to the above data collection methods, geophysical survey was done in Pepel Island, Port Loko districts. Meter was employed in the investigation to determine rock conductivity using the Vertical Electrical Sounding (VES) method.

Five soundings were executed (VES1, VES2, VES3, VES4, and VES5) using the Schlumberger Electrode Configuration. Equation 3-1 represents apparent resistivity using the Schlumberger Configuration is given as:

$$\rho_{\alpha} = \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \pi\left(\frac{V}{I}\right) \tag{3-1}$$

where:

ρ_{α} = Apparent resistivity (Ωm);

I = Current (A)

AB = Current electrode separation (m);

MN = Potential electrode separation (m);

V = Potential difference (V) between MN

During the survey data, control was ensured by plotting the VES results in the field as measurements were in progress. Questionable values that registered high standard deviation (sd) greater than unity was rejected and sounding repeated at the same spot several times until reasonable values were recorded.

VES is the determination of vertical variation of resistivity through earth material and is very reliable for groundwater exploration particularly in moderate terrain with less subsurface complexity as in the case of the Bullom group sand sediments.

3.6.4 Groundwater Quality Data

Well construction information was obtained from the field. Observations at each well noted the location of nearby possible contamination sources such as septic pits, large-scale agriculture, or livestock enclosures. Well locations were recorded using a Geographic Positioning Satellite (GPS) unit. Water temperature, pH, and specific electrical conductance were measured in the field.

Groundwater samples were collected as close to the well head as possible. All samples were collected in laboratory supplied pre-cleaned bottles and were stored in an iced cooler until delivery to the lab. Field staff wore new nitrile gloves during sample collection to minimize contamination during the sample handling process.

CHAPTER 4

METHODOLOGY

4.1 Introduction

This chapter details the investigation methodology and the application of various software such as **GIS** to model the aquifer depths, which range from 5m to 16 m below surface level depending on the elevation. ZOND VESIP to plot the resistivity values and to describe the sub-surface layers and Aquifer Test Pro – an aquifer test software - to process the pumping test data and qualitatively analyzing the water.

The research involved 74 boreholes; 34 boreholes were drilled in the sedimentary sequence (Pepel) and 39 in the fractured basement aquifer (Tonkolili). Pumping tests were done in all the boreholes. In this chapter, the methodologies used in groundwater investigation and water quality analyses are outlined and the steps involved in achieving the results with the software used are discussed.

4.2 Pumping Test for Tonkolili and Port Loko Sites

Pumping test was performed to determine the capacity of the wells and the hydraulic characteristics of the aquifer. In order to estimate transmissivity and hydraulic conductivity, the tests were carried out in the study area using the single well pumping test approach for ten existing boreholes.

Before pumping, the static water level was recorded and after pumping, the drawdown was measured again in the well after the specific time interval. A container of known volume was used to collect the pumped water and subsequently, discharge was calculated with respect to time. Aquifer Test Pro software was used to compute the values of transmissivity and hydraulic conductivity from pump test data for the ten wells in the area investigated.

The pumping test data are analyzed below. During the analysis, a semi-logarithmic graph of drawdown versus time was plotted for each data. Alternately, with the drawdown and the time values obtained, the transmissivity can be calculated using the following equation:

T=Kb,

Where T= Aquifer transmissivity (m^2/s)

K= Aquifer hydraulic conductivity (m/s).

b= Confined aquifer thickness (m).

Aquifer transmissivity is a useful parameter in groundwater flow modeling. Transmissivity includes the aquifer hydraulic conductivity, which is a property of the aquifer. Hydraulic conductivity is a function of the fluid moving through the porous medium (i.e. aquifer, formation) and the permeability of the formation

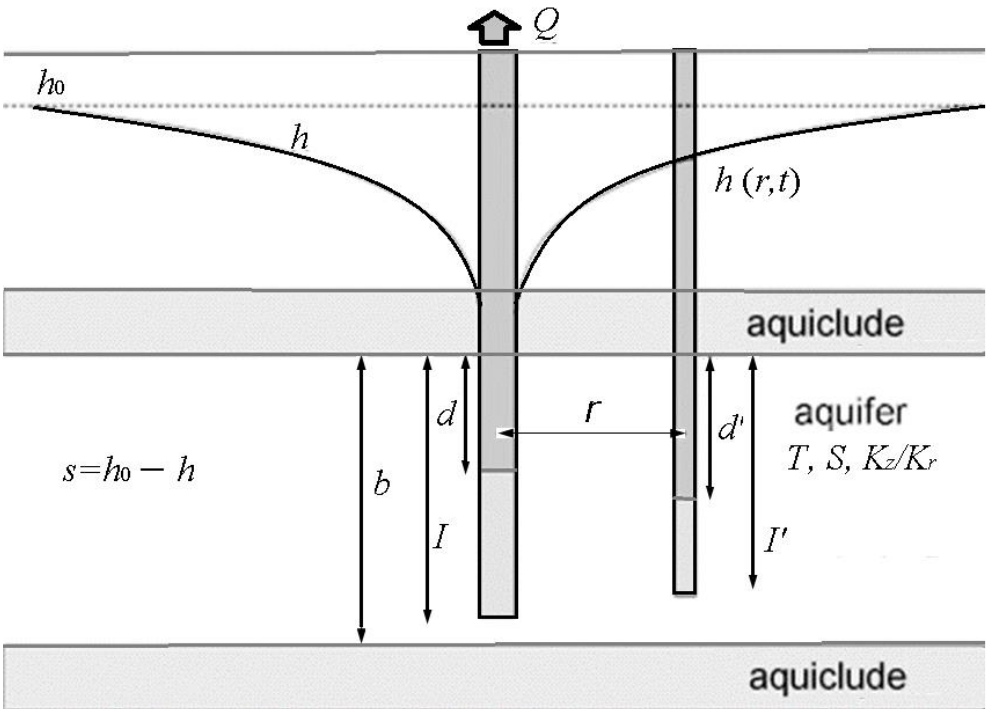


Figure 4-1: Non-Leaky Aquifer

Theis (1935) developed an analytical solution tool for determining the hydraulic properties (transmissivity and storativity) of non-leaky confined aquifers as shown in the figure below.

Analysis with the Theis method is performed by matching the Theis type curve to drawdown data plotted as a function of time on double logarithmic axes. The Theis equation for flow to a fully penetrating line sink discharging at a constant rate in a homogeneous, isotropic and non-leaky confined aquifer of infinite extent is as follows:

$$S = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}dy \quad ; \quad u = \frac{r^2 S}{4Tt} \tag{4-1}$$

The equation in compact notation is as follows

$$S = \frac{Q}{4\pi T} w(u) \tag{4-2}$$

4.2.1 Tonkolili District

The pumping test data of the five selected boreholes for Tonkolili district are shown below with their analysis using Theis method.

1) Boreholes location: Makoni Line

Yield during pumping: 2.5 m^3/hr.

T = 0.360 m^2/hr.

Confine Aquifer.

Table 4-1: Data of drawdown (m) and Time (s) for Makoni Line

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
30	4.92	0.00
60	7.20	2.28
120	9.20	4.28
180	10.97	6.05
240	12.19	7.27
300	13.42	8.50
360	14.90	9.98
420	16.33	11.41
480	17.60	12.68
540	18.50	13.58

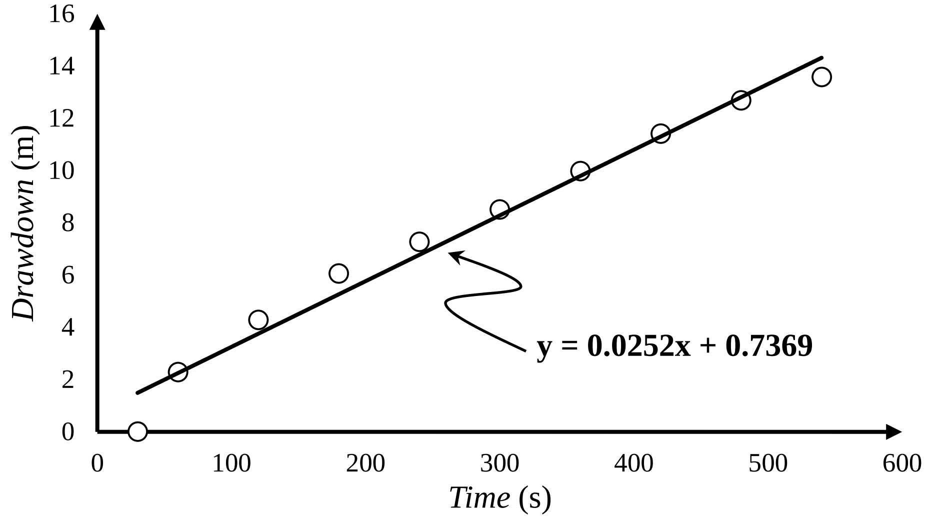


Figure 4-2: Linear time drawdown graph for Makoni Line

2) Boreholes location: Petifu Line

Yield during pumping: 1.8 m³/hr.

T = 0.52 m²/hr.

Confine Aquifer.

Table 4-2: Data of drawdown (m) and Time (s) for Petifu Line

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
10	7.70	0.00
60	10.49	2.79
120	12.37	4.67
180	13.53	5.83
240	15.65	7.95
300	16.26	8.56
360	16.58	8.88
420	16.66	8.96
480	16.73	9.03
540	16.78	9.08
600	16.80	9.10

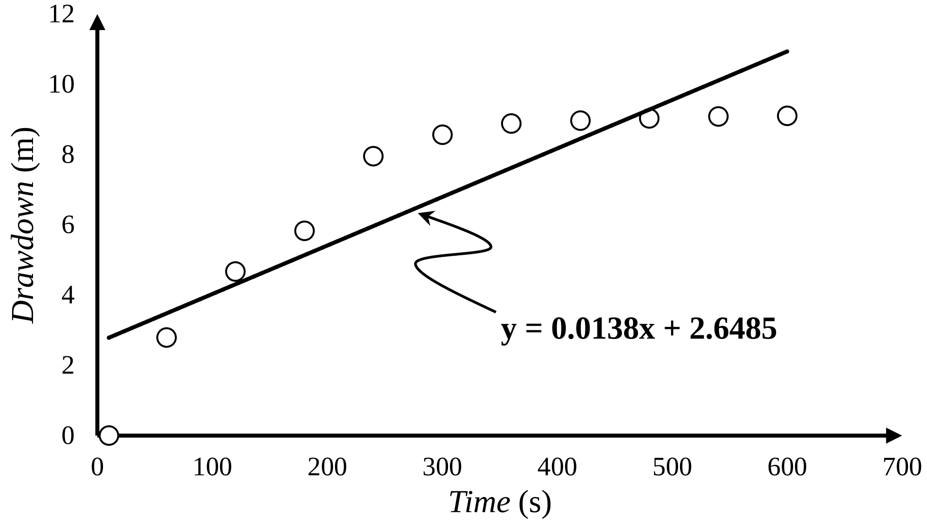


Figure 4-3: Linear time drawdown graph for Petifu Line

3) Boreholes location: Masingbi (School)

Yield during pumping: 1.4 m^3/hr

T = 0.28 m^2/hr.

Confine aquifer

Table 4-3: Data of drawdown (m) and Time (s) for Masingbi (School)

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
0	8.60	0.00
60	10.63	2.03
120	13.49	4.89
180	14.78	6.18
240	16.22	7.62
300	18.30	9.70
360	19.58	10.98
420	20.34	11.74
480	20.87	12.27
540	20.99	12.39
600	21.35	12.75

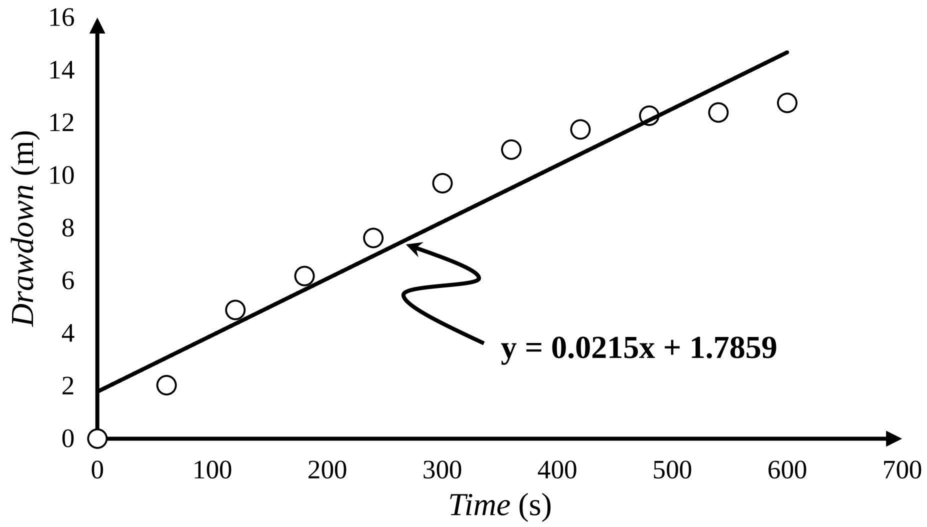


Figure 4-4: Linear time drawdown graph for Masingbi (School)

4) Boreholes location: Masingbi (Masiaka Street)

Yield during pumping: 2.4 m^3/hr

T = 0.314 m^2/hr.

Confine aquifer

Table 4-4: Data of drawdown (m) and Time (s) for Masingbi (Masiaka Street)

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
0	7.35	0.00
60	7.74	0.39
120	7.79	0.44
180	7.81	0.46
240	7.82	0.47
300	7.83	0.48
360	7.95	0.60
420	8.02	0.67
480	8.28	0.93
540	8.47	1.12
600	8.70	1.35
900	8.77	1.42
1200	8.84	1.49

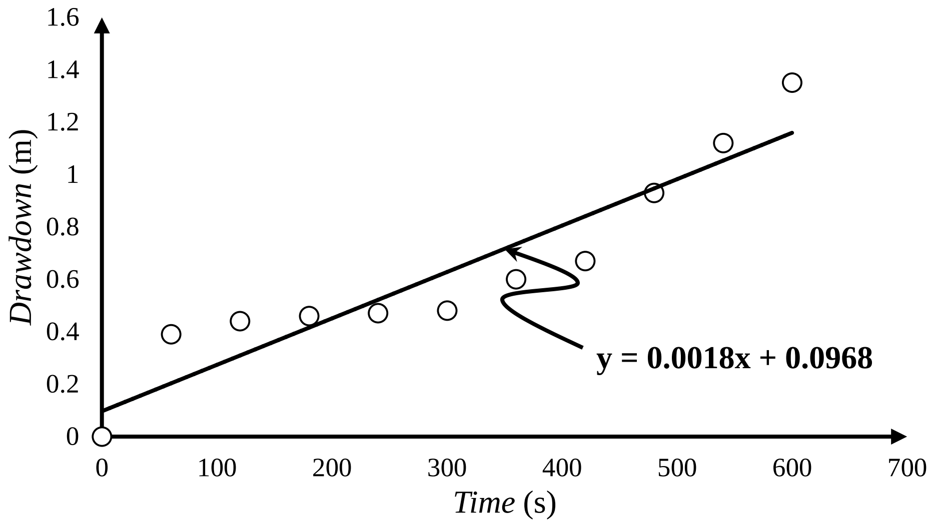


Figure 4-5: Linear time drawdown graph for Masingbi (Masiaka Street)

5) Boreholes location: Barraynin

Yield during pumping: 2.12 m^3/hr

T = 1.049m^2/hr.

Confine Aquifer.

Table 4-5: Data of drawdown (m) and Time (s) for Barraynin

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
0	7.88	0.00
60	8.34	0.46
120	8.42	0.54
180	8.46	0.58
240	8.50	0.62
300	8.52	0.64
360	8.52	0.64
420	9.78	1.90
480	11.43	3.55
540	12.88	5.00
600	14.47	6.59
900	15.00	7.12

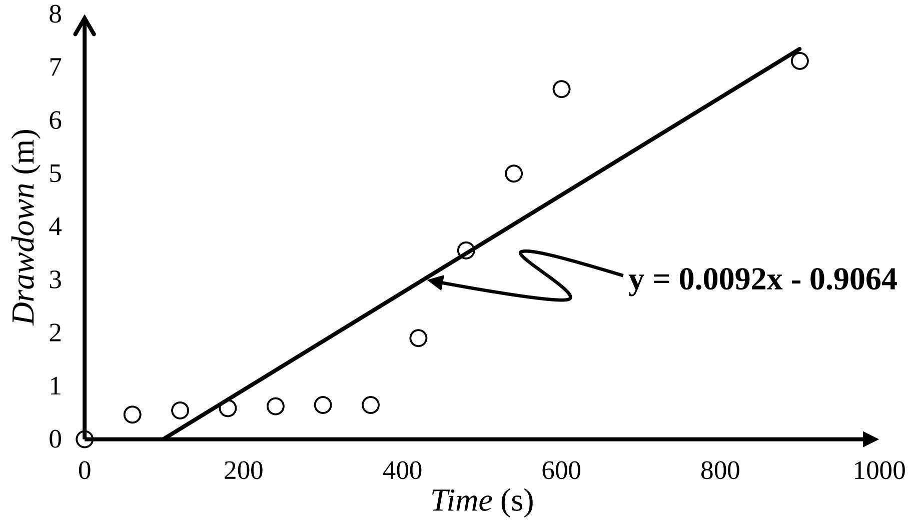


Figure 4-6: Linear time drawdown graph for Barraynin

4.2.2 Pepel, Port Loko District

The pumping test data of the five selected boreholes for Port Loko district are shown below with their analysis using Theis method.

1) Boreholes location: Pepel Camp Site

Yield during pumping: 1.8 m^3/hr

T = 1.433 m^2/hr.

Confine aquifer.

Table 4-6: Data of drawdown (m) and Time (s) for Pepel Camp Site

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
0	11.83	0.00
60	12.02	0.19
120	12.04	0.21
180	12.05	0.22
240	12.06	0.23
300	12.07	0.24
360	12.08	0.25
420	12.09	0.26
480	12.11	0.29
540	12.12	0.30
600	12.13	0.30
690	12.4	0.31
720	12.15	0.32

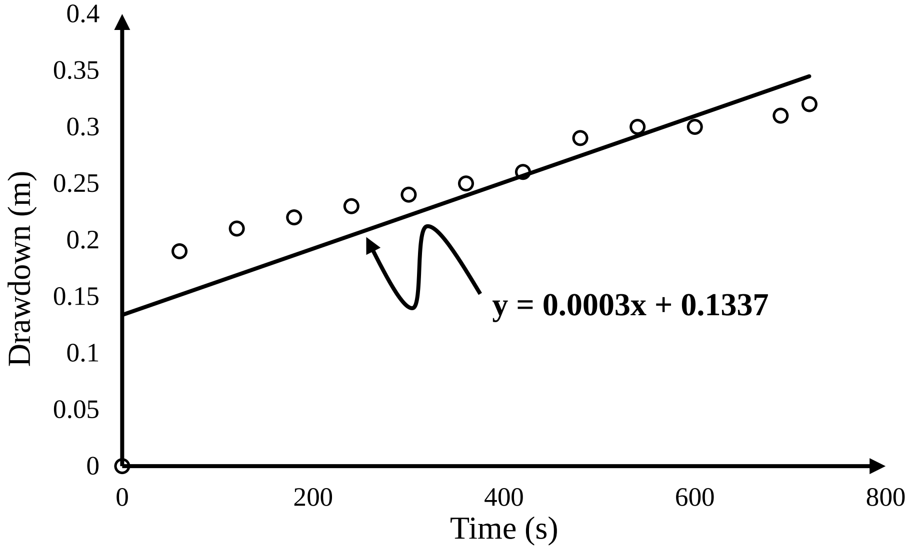


Figure 4-7: Linear time drawdown graph for Pepel Camp Site

2) Boreholes location: Pepel, Junior Staff Canteen

Yield during pumping: 1.8 m^3/hr

T = 1.33 m^2/hr.

Confine aquifer

Table 4-7: Data of drawdown (m) and Time (s) for Pepel, Junior Staff Canteen

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
0	10.02	0.00
60	10.24	0.22
120	10.29	0.27
180	10.31	0.29
240	10.34	0.32
300	10.36	0.34
360	10.40	0.38
420	10.44	0.42
480	10.48	0.46
540	10.50	0.48
600	10.51	0.49
690	10.52	0.50
720	10.53	0.51

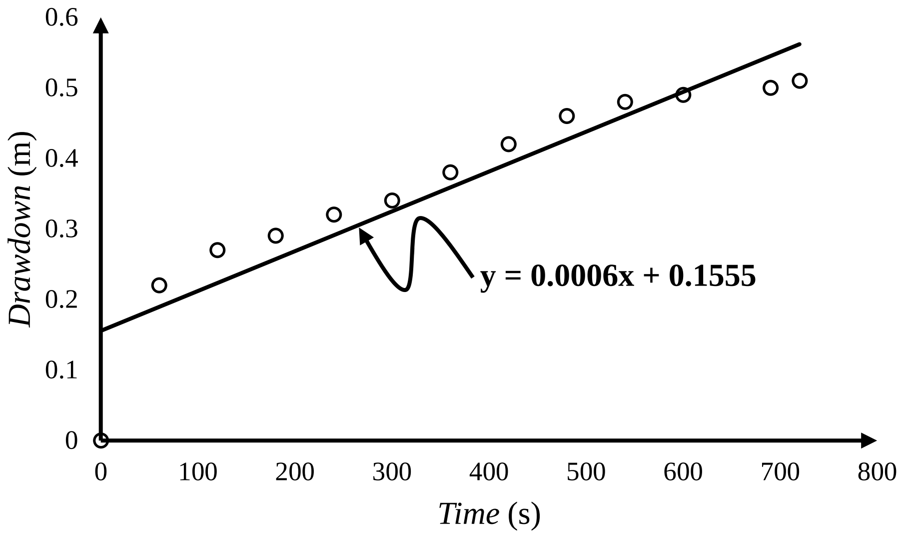


Figure 4-8: Linear time drawdown graph for Pepel, Junior Staff Canteen

3) Boreholes location: Pepel, Palampou

Yield during pumping: 1.6 m^3/hr

T = 1.52 m^2/hr.

Confine aquifer

Table 4-8: Data of drawdown (m) and Time (s) for Pepel, Palampou

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
0	6.50	0.00
60	6.74	0.24
120	6.74	0.24
180	6.74	0.24
240	6.75	0.25
300	6.76	0.26
360	6.76	0.26
420	6.78	0.28
480	6.79	0.29
540	6.80	0.30
600	6.81	0.31
690	6.81	0.31
720	6.82	0.32

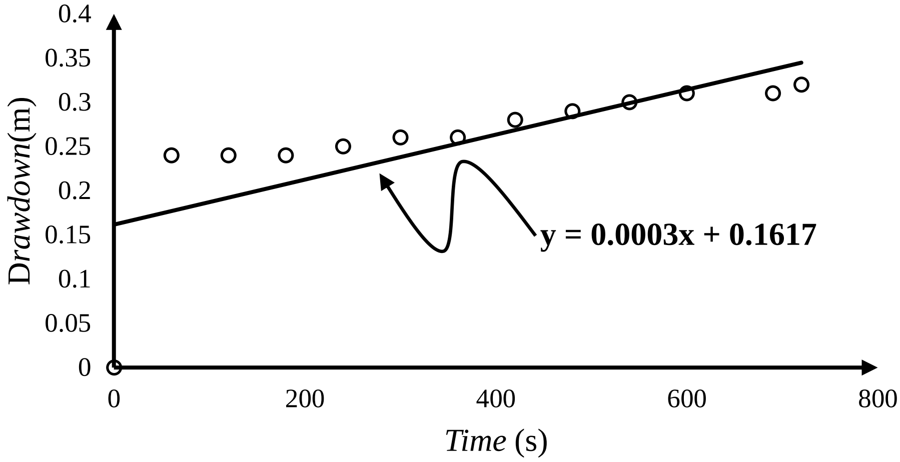


Figure 4-9: Linear time drawdown graph for Pepel, Palampou

4) Boreholes location: Pepel, Septic Tank Area

Yield during pumping: 1.8 m^3/hr.

T = 0.95 m^2/hr.

Confine aquifer

Table 4-9: Data of drawdown (m) and Time (s) for Pepel, Septic Tank Area

*Time (*s)	*D. W. L. h* (m)	*Drawdown* (m)
0	11.14	0.00
60	11.56	0.42
120	11.56	0.42
180	11.57	0.43
240	11.57	0.43
300	11.59	0.45
360	11.60	0.46
420	11.61	0.47
480	11.61	0.47
540	11.63	0.49
600	11.64	0.50
690	11.64	0.50
720	11.65	0.51

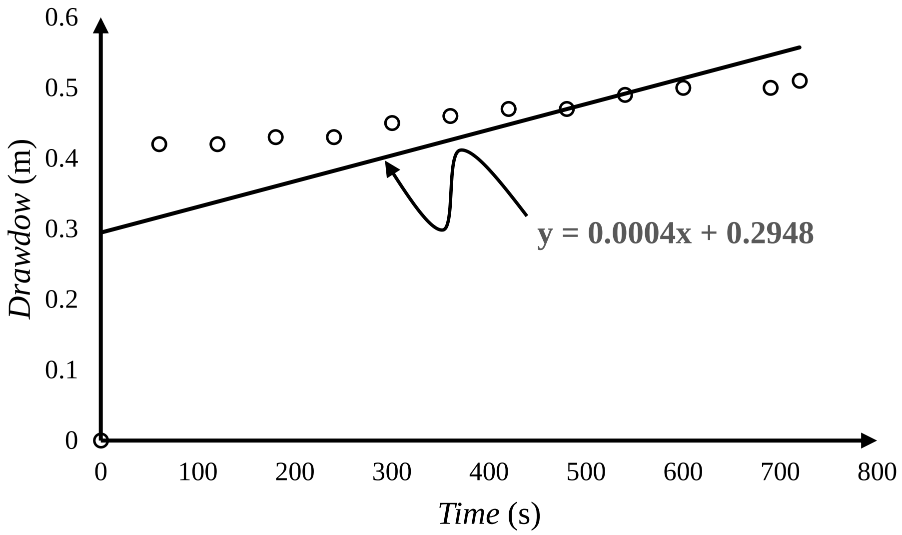


Figure 4-10: Linear time drawdown graph for Pepel, Septic Tank Area

5) Boreholes location: Pepel, Village Health Centre

Yield during pumping: 1.6 m^3/hr.

T = 1.28 m^2/hr.

Confine aquifer

Table 4-10: Data of drawdown (m) and Time (s) for Pepel, Village Health Center

Time (s)	*D. W. L. h* (m)	*Drawdown* (m)
0	13.40	0.00
60	14.05	0.65
120	14.06	0.66
180	14.06	0.66
240	14.06	0.66
300	14.07	0.67
360	14.07	0.67
420	14.07	0.67
480	14.08	0.68
540	14.08	0.68
600	14.09	0.69
690	14.09	0.69
720	14.09	0.69

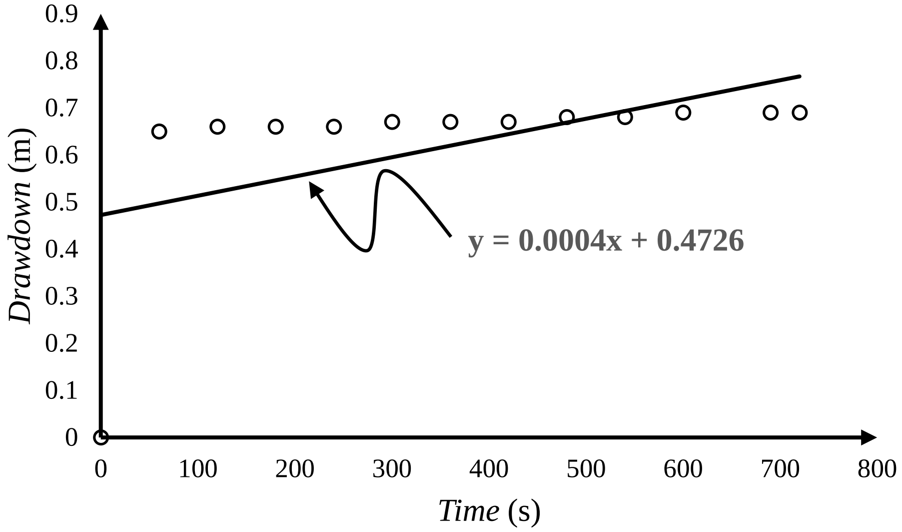


Figure 4-11: Linear time drawdown graph for Pepel, Village Health Center

The semi-log plot of the pumping tests from the two areas refer to an ideal, confined, homogeneous and isotropic, and pumped at a constant rate by a fully penetrating well of very small diameter. From the semi-log plots, we can see that the time-drawdown has a positive linear relationship. From the pumping tests, it is deduced that over abstraction on the shallow boreholes near the sea will lead to saline intrusion, which is evidenced in Pepel area.

4.3 Earth Resistivity Survey for Port Loko

A multifunction electrical meter (SAS 1000/4000 DZD 6A) was employed in the investigation to determine rock conductivity using the Vertical Electrical Sounding (VES) method. Five soundings were executed (VES1, VES2, VES3, VES4, and VES5) using the Schlumberger Electrode Configuration. The Equation for apparent resistivity using the Schlumberger Configuration is given as:

$$\rho_\alpha = \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \pi \left(\frac{V}{I}\right) \qquad (4\text{-}5)$$

Where:

ρ_{α} = Apparent resistivity (Ωm);

I = Current (A)

AB = Current electrode separation (m);

MN = Potential electrode separation (m);

V = Potential difference (V) between MN

During the survey data, control was ensured by plotting the VES results in the field as measurements were in progress. Questionable values that registered high standard deviation (sd) greater than unity was rejected and sounding repeated at the same spot several times until reasonable values were recorded. VES is the determination of vertical variation of resistivity through earth material and is very reliable for groundwater exploration particularly in moderate terrain with less subsurface complexity as in the case of the Bullom group sand sediments.

The VES data for the five survey stations are presented in Table1. Apparent Resistivity values (ρ_{a}) obtained from the sounding were plotted against half the Current Electrode Spacing (AB/2) using ZOND VESIP software. The output showed the values of resistivity and the depth of the various formations. The geological information therefore serves as a guide in geophysical survey. The VES field curves of the geoelectric data show the relation between the apparent resistivity and half the current electrode spacing as shown in the VES curves and sections below.

Table 4-11: Apparent resistivity values and layer thicknesses as model output

	No.	Apparent Resistivity(P) (Ωm)	Thickness (h) (m)	Depth(z) (m)	Sub-surface layers
VES1	1	103.29	1.22	0/0	Sandy top soil
	2	589.26	5.48	1.22	Clay sand
	3	226.14	9.49	6.71	Wet sand (aquifer)
	4	506.38		16.20	Coarse Sand gravel
VES2	1	321.71	1.41	0/0	Sandy top soil
	2	2562.98	6.95	1.41	Clay sand
	3	285.86		8.37	Wet sand (aquifer)
VES3	1	756.98	2.24	0/0	Sandy top soil
	2	218.00	10.01	2.24	Clay sand
	3	455.14	3.95	12.25	Wet sand (aquifer)
	4	219.86		16.20	Coarse Sand gravel
VES4	1	3369.71	0.71	0/0	Sandy top soil
	2	11666.20	3.48	0.71	Clay sand
	3	513.93		4.18	Wet sand (aquifer)
VES5	1	608.21	1.58	0/0	Sandy top soil
	2	2059.68	7.77	1.58	Clay sand
	3	464.50		9.35	Wet sand (aquifer)

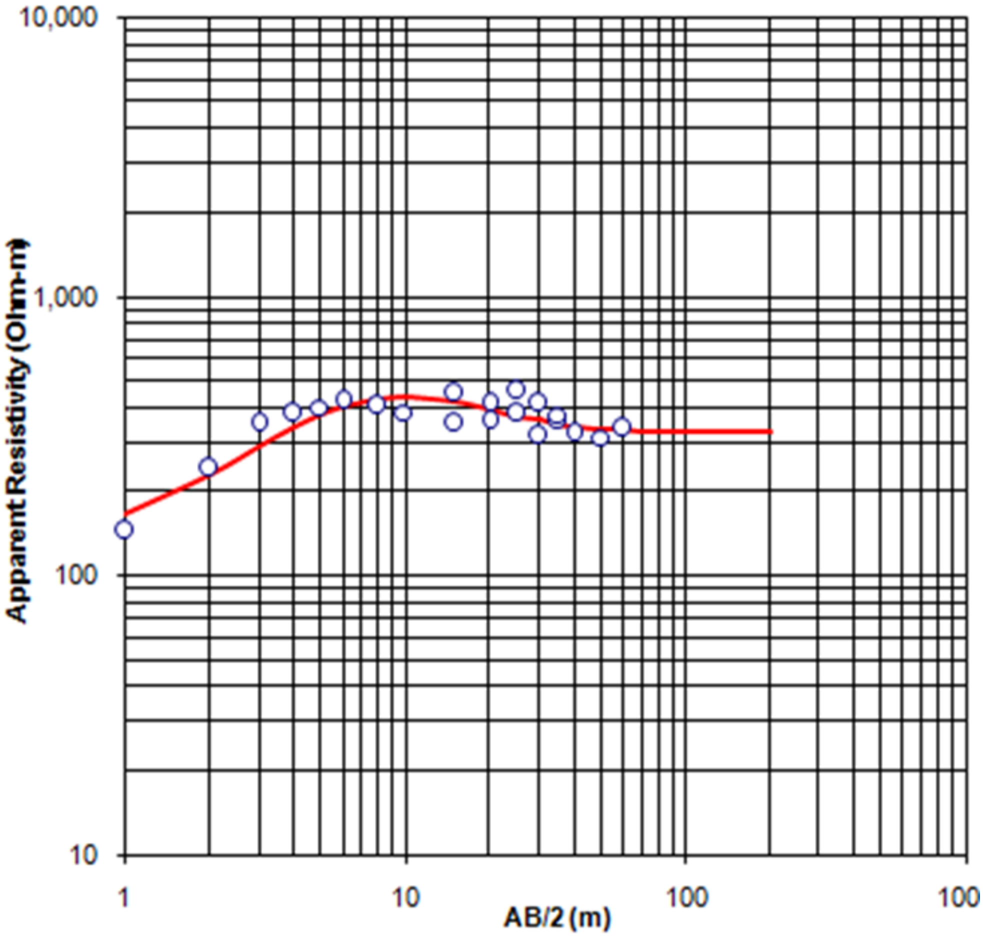


Figure 4-12: VES Curve at BH1 in Pepel

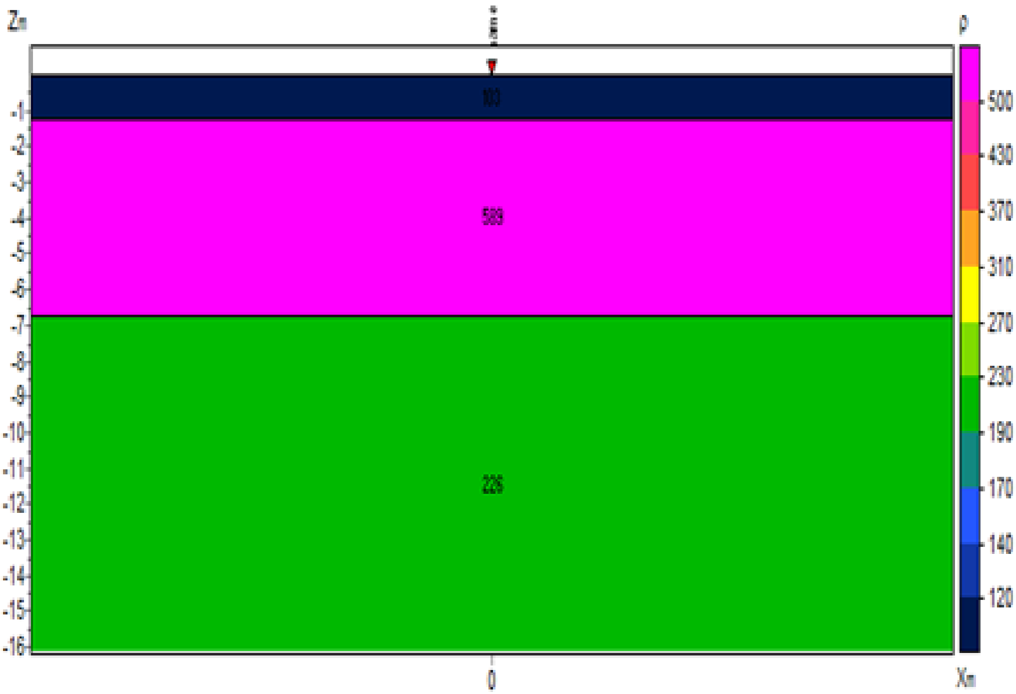


Figure 4-13: VES Pseudo-Section at BH1 in Pepel

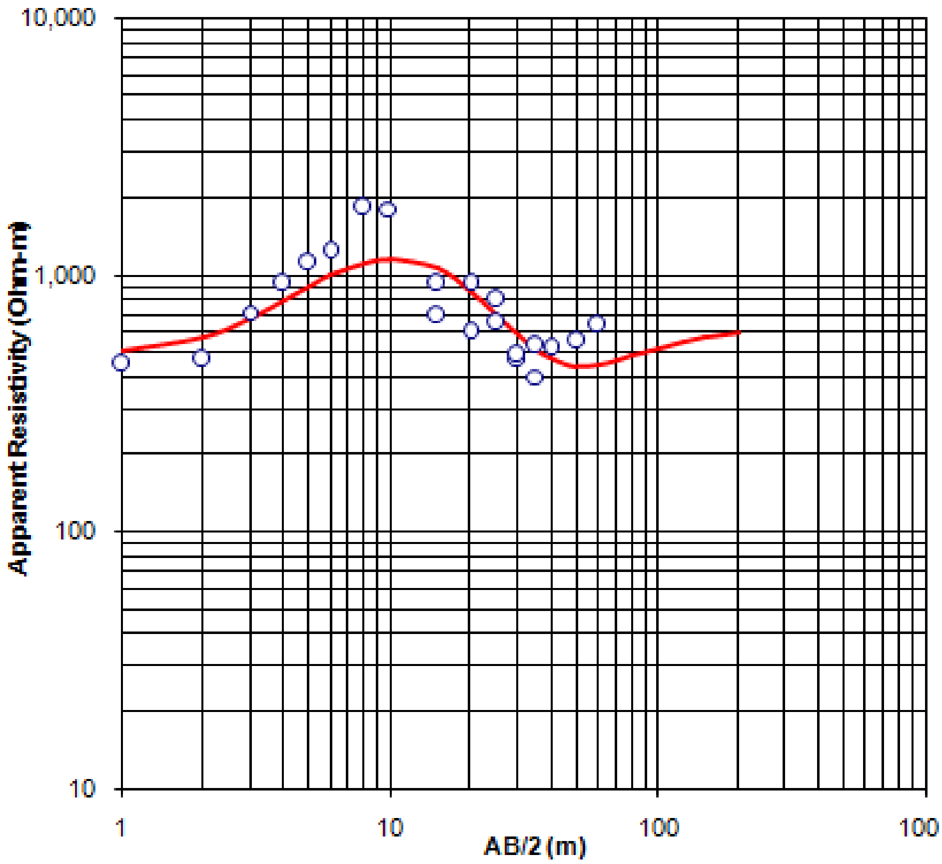


Figure 4-14: VES Curve at BH2 in Pepel

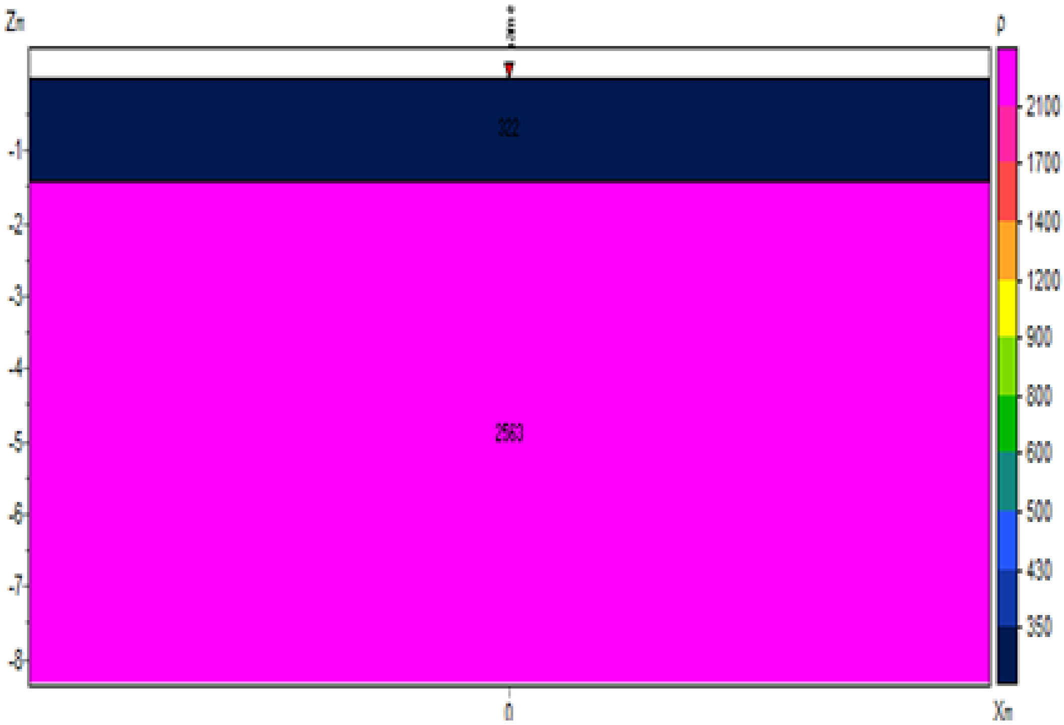


Figure 4-15: VES Pseudo-Section at BH2 in Pepel

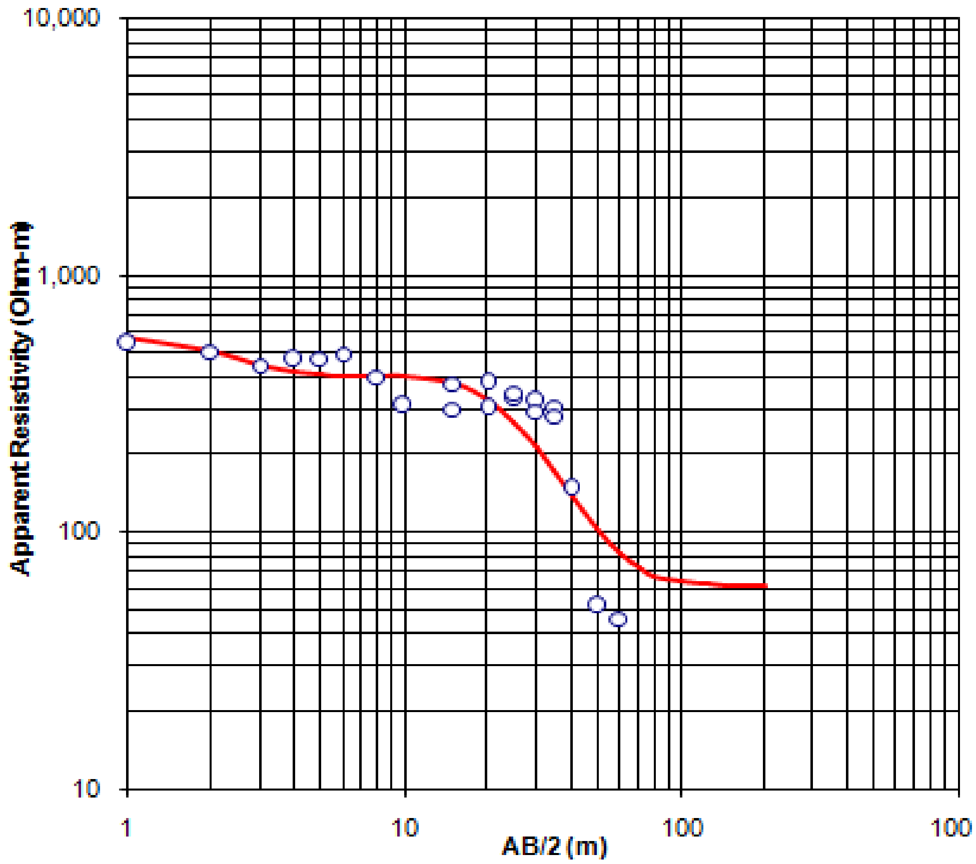


Figure 4-16: VES Curve at BH3 in Pepel

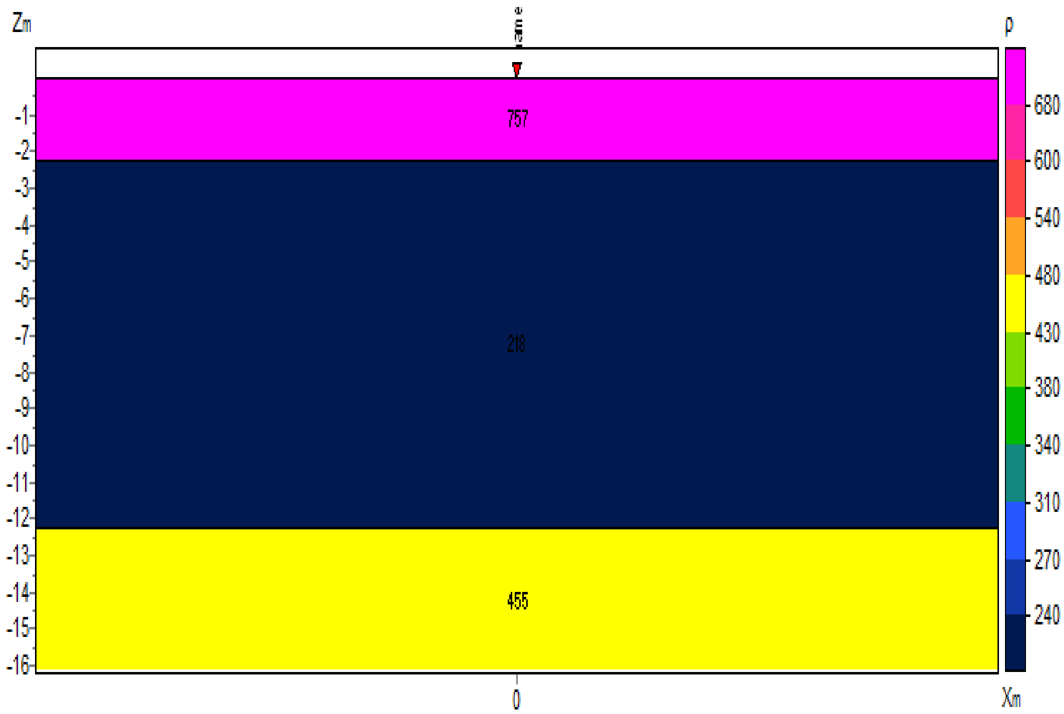


Figure 4-17: VES Pseudo-Section at BH3 in Pepel

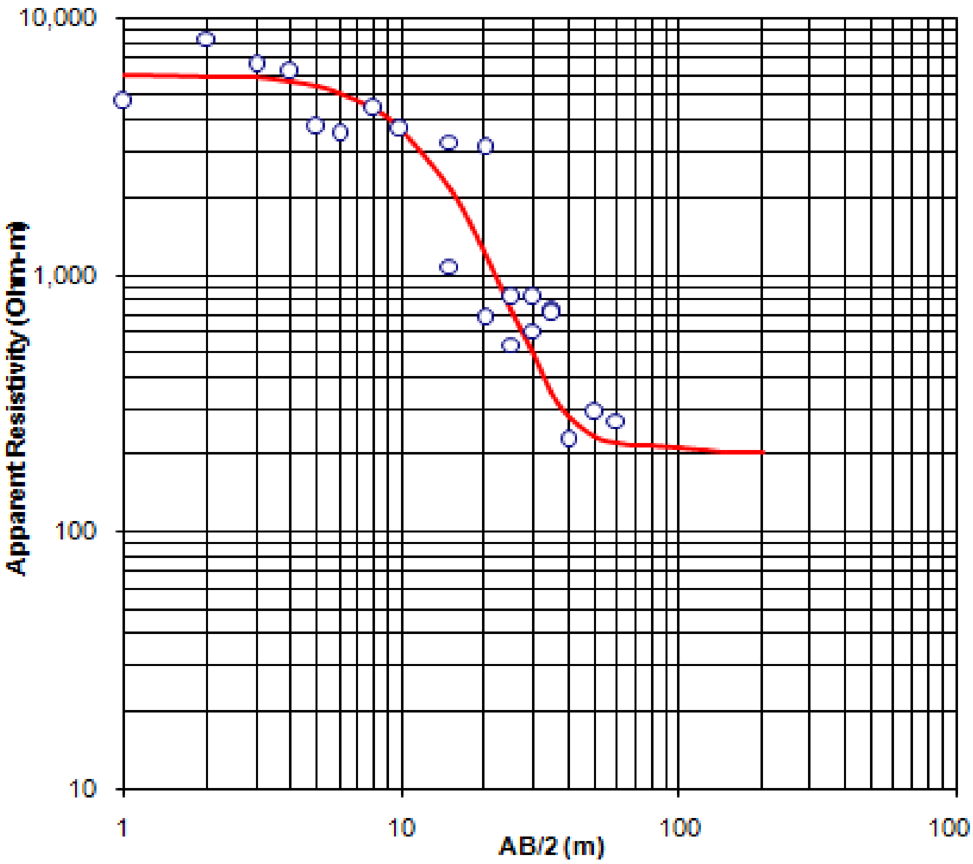


Figure 4-18: VES Curve at BH4 in Pepel

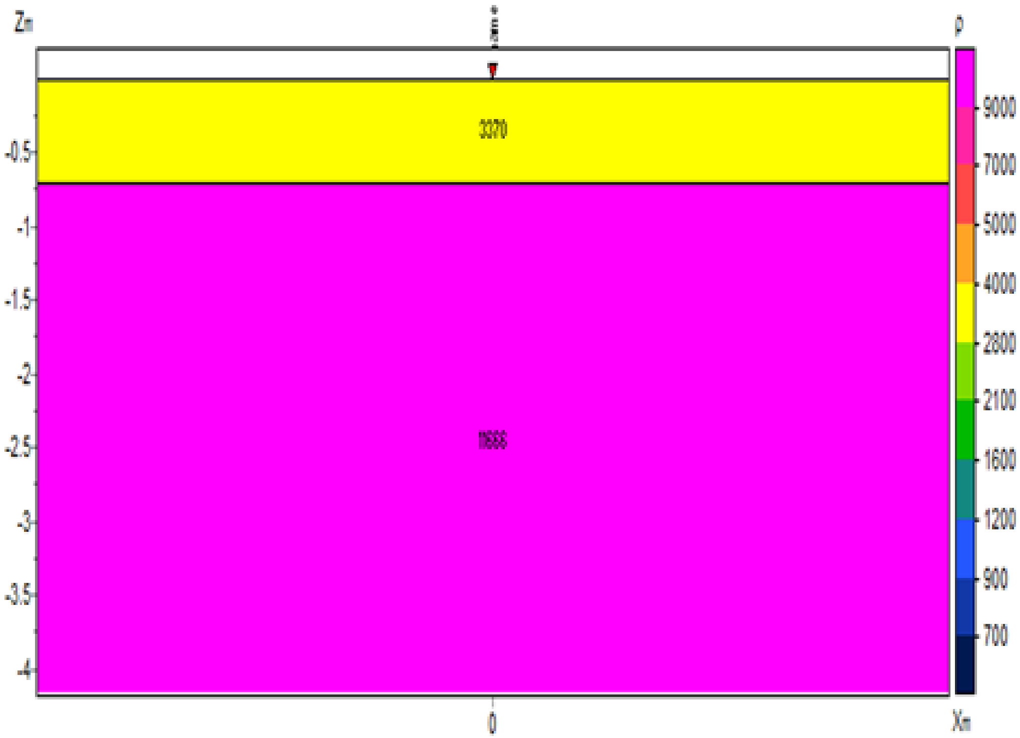


Figure 4-19: VES Pseudo-Section at BH4 in Pepel

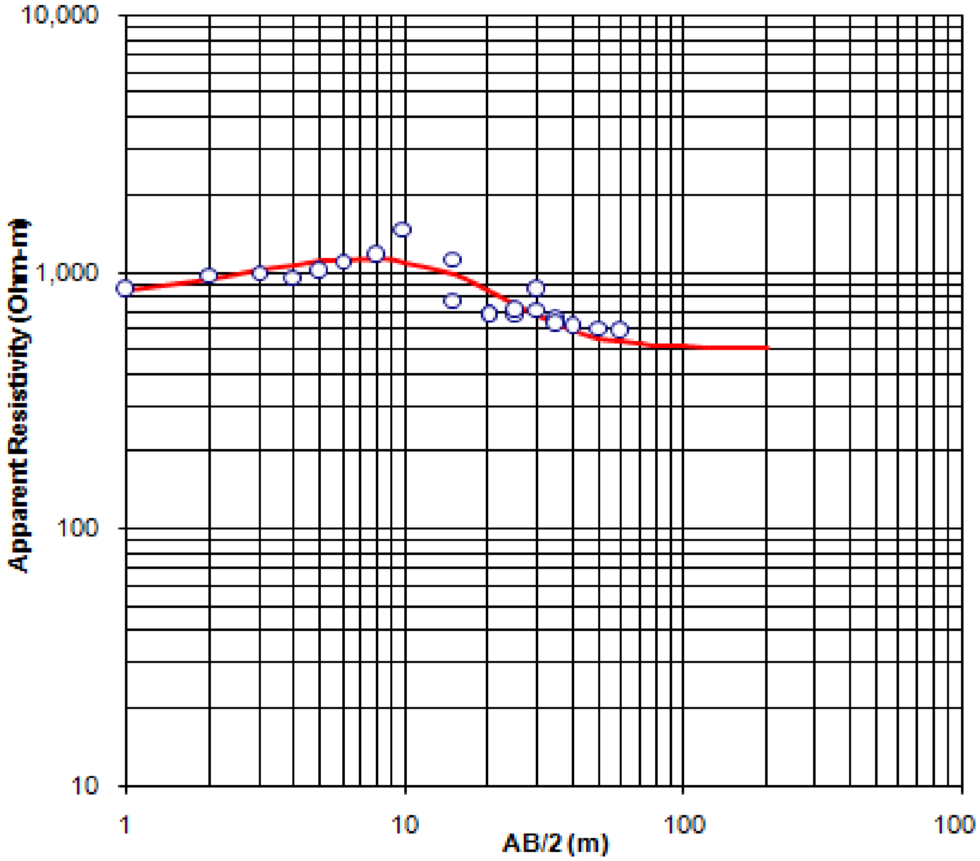


Figure 4-20: VES Curve at BH5 in Pepel

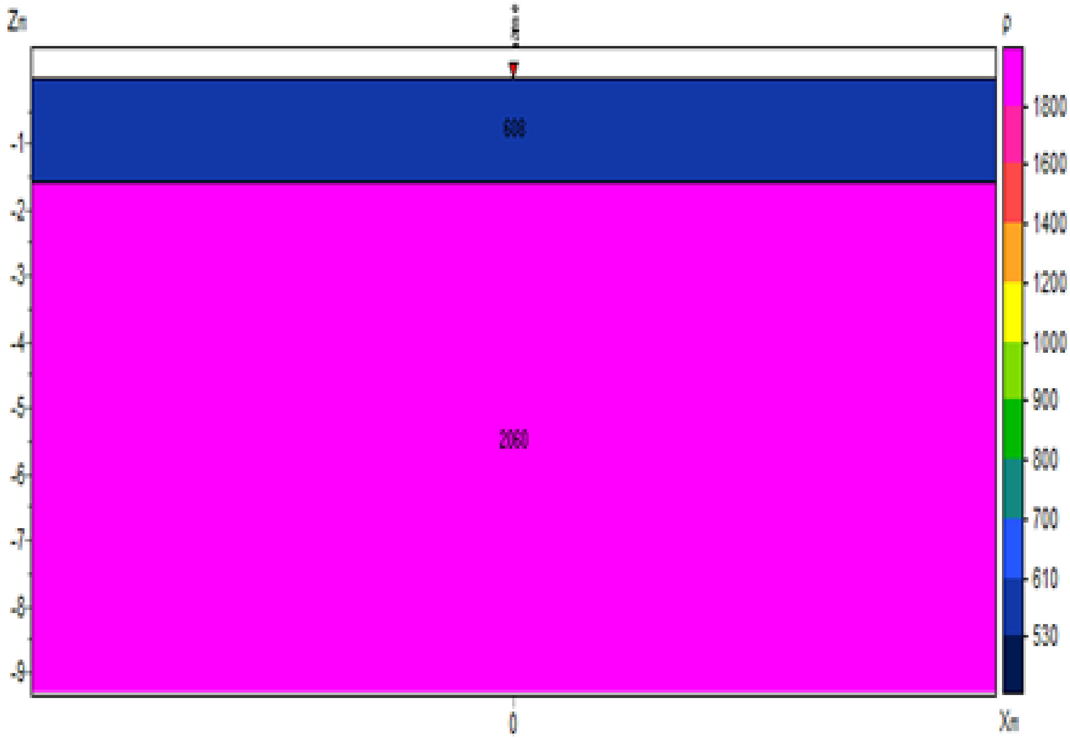


Figure 4-21: VES Pseudo-Section at BH5 in Pepel

4.4 Groundwater Quality Measurement

Water samples from 74 selected borehole wells were collected from May – June 2017. Samples were collected from each well for Groundwater quality analyses within the Tonkolili and Port Loko districts for Physico-chemical and bacteriological analysis. The parameters tested are pH, Temperature, Color, Total Dissolved Solid, Conductivity, Calcium, Nitrate, Manganese, Chloride, Fluoride, Iron, Copper, Turbidity and Sulphate.

The result obtained was compared with World Health Organization (WHO) standards for water quality. In-situ measurements of temperature, hydrogen ion concentration (pH) dissolved oxygen (DO) and dissolved iron were taken using mercury-in glass thermometer, digital pH and DO meters and the Dr/2010 HACH spectrophotometer, respectively.

Conductivity and total dissolved solids (TDS) were measured using the HACH portable conductivity meter (CO150). Turbidity was estimated using the turbidity meter. Copper (Cu), manganese (Mn), nitrate (NO3-), chloride (Cl), were determined spectrophotometrically (APHA, 2005).

4.4.1 Groundwater Quality for Tonkolili District

The tables 4-12 to 4-14 below show the results obtained form Physico-chemical and Bacteriological analyses for boreholes in Tonkolili District and the values were compared to the WHO standards for drinking water.

Table 4-12: Physical Parameters of drinking water in Tonkolili District

Physical Parameters						
Location	Temperature °C	Turbidity (NTU)	Conductivity (µS/cm)	TDS (mg/l)	PH	Yield (m^3/hr.)
BH1	1.9	1.0	149	45	5.8	1.8
BH2	26.7	0.5	185.3	92.7	6.7	1.5
BH3	27.7	0.6	24.1	12.3	7.9	1.7
BH4	28	2	201	99.9	5.9	1.9
BH5	27.1	0.8	141.5	70.5	5.2	1.5
BH6	26.2	0.4	136.7	68.2	6.1	1.6
BH7	27.6	1	298	149	6.9	1.6
BH8	27.5	0.2	137.5	68.5	5.5	1.7
BH9	28.2	0.3	210	105	6.9	1.2
BH10	27.8	0.8	368	184	7.1	1.9
BH11	29.2	0.5	147.3	74.2	6.3	1.5
BH12	27.9	1.1	138.1	69.2	5.6	1.8
BH13	27.9	1.2	43.8	22.2	5.5	1.2
BH14	28.8	0.7	108.4	54.2	5.1	1.3
BH15	28.2	0.9	90.6	45.1	5.7	2.3
BH16	28.1	0.8	54.8	27.4	5.3	1.6
BH17	27.3	1	154.1	76.8	6	1.5
BH18	29.4	0.2	187.7	93.6	4.5	2.1
BH19	28.3	0.9	247	123	5.8	1.4
BH20	28.3	1.3	338	169	6.2	1.9
BH21	28.5	18	125.7	62.6	6.2	2.7
BH22	25	1.5	69.5	37.1	5.1	3.2
BH23	27.7	0.7	126	62.9	5.8	2
BH24	27.7	2.3	373	187	6.6	1.3
BH25	28.3	0.1	93.3	46.6	5.4	2.1
BH26	28.3	0.8	106	53.2	6	1.2
BH27	27.5	1	45.2	22.3	5.6	3.6
BH28	28.8	0.8	76.8	38	5.2	2.1
BH29	28.8	0.6	153.3	76.6	6.5	3.6
BH30	26.6	5.3	108.1	54	5.1	2
BH31	26.2	0.5	119.7	61	6.2	1.6
BH32	27.3	0.5	204	102	8.8	2.3
BH33	27.7	0.27	62.9	31.4	5.1	2.1
BH34	28.1	0.5	184	91.5	6.4	2.4
BH35	27.6	0.3	74	36.8	5.6	2.1
BH36	28.5	1.2	131.6	65.7	6.3	2.1
BH37	27.7	3.4	177.4	97.1	6.7	1.2
BH38	27.2	1.3	252	126.5	6.5	1.3
BH39	27.7	1	276	138	6.6	1.6
WHO Standard	No Value	< 5	< 450	< 248	6.5-8.5	

Table 4-13: Chemical Parameters of drinking water in Tonkolili District

	Chemical Parameters								
Location	pH	Iron Fe mg/l	Nitrate NO3 mg/l	Manganese Mn mg/l	Sulphate S04 mg/l	Chloride Cl mg/l	Cooper Cu mg/l	Calcium Ca mg/l	Fluoride Fl mg/l
BH1	5.8	0.01	5.2	0.04	7.2	15	0.05	28	0.26
BH2	6.7	0	1	0.08	3	9.4	0.01	29	0.39
BH3	7.9	Nil	0.6	0.03	2.1	6	0.012	38	0.37
BH4	5.9	0	0.52	0.06	1.8	32.1	0.012	15	0.23
BH5	5.2	0	10.1	0.01	3.9	15	0.01	45	0.22
BH6	6.1	0	0.7	0.14	2.1	35	0.16	45	0.15
BH7	6.9	0	0.13	0.06	23	20	0.01	29	0.15
BH8	5.5	0	0.7	0.12	6.7	20	0.03	17	0.15
BH9	6.9	0	0.8	0.06	17.8	15	0.012	24	0.13
BH10	7.1	0	0.14	0.11	3.5	21	0.08	26	0.31
BH11	6.3	0	0.5	0.04	3.2	21	0.09	42	0.44
BH12	5.6	0	0.5	0.01	2.8	24.1	0.08	48	0.6
BH13	5.5	0.3	0.6	0.2	5.4	17.3	0.02	26	0.2
BH14	5.1	0	1.2	0.02	3.4	16.3	0.03	35	0.12
BH15	5.7	0	0.78	0.01	5	17.4	0.01	37	0.24
BH16	5.3	0	0.48	0.02	3.5	11.2	0.06	56	0.23
BH17	6	0.09	0.84	0.04	3	29	0.06	51	0.34
BH18	4.5	0	0.5	0.3	5	21.4	ND	37	0.31
BH19	5.8	0	0.3	0.02	8	6.8	ND	26	0.21
BH20	6.2	0.01	0.91	0.02	3	1.7	0.07	25	0.4
BH21	6.2	0.04	0.8	0.02	2	11.2	0.07	12	0.58
BH22	5.1	0	0.74	0.03	1	12.3	0.01	28	0.39
BH23	5.8	0	0.48	0.06	4	4	0.013	17	0.3
BH24	6.6	0.1	0.7	0.02	3	30.2	0.03	25	0.42
BH25	5.4	0	1.3	0.14	2.8	53	0.05	1930	0.34
BH26	6	0	0.8	0.01	2.8	22	0.02	27	0.23
BH27	5.6	0	0.8	0.01	8.7	3.6	0.03	39	0.11
BH28	5.2	0	0.32	0.06	6.9	17.3	0.18	45	0.58
BH29	6.5	0.1	0.6	0.06	4.7	23.6	0.03	34	0.48
BH30	5.1	0.07	0.66	0.08	4	34	0.01	57	0.36
BH31	6.2	0	0.6	0.12	3	8.8	0.02	24	0.32
BH32	8.8	0.02	0.65	0.01	2	10.1	0.02	32	0.31
BH33	5.1	0.02	9.2	0.06	1	12	0.2	18	0.36
BH34	6.4	0	1.3	0.06	3	7	0.31	22	0.14
BH35	5.6	0	0.5	0.01	4.3	15	0.01	39	0.26
BH36	6.3	0	0.36	0.01	2.1	2	0.06	40	0.24
BH37	6.7	0.02	0.6	0.02	1.8	3.8	0.06	35	0.39
BH38	6.5	0	0.7	0.02	1.5	26	0.04	45	0.25
BH39	6.6	0	0.8	0.03	3.9	13.8	0.02	41	0.13
WHO Standards	6.5-8.5	<3	< 10	< 0.4	< 400	< 250	< 2.0	< 500	< 1.5

Table 4-14: Bacteriological Parameters of drinking water in Tonkolili District

Bacteriological Parameters		
Location	Faecal Coliform (cfu)/100 mL	Non-Faecal Coliform (cfu)/100 mL
BH1	15	30
BH2	Nil	40
BH3	Nil	10
BH4	Nil	Nil
BH5	Nil	Nil
BH6	Nil	0
BH7	Nil	Nil
BH8	10	0
BH9	15	Nil
BH10	Nil	Nil
BH11	Nil	20
BH12	10	15
BH13	Nil	25
BH14	Nil	Nil
BH15	Nil	10
BH16	20	35
BH17	25	40
BH18	15	Nil
BH19	Nil	Nil
BH20	Nil	0.5
BH21	Nil	Nil
BH22	Nil	0.1
BH23	Nil	0.2
BH24	Nil	0
BH25	10	0
BH26	10	0
BH27	Nil	0
BH28	Nil	0
BH29	Nil	0
BH30	Nil	Nil
BH31	Nil	Nil
BH32	Nil	0.5
BH33	Nil	0.6
BH34	Nil	Nil
BH35	Nil	Nil
BH36	Nil	Nil
BH37	Nil	Nil
BH38	Nil	Nil
BH39	Nil	Nil
WHO Standard	Zero	< 10

4.4.2 Groundwater Quality for Port Loko District

The tables 4-15 to 4-17 below show the results obtained form Physico-chemical and Bacteriological analyses for boreholes in Port Loko district.

Table 4-15: Physical Parameters of drinking water in Port Loko District

Physical Parameters						
Location	Temperature ◦C	Turbidity (NTU)	Conductivity (µS/cm)	TDS (mg/l)	PH	Yield (m^3/hr)
BH1	28.8	17.5	118	94	4.9	2.12
BH2	28.4	6.7	175.1	87.6	5.3	1.8
BH3	29.4	0.8	95.7	48.0	5.8	1.8
BH4	25.4	119	82.6	41.3	6.5	1.6
BH5	29.2	2.7	108.5	54.2	7.2	2.0
BH6	29.1	6.3	135.8	64	6.3	1.6
BH7	29.3	5.4	224	107	5.4	1.7
BH8	28.2	9.0	120	56	5.9	1.8
BH9	29.8	8.5	148	69	6.0	1.64
BH10	30.6	2.2	137.3	65	5.9	1.9
BH11	30.1	1.8	135	69.1	5.9	1.58
BH12	28.9	4.8	110.4	45.8	6.5	1.72
BH13	28.7	0.7	108.4	54.2	69	2.4
BH14	29.1	0.9	90.6	45.1	6.7	1.9
BH15	28.7	0.8	54.8	27.4	7.2	1.8
BH16	28.3	1	154.1	76.8	6.0	1.6
BH17	28.4	5.3	187.7	93.6	7.1	2.5
BH18	28.3	0.9	247	123	6.4	2.3
BH19	28.6	1.3	338	169	6.7	2.5
BH20	28.5	18	125.7	62.6	6.9	2.1
BH21	26.2	1.9	69.5	37.1	5.8	1.8
BH22	27.9	1.7	126	62.9	5.9	1.8
BH23	27.8	6.3	373	187	6.9	2
BH24	28.6	0.1	93.3	46.6	5.6	1.7
BH25	28.4	0.8	106	53.2	7.0	1.8
BH26	27.8	12.1	45.2	22.3	6.6	1.8
BH27	28.8	1.8	76.8	38	6.2	3
BH28	28.9	0.6	153.3	76.6	6.5	1.8
BH29	26.9	5.5	108.1	54	5.1	3.2
BH30	26.8	0.5	119.7	61	6.2	1.5
BH31	27.3	1.5	204	102	7.3	3.4
BH32	28.7	2.27	62.9	31.4	5.9	1.6
BH33	28.1	1.5	184	91.5	6.4	3
BH34	27.6	2.3	74	36.8	6.6	2.2
BH35	28.5	2.8	131.6	65.7	6.9	2.5
WHO Standard	No Value	< 5	< 450	< 248	6.5-8.5	

Table 4-16: Chemical Parameters of drinking water in Port Loko District

	Chemical Parameters								
Location	PH	Iron Fe mg/l	Nitrate NO3 mg/l	Manganese Mn mg/l	Sulphate S04 mg/l	Chloride Cl mg/l	Cooper Cu mg/l	Calcium Ca mg/l	Fluoride Fl mg/l
BH1	4.9	0.2	2.6	Nil	1	13.1	0.13	28	0.23
BH2	5.3	0.3	9.1	0.01	1	25	0.25	12	0.65
BH3	5.8	0.2	4.2	Nil	Nil	22	0.2	35	0.28
BH4	6.5	0	7	0.02	Nil	52	0.012	8	0.02
BH5	7.2	0	6.4	Nil	Nil	34	0.012	12	0.67
BH6	6.3	0.07	6.1	0.02	3	16	1	28.9	0.32
BH7	5.4	0.03	5.1	0.01	3.8	32	0.16	18.4	0.3
BH8	5.9	0.6	6.5	0.06	2	20	0.01	36	0.85
BH9	6	nil	4.5	0.12	14	20	0.04	36.1	0.3
BH10	5.9	nil	3.4	0.04	2	15	0.012	40	0.71
BH11	5.9	nil	0.5	0.05	3	21	0.06	22	0.25
BH12	6.5	0	1.6	0.04	2	21	0.09	33.2	0.44
BH13	69	0	5.5	0.01	2	25	0.3	19.6	0.12
BH14	6.7	0.3	3.8	0.2	1	18	0.13	26	0.18
BH15	7.2	0	4.4	0.03	4.1	42	0.03	8.8	0.32
BH16	6	0	2.6	0.01	3.1	48	0.02	10	0.24
BH17	7.1	0	2.8	0.02	2.1	11.2	0.08	12	0.42
BH18	6.4	0.05	2.4	0.04	3	29	0.03	12	0.66
BH19	6.7	0.15	7.2	0.3	5	34	0.02	37	0.39
BH20	6.9	1.5	3.1	0.02	6.1	6.8	0.04	26	0.21
BH21	5.8	0.6	9.2	0.02	5	1.7	0.05	25	0.49
BH22	5.9	0.05	8	0.02	2	11.2	0.05	12	0.53
BH23	6.9	0	7.4	0.03	1	12.3	0.03	16	0.07
BH24	5.6	0	4.8	0.06	4	4	0.013	17	0.21
BH25	7	0.02	7	0.01	3	30.2	0.03	45	0.42
BH26	6.6	nil	1.3	0.01	3.5	53	0.05	1930	0.34
BH27	6.2	nil	8.1	0.01	2.5	22	0.02	27	0.19
BH28	6.5	nil	2.7	Nil	4.2	3.6	0.03	15	0.11
BH29	5.1	0.15	3.2	Nil	3.1	32	0.18	34	0.34
BH30	6.2	0.1	6.1	0.06	3.7	23.6	0.03	34	0.42
BH31	7.3	0.07	6.6	0.08	4	34	0.08	25	0.36
BH32	5.9	0	3.4	0.12	3	58	0.02	24	0.32
BH33	6.4	0.02	6.5	0.01	2	37	0.09	32	0.35
BH34	6.6	0.02	9.2	0.06	1	39	0.2	34.5	0.36
BH35	6.9	0.06	1.3	0.06	3	43	0.01	23.1	0.23
WHO Standards	6.5-8.5	<3	< 10	< 0.4	< 400	< 250	< 2.0	< 500	< 1.5

Table 4-17: Bacteriological Parameters of drinking water in Port Loko District

	Bacteriological Parameters	
Location	Faecal Coliform (cfu)/100 mL	Non-Faecal Coliform (cfu)/100 mL
BH1	Nil	0
BH2	Nil	Nil
BH3	Nil	Nil
BH4	10	Nil
BH5	15	Nil
BH6	Nil	10
BH7	Nil	75
BH8	Nil	0
BH9	Nil	Nil
BH10	20	Nil
BH11	Nil	Nil
BH12	10	35
BH13	Nil	20
BH14	15	Nil
BH15	10	Nil
BH16	20	Nil
BH17	Nil	0
BH18	Nil	Nil
BH19	Nil	Nil
BH20	Nil	0.1
BH21	20	Nil
BH22	10	5
BH23	20	5
BH24	Nil	0
BH25	Nil	0
BH26	Nil	0
BH27	Nil	0
BH28	Nil	0
BH29	Nil	0
BH30	Nil	Nil
BH31	Nil	Nil
BH32	Nil	0.5
BH33	10	0.6
BH34	10	Nil
BH35	Nil	Nil
WHO Standards	Zero	< 10

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Introduction

This chapter discusses the results of both quantitative and qualitative analyses of the investigation. Whilst the granitic terrain comprises of fractured basement aquifer system (confine aquifer) and a clay layer (aquitard), the Bullom Group of sediments comprises of sand porous aquifer system (confine aquifer) that exhibit high yield potential.

The final analysis gives a clear understanding of the aquifer system in the fracture basement and the Bullom group of sediments. It also discussed and give understanding of the subsurface layers of the Bullom group of sediments with the results obtained from Earth Resistivity Survey. Finally, water quality tests done in the boreholes showed how pH, Fecal and Non-Fecal coliforms differ in both districts with respect to WHO standards recommended values for drinking water. The cause of variance of pH and fecal coliform in both districts are also highlighted.

5.2 Quantitative Analyses

The quantitative analyses are widely seen as the process of assigning numbers to a phenomenon or investigation according to prior given numbers or set of rules. This form of analyses is numerical and may be characterized by computational and calculative procedures. In order words, it relates to a comparison of simple numerical measurements based on the results obtained from pumping tests such as the average yields of boreholes from the different project areas. The average numerical results of the boreholes (yields) of the two districts are compared quantitatively based on their output.

5.2.1. Yield Analysis for Tonkolili and Port Loko Districts

From the pumping test analysis, results have shown that both studied areas comprised of confined aquifer system with average yield of (2.04 m^3/hr.) in Pepel, Port Loko district and (1.90m^3/hr) in Tonkolili district as shown in figure 5-1 below. The productivity of the boreholes in both Tonkolili and Pepel can supply enough water to the community.

However, increase in the number of the local population is posing some challenges in the availability of water.

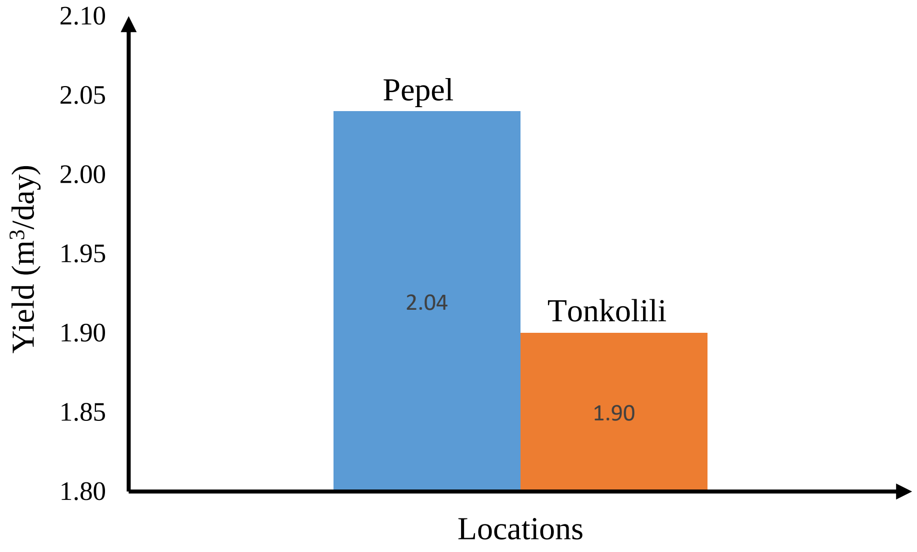


Figure 5-1: Average borehole yields in both districts

5.3 Qualitative Analyses

The qualitative analyses can be described as an in-depth analysis, which considers or narrows down the study to a small section of the sample data to investigate and compare conformity of two sets of data with respect to each other. The qualitative analysis carried out in this research is a comparison of a small sample area in the overall case study area from earth resistivity survey in Pepel, Loko district. Resistivity values were compared with the transmissivity and depth in relation to the sub surface formation of the five boreholes to determine the cause of variance.

In addition, water quality analyses were carried out. The water samples data obtained were analyzed for their central tendencies using descriptive statistics. The data for physical, chemical and bacteriological analyses with the exception of temperature were compared to WHO water quality standards and the cause for the variance of the water quality parameters are determined.

5.3.1 Pepel Port

Pepel is a shipment port for Shandong Steel Company. When the iron ore in mined from Tonkolili the iron concentrates are stockpiled at Pepel for shipping. See figure 5-2 below.

Figure 5-2: Shows Pepel Port (African Minerals website, 2018)

1) Analyses of Resistivity values

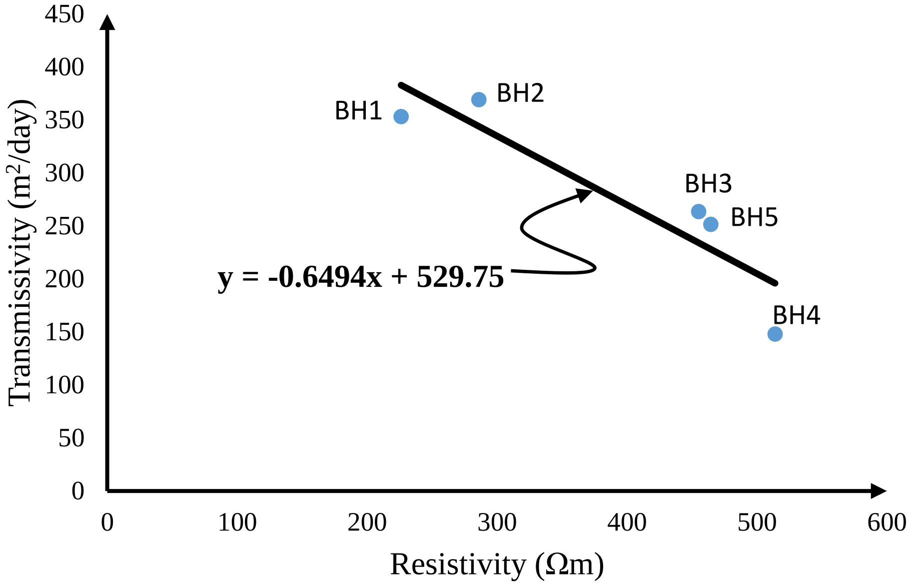


Figure 5-3: Linear relationship between resistivity, transmissivity and depth

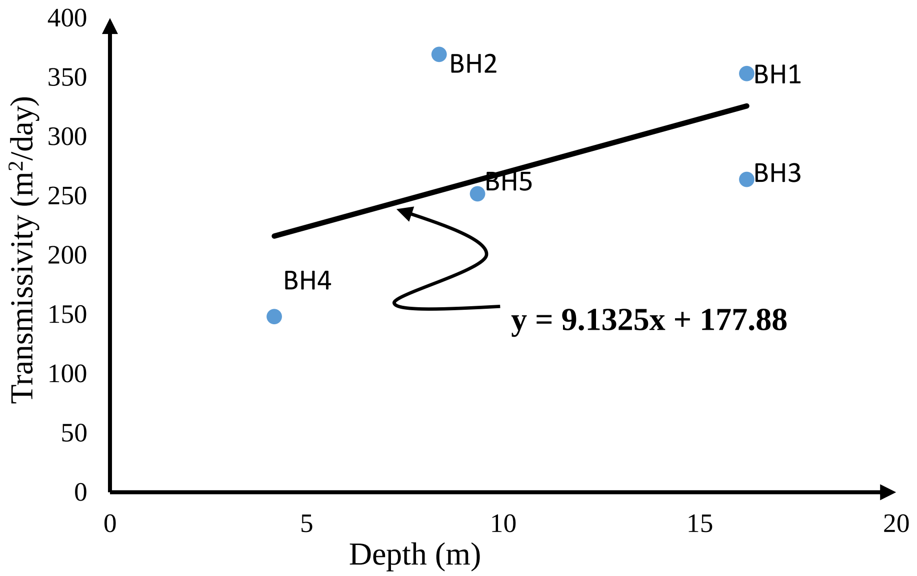


Figure 5-4: Linear relationship between transmissivity and depth

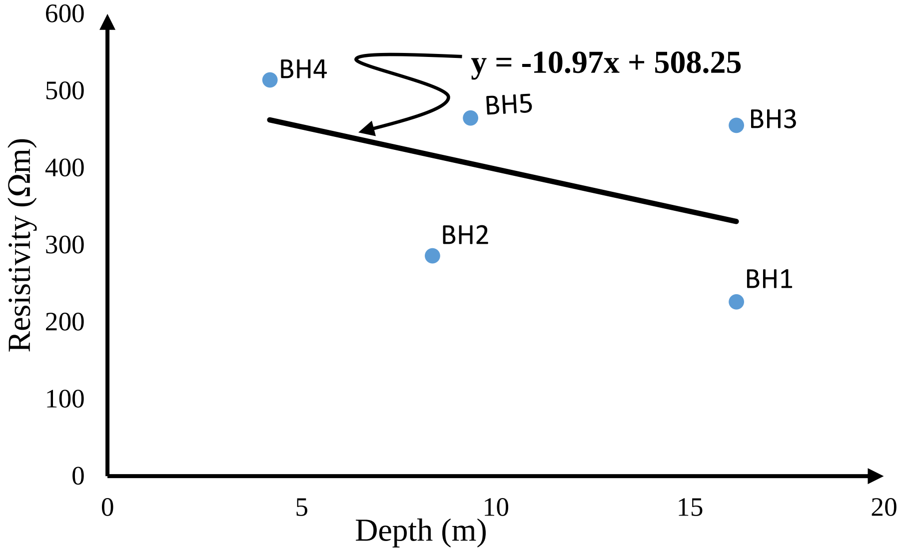


Figure 5-5: Linear relationship between resistivity and depth

Figure 5-3, above shows a negative linear relationship between transmissivity and resistivity. Resistivity increases with decrease in transmissivity at water level depth. Figure 5-4, shows a positive linear relationship between transmissivity and depth. Transmissivity increases with increase in depth, which cut across all the five boreholes. Figure 5-5, shows a negative linear relationship where resistivity tend to decrease with increase in depth.

Generally, the results show that there is a linear relationship between resistivity, transmissivity and depth through sandy soil formations (porous aquifer).

Resistivity values plotted against pH, faecal and non-faecal coliform values determines that there was no relationship between them.

5.3.2 Tonkolili and Pepel

Tonkolili is an iron ore-mining region. See figure 5-6 to figure 5-7 below.

Figure 5-6: Iron Ore mining (African Minerals website, 2018)

Figure 5-7: Waste dumped with manganese (African Minerals website, 2018)

1) Analyses of Physical Parameters

The results of the groundwater from the boreholes analyses show an average temperature range of 24.4 °C to 30.6 °C in both regions. The physical parameters such as turbidity, conductivity and TDS was compared with pH in order to understand their relationship within the region. The results are shown in figure 5-8, 5-9 and 5-10 below.

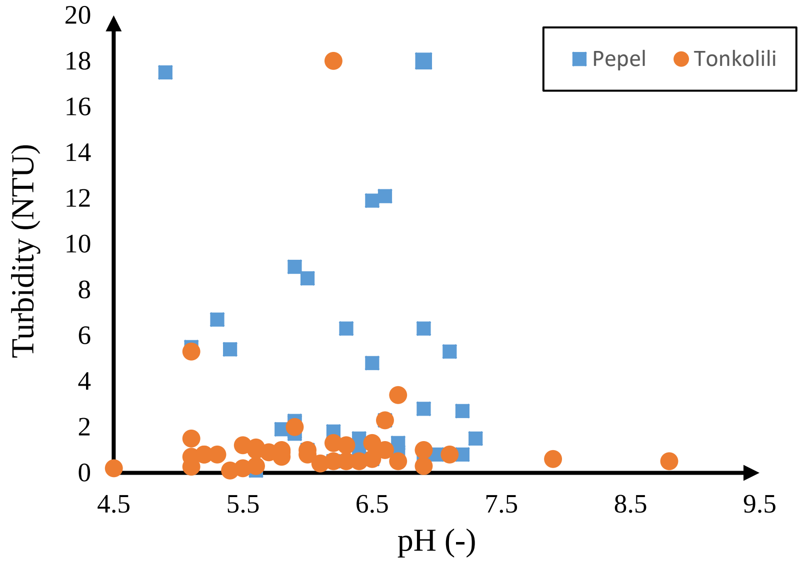


Figure 5-8: Linear relationship between turbidity and pH

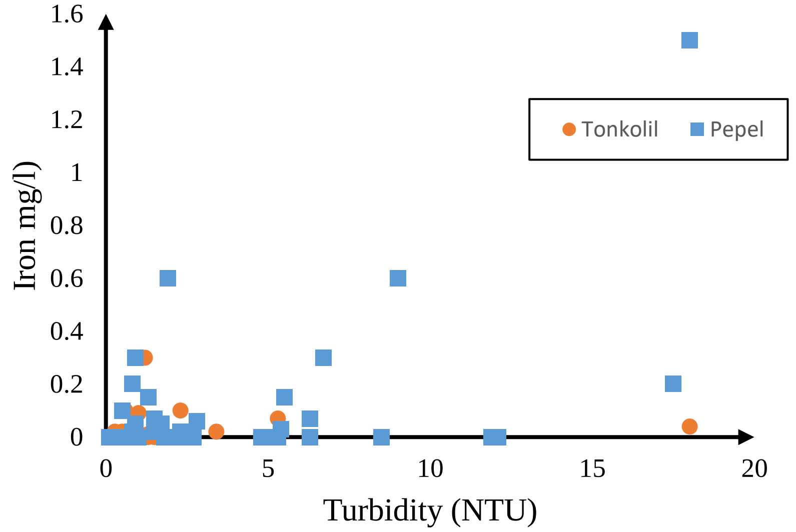


Figure 5-9: Linear relationship between Iron and turbidity

Turbidity is measured in Naphenometric Turbidity Units (NTU) and it varies largely between the two districts. Results from figure 5-8 show that there is a negative linear relationship between pH and turbidity in the two regions. Turbidity increases with decrease in pH waters. The water in Pepel is more turbid than that in Tonkolili as depicted by the analyses. Figure 5-9 show a positive linear correlation between iron and turbidity. That is the lower the iron content the lower the turbidity, which means iron contributes to turbid water. Turbidity is a physical factor that reduces the clarity of water and it is caused by suspended organic, inorganic matter, plankton and microbes in water. The thresh hold at which water turbidity can be detected by naked eye is above 5 NTU.

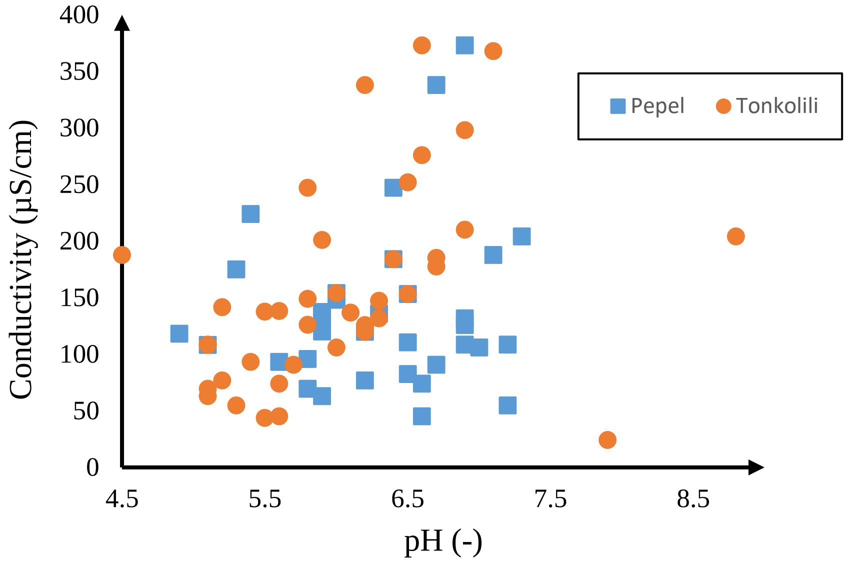


Figure 5-10: Linear relationship between conductivity and pH

Electrical conductivity (EC) is measured in microSiemens per centimeter (μS/cm) (Commonwaelth of Australia 2002) using conductivity meter. There is a positive linear correlation between pH and conductivity as shown in figure 5-10 above. A positive correlation implies that pH increases with increase in conductivity in groundwater. The EC varied between 24.1 μS/cm to 368 μS/cm in Tonkolili district and 69.5 μS/cm to 338 μS/cm in Pepel, Port Loko. Welcome (1985) described conductivity as a measure of the total amount of ions present in a body of water. The variation in conductivity of the water samples may be due to environmental differences and variation in total dissolve solids

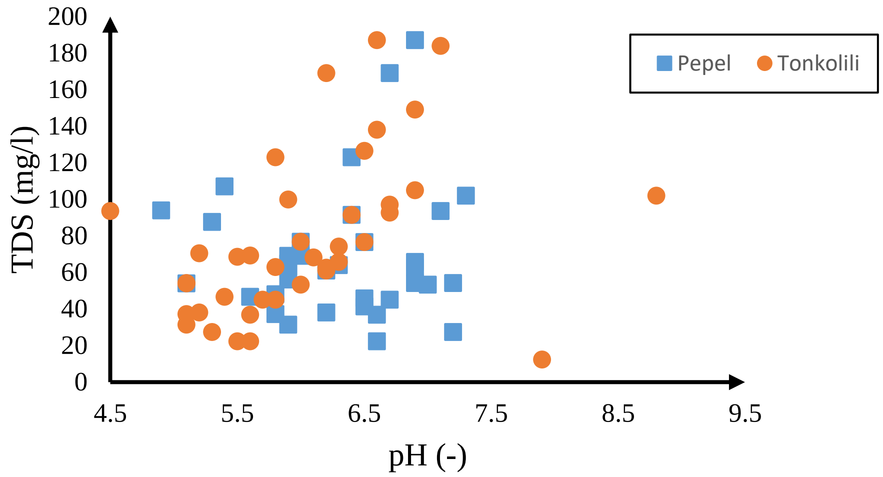


Figure 5-11: Linear relationship between TDS and pH

Results from figure 5-11 show that there is a positive linear correlation between TDS and pH. TDS increases with increase in pH. The total dissolved solids (TDS) measured ranged from 38 mg/l to 187 mg/l in Tonkolili district and 38 mg/l to 93.6 mg/l in Pepel, Port Loko district. In general, pH is strongly related to the physical parameters of the sampled waters.

2) Analyses of Chemical Parameters

The pH of water samples measured with a digital HACH portable pH meter showed that 29 (74 %) out of 39 water samples in Tonkolili district and 19 (54 %) out of 35 water samples in Pepel, Port Loko district are below WHO recommended pH limits of 6.5-8.5. See figure 5-12 and 5-13 below show the number of boreholes that are below pH limits.

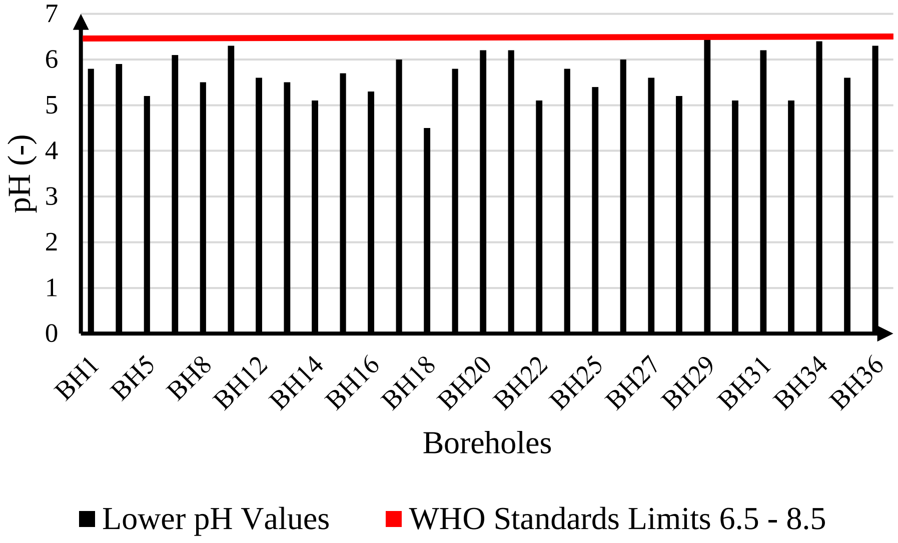


Figure 5-12: Boreholes with low pH values out of WHO limits in Tonkolili

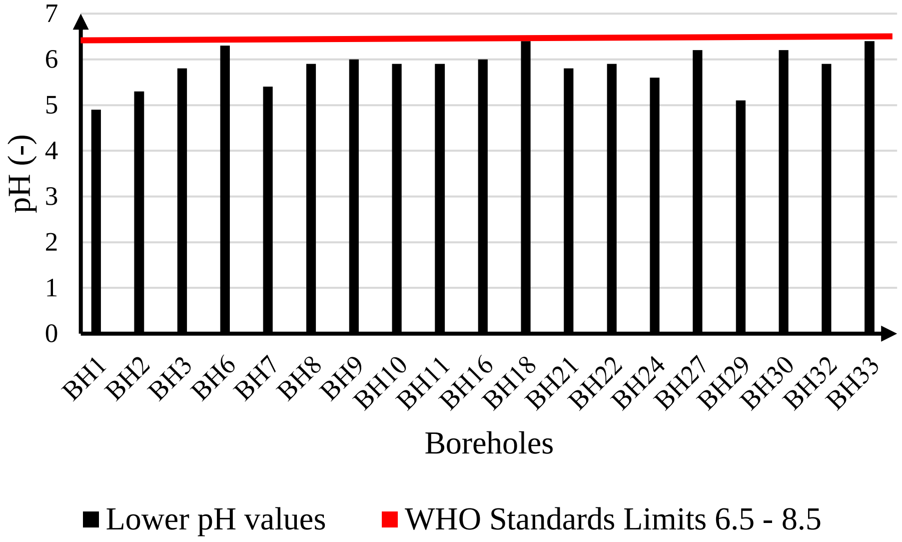


Figure 5-13: Boreholes with low pH values out of WHO limits in Pepel

The pH was compared with iron, manganese and sulphate to determine their relationship with regards to the lower pH values within the two areas. More than 60% of the boreholes have low pH. The results of the analyses are presented in figure 5-14, figure 5-15, figure 5-16 and figure 5-17 below.

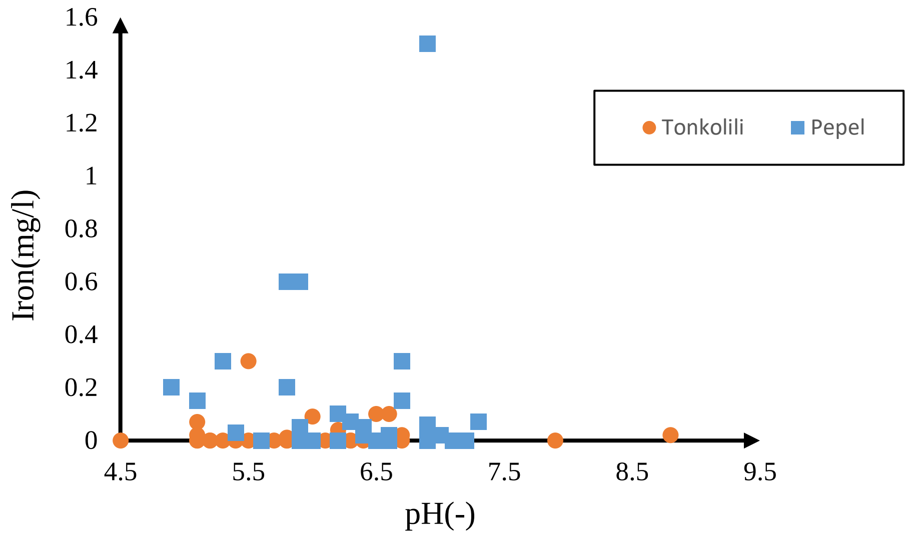


Figure 5-14: Linear relationship between TDS and pH

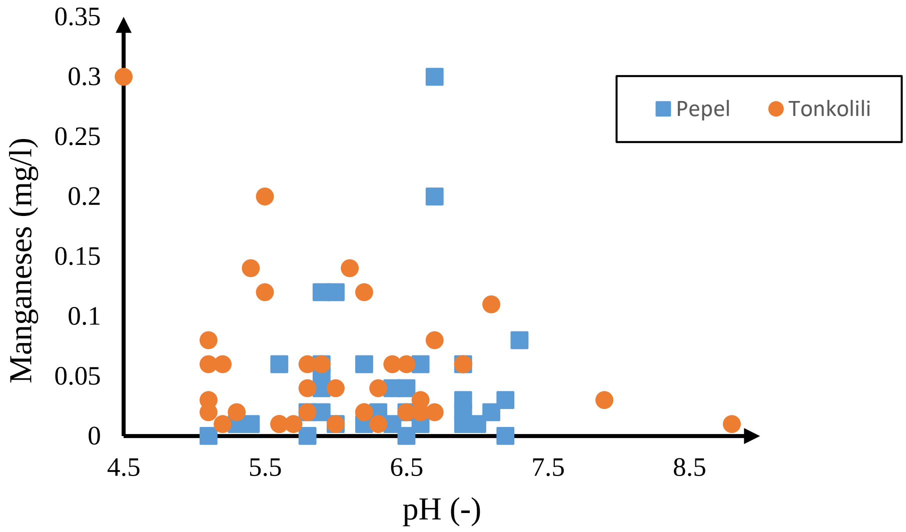


Figure 5-15: Linear relationship between manganese and pH

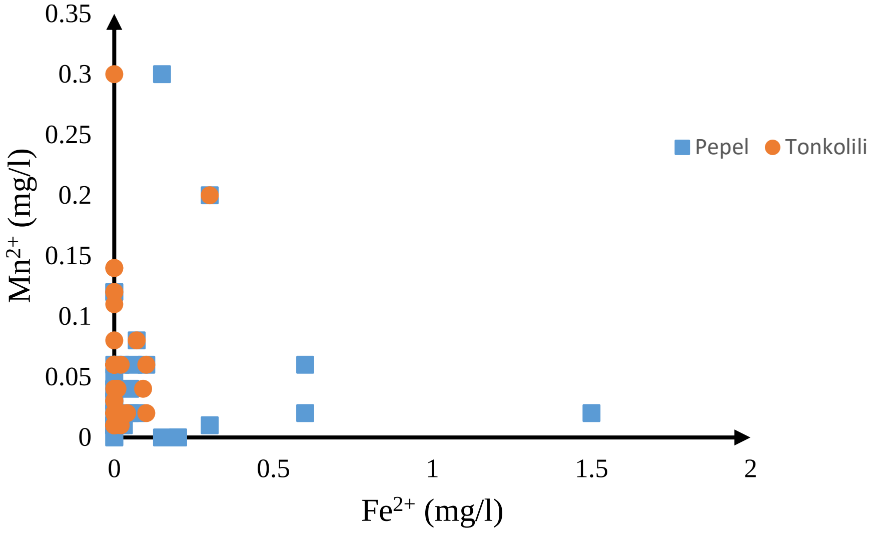


Figure 5-16: Linear relationship between manganese and Iron

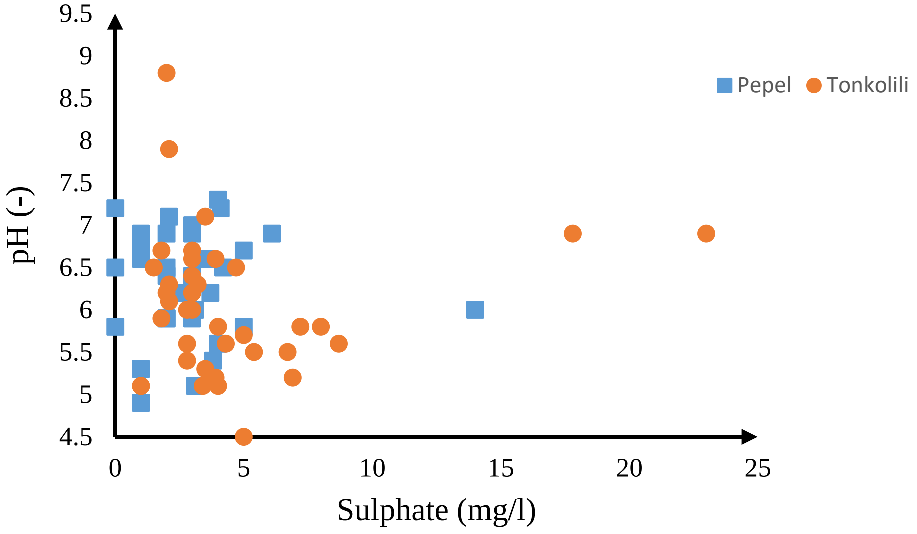


Figure 5-17: Linear relationship between pH and sulphate

From the analyses above, pH show a negative correlation with Mn^{2+} and Fe^{2+}. A negative correlation implies that, a decrease in pH is associated with increase in Mn^{2+} and Fe^{2+}. Figure 5-17 shows that pH has a negative relationship with sulphates. This means that as sulphates increase the pH of waters lowers. As the pH of water becomes low, the water becomes more acidic and more Mn^{2+} and Fe^{2+} are dissolved. The reason is that as the acid waters interact with the iron concentrate on the surface in Pepel and waste rocks of iron ore in Tonkolili, Fe^{2+} and Mn^{2+} are dissolved because of low pH. This may leach through the ground slowly to contaminate the underground water resources. The recorded values are within WHO recommended limits (2.0 mg/l) for drinking.

The contamination process in this research is different from previous acid mine drainage system in which case the oxidation of sulfide to sulphate to release H^+ to lower the pH is the cause of acid water (equation 5-1).

$$2FeS_2 + 7O_2 + 2\ H_2O = 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (5\text{-}1)$$

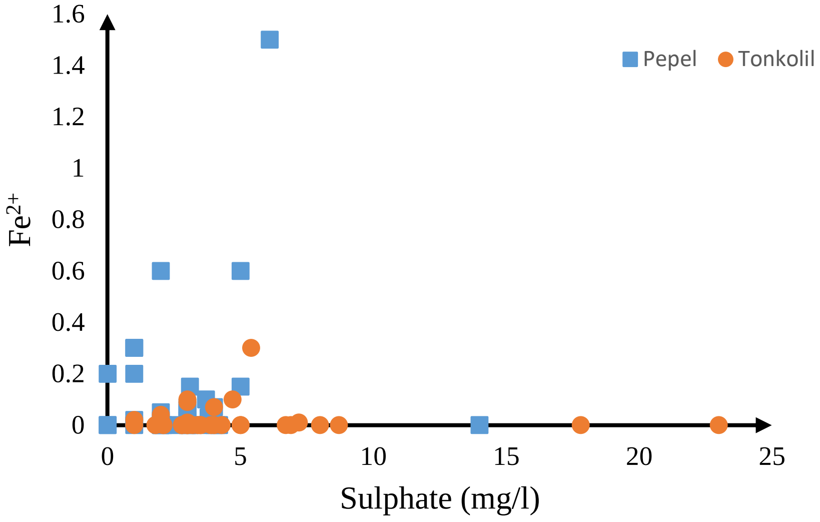


Figure 5-18: Relationship between Fe^{2+} and sulphate

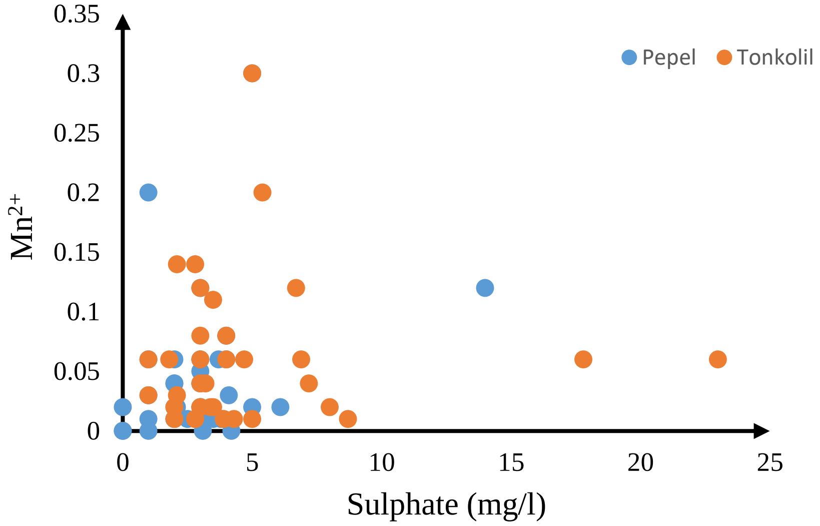


Figure 5-19: Relationship between Mn^{2+} and sulphate

Figure 5-18 and figure 5-19, show low concentration of sulphate in both districts. Because of low sulphate in both districts, it is concluded that sulphate may not be the reason for the release of H^+ that lowers the pH of waters around the areas.

3) Analyses of Bacteriological Parameters

Bacteriological water quality analysis was carried out on all the water samples using the membrane filtration technique. 10ml, 20ml and 50ml volumes of water samples were measured out. The different volumes were filtered through filter pads. The filter pads were rested on filter membrane containing agar medium, coliform broth, in already sterilized Petri-dishes with cover. The Petri-dishes with their contents were incubated in an incubator for 3 hours at a temperature of 400C. Based on blue and pink colour of colonies formed, fecal and non-fecal coliforms were identified (Bonde, 1977), enumerated and expressed per 100ml of water sample.

Fecal coliform is a group of bacteria found in the feces of warm-blooded animals such as people, livestock, pets, and wildlife. The amount of fecal coliform in water bodies increases with the amount of sewage waste and/or manure. Fecal coliform contamination can come from sewage treatment plants or some industries. Often, it comes from many small sources, each contributing a little to the overall problem. Each of us who live in a watershed contribute to these small sources through the way we manage our on-site septic systems, livestock waste and pet waste. Wildlife and birds also contribute. Whatever the source, as the amount of fecal coliform bacteria in water increases, the risk to public health also rises.

1) Fecal Coliform

In Tonkolili district, 9 (23 %) out of 39 water samples have high level of Fecal coliforms, while in Pepel, Port Loko district 12 (34%) out of 35 water samples have high levels of Fecal coliforms. See Figure 5-20 and 5-21. The values recorded exceeded the WHO recommended values for portable water.

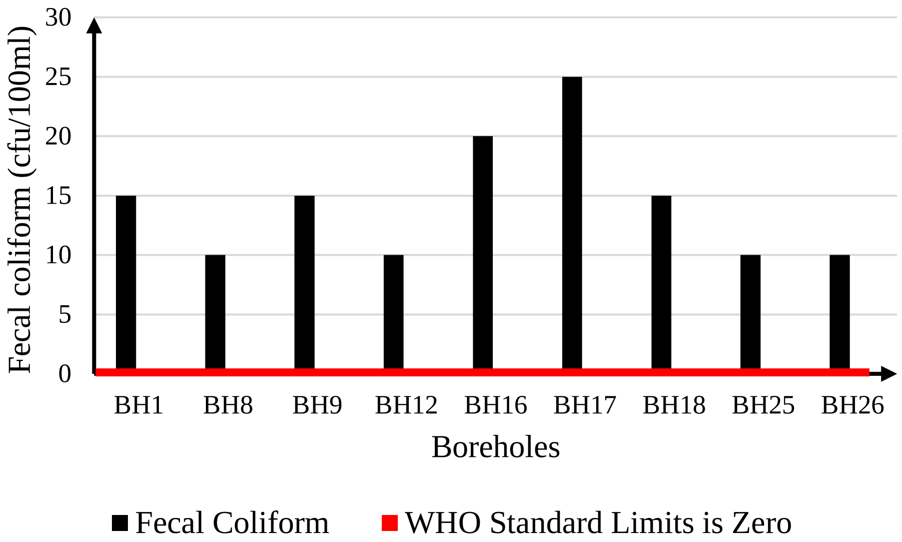


Figure 5-20: Number of boreholes with Fecal coliform from Tonkolili

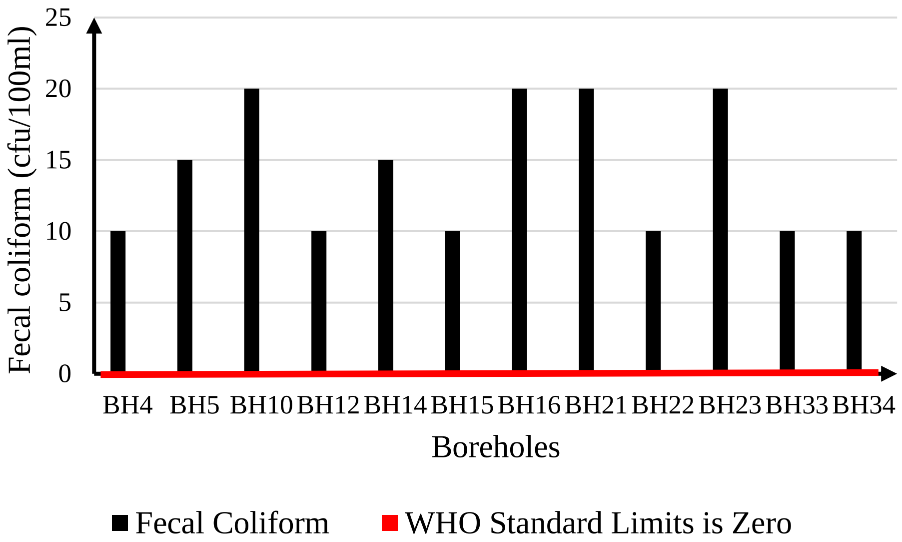


Figure 5-21: Number of boreholes with Fecal coliform from Pepel

Analyses of the fecal coliform were compared with turbidity and pH to determine if there is any relationship between them. The results are shown in figure 5-22 to 5-23 below.

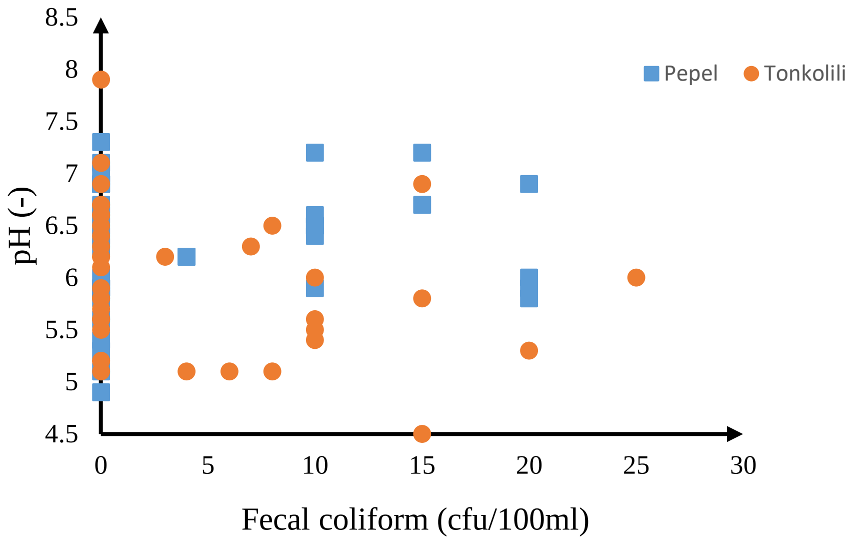


Figure 5-22: Non-linear relationship between ph and fecal coliform

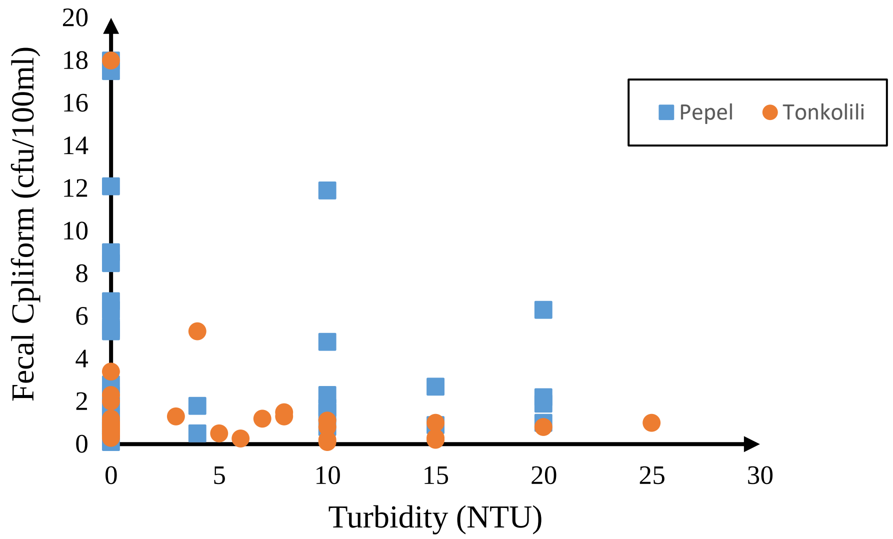


Figure 5-23: Non-linear relationship between fecal coliform and tubidity

However, Fecal-coliform showed no relationship with pH in both districts. The presence of fecal coliforms in most of the wells may be due to movement of pollutants from closely located, pit latrines and leaking septic tanks as well as indiscriminate defecation around the wells. Therefore, the low pH and presence of fecal-coliform are the cause of the waterborne disease in the region even though their concentration is low.

The most frequently used indicators of faecal pollution are the coliform bacteria (e.g.Escherichia coli), Streptococci and Closteridium perfringens (Mason, 1996). Bonde (1977) had indicated that the presence or absence of faecal coliforms, especially, E. coli was a better indicator of sewage contamination than total coliforms.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Introduction

This chapter is a summary and conclusion of the findings and a recommendation for future studies on groundwater investigation and water quality analyses in the studied areas. Conclusion and recommendation are drawn based on the findings from the two research areas, which will form the bases for future research.

6.2 Discussion of WHO Standard in Relation to the Results

World Health Organization (WHO) developed water quality standards for portable water to make sure every nation provides safe drinking water for its people. According to the organization's research, in developing countries like Sierra Leone, 80% of the diseases is caused by contaminated drinking water. This standard will help to reduce water bone diseases and foster healthy living. Exposure to microbial pathogens that contaminate water supplies is responsible for a significant number of the public health burden faced by low-income countries. Unsafe drinking water is a major cause of diarrhea, which is responsible for an estimated 10% of the global mortality among children under the age of five (WHO 2014). Viral and parasitic infections, environmental enteropathy, and undernutrition are other health concerns associated with unsafe water. Consequently, information about drinking water quality is essential for guiding efforts to reduce waterborne diseases. Reliable, up-to-date water quality data can identify high-risk water sources, determine effective water treatment methods, and contribute to the evaluation of water and sanitation improvement programs. However, Sierra Leone does not have national standards and independent regulatory bodies are unlikely to alleviate these constraints without parallel commitments to implementation of the policies enacted by government, such as greater resource allocations for monitoring in small towns and rural areas.

The research found that regulated water quality monitoring activities in Sierra Leone did not achieve testing levels specified by WHO Guidelines, particularly among smaller water suppliers and other agencies such as the main water supply companies SALWACO and GUMA Valley. The results of the analyses showed that the waterborne diseases that is prevalent in the project area is a simple testament to the lack of adherence to WHO standards for water quality. This means that it is fair to justify WHO standards that aim at providing access to safe portable water through adherence of its water quality standards.

6.3 Conclusion

The methodologies used in groundwater investigation and water quality analyses have been studied and applied in this research. Various methods such as Engineering survey, GIS, Earth Resistivity survey and Pumping test were used. The research involved 74 boreholes, 35 boreholes were drilled in the sedimentary sequence (Pepel) and 39 in the fractured basement aquifer (Tonkolili). The resistivity values were plotted to describe the sub-surface layers, pumping tests were done in all the boreholes to determine the yield and water quality analyses to determine the cause of variance of the physical, chemical and bacteriological parameters. This could be used as bases for future guide/information that might help government agencies and various stakeholders to properly manage the water resources.

Geophysical survey results from Pepel revealed that resistivity is related to transmissivity through sandy formation except in clayey formation, which serves as aquitard. Therefore, resistivity increases in the presence of clayey materials unlike transmissivity. Four geoelectric layers were identified viza-vis a top sandy soil, a wet clay layer, and a fine-medium-coarse sand layer identified as the aquifer layer and the fourth sandy gravel layer as the confine aquifer, which is the source of portable water in the study area. Depth to the aquifer ranges from 4.18m near VES 4, 8.37 near VES 2, 9.35m near VES 5. Both VES 1 and VES 3 have depth of 16.20 m each. The absence of legitimate surface water sources clearly indicates that most of the rainfall goes into storage in the subsurface, which indicate that the groundwater potential in the area is good.

Pumping test have shown that boreholes in Pepel, Port Loko districts have higher average yield (2.04 m^3/hr.) than those in Tonkolili district (1.90 m^3/hr.). The productivity of the boreholes in both Tonkolili and Pepel can supply enough water to the locals in the areas. However, increase in the number of the local population will pose some challenges in the availability of water in the future.

Water quality tests results showed that 29 (74%) of boreholes in Tonkolili district and 19 (54%) of boreholes in Pepel, Port Loko district have pH values outside WHO recommended value of 6.5-8.5. This shows that water quality of those areas are more acidic. The research found that in Pepel, pH has a negative correlation with Fe^{3+} and Mn^{2+}. It implies that decrease in pH is related to increase in Fe^{3+} and $Mn^{2+,}$ which results in increase of turbidity in Pepel. The reason is that as rain water interact with the iron concentrate on the surface in Pepel, dissolved Fe^{3+} and Mn^{2+} are increased and the waters becomes more acidic because of low pH. This may leach through the ground to contaminate the underground water resources. In Tonkolili, pH has negative correlation with Mn^{2+}, which means that increase in manganese is associated with decrease in pH.

When the acid waters interact with the iron concentrate on the surface in Pepel and waste rocks of iron ore like manganese in Tonkolili, Fe^{2+} and Mn^{2+} are dissolved because of low pH. This may leach through the ground slowly to contaminate the underground water resources. Fecal-coliform showed no correlation with pH in in both districts.

In Tonkolili, 18 (46 %) out of 39 of the boreholes analyzed did not meet the WHO standards for drinking for fecal and non-fecal-coliform. In Pepel, 16 (45 %) out of 35 of the boreholes analyzed did not meet WHO standards for drinking for Fecal and Non-Fecal-coliform. This poses a potential outbreak of waterborne diseases in the community, which is evident with the high number of water related diseases reported at health centers in the project areas. The presence of fecal coliforms in most of the wells may be due to movement of pollutants from closely located waste dumps, pit latrines and leaking septic tanks as well as indiscriminate defecation around the wells. However, even though, there is high faecal coliform and low pH waters, but the water is still portable. That means the contamination is slow and can be prevented.

6.4 Recommendation

The recommendations are based on the experienced and results obtained by the researcher from the studied areas Sierra Leone. They are strictly based on the researcher's point of view and could be within the acceptance limit, specifically for the areas of study or similar research in the same or similar field. The researcher would like to recommend the following:

1) Sierra Leone should development national water quality standards and creates independent regulatory bodies with government commitment to enact and implement policies, such as water quality monitoring in small towns, villages and big cities, especially mining areas.
2) Before well construction, there should be a geological, geophysical investigation of the area for proper siting of the aquifer to determine the average depth to aquifer to avoid boreholes to dry up.
3) Drilling of new boreholes in every village to alleviate the problem of water shortage due to influx of people and implementing agencies should be monitored so that the problems reported by the community are solved.
4) There should be a regular monitoring of the physical, chemical and bacteriological parameters of the borehole waters within the area to adhere to WHO standards to prevent outbreak of prevalent waterborne diseases. .
5) Finally, despite the groundwater being suitable for drinking, it is recommended for chlorination to ensure that it remains free of E. coli and total coliforms.

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