Pan African University
Institute of Water
and Energy Sciences

PAN-AFRICAN UNIVERSITY

INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

WATER POLICY

Presented by

Sahid Ali KOROMA

MAPPING OF GROUNDWATER FLOW PATTERN: A CASE STUDY OF JUI AND ALLEN TOWN COMMUNITY, SIERRA LEONE.

Submitted on 01/10/2020

Defended on 20/09/2020 Before the Following Committee:

Chair	Bernhard **TISCHBEIN**	PhD	University of Bonn, Germany.
Supervisor	Navneet **KUMAR**	PhD	Centre for Development Research (ZEF) University of Bonn, Germany.
External Examiner	Benaabidate **LAHCENE**	Prof	University of Fez, Morocco.
Internal Examiner	Kamila Baba **HAMED**	Prof	University of Tlemcen, Algeria.

DEDICATION

I dedicate my dissertation work to my family and my friends. A special feeling of gratitude goes to my loving and caring mother whose words of encouragement and continuous support has kept me going all this while. I am also grateful for the many hours of proofreading and Allah's grace and strength that saw me complete this project.

I also dedicate this dissertation to my father, who has been sick for quite a long time now. I pray for Allah's divine healing and protection over his life. Finally, my sincere gratitude goes to Dr Mustapha O. Thomas whose idea was developed to come up with this research topic.

DECLARATION

I, Sahid Ali KOROMA, hereby declare that this thesis is a representation of my personal work, realized to the best of my knowledge. I also declare that all information, material, and inclusions from other works presented here, have been fully cited and referenced following the academic rules and ethics.

Name: KOROMA Sahid Ali **Date: 13/10/2020**

Signature:

Reg. No: WP06

CERTIFICATION

This is to certify that the master's thesis entitled "**Mapping of Groundwater Flow Pattern; A Case Study of Jui and Allen Town Community, Sierra Leone.**" is a record of the original bona fide work done by Sahid Ali KOROMA in partial fulfilment of the requirement for the award of Master of Science Degree in Water Policy track at Pan African University Institute of Water and Energy Sciences (including Climate Change) - PAUWES during the Academic Year 2019-2020.

Supervisor (Dr.-Ing. Navneet Kumar)

Signature: Navneet Kumar **Date: 14.10.2020**

……………………….....................

ABSTRACT

The groundwater mapping procedure that was employed in this research is a process which was done basically to delineate flow direction, identify possible recharge and discharge areas and generate groundwater maps that will provide useful information on its use and sustainability. A study was carried out at Jui and Allen Town Community, located in the eastern part of Freetown using the global positioning system (GPS) and a Dipmeter to determine the groundwater flow pattern of the area. The longitudes, latitudes and elevations of fifty (50) hand dug wells or borehole locations distributed within the study area were measured and recorded. The depths to the water level in the hand-dug wells were measured directly with the aid of a Dipmeter. A computer based software package known as Surfer was used to generate a water elevation contour map of the study area which revealed that groundwater flow direction is from the West to the Eastern part of the area. It is therefore recommended that dumpsites should be sited within the south or south-eastern part of the area while boreholes for potable groundwater exploitation could be sited in the north, east and western regions in order to minimize groundwater contamination. From the results obtained in this study in relationto flow direction and its implication regarding the vulnerability of groundwater to pollution, it can be seen that the east and south-eastern parts of the area or aquifer is more susceptible to pollution. Therefore, communities within the North, West and Southern regions of Jui and Allen Town Community should take steps to ensure that land use activities will not pose a threat on the quality of groundwater. The present study act as a guide for future groundwater exploration, hence the information will be useful to both the Government of Sierra Leone and other individuals particularly those in water industries in sinking and maintaining boreholes for optimum groundwater exploitation.

Key Words

Groundwater, Static Water Level, Surface Elevation, Flow Direction, Mapping.

RÉSUMÉ

La procédure de cartographie des eaux souterraines qui a été utilisée dans cette recherche est un processus qui a été effectué essentiellement pour délimiter la direction de l'écoulement, identifier les zones de recharge et de rejet possibles et générer des cartes des eaux souterraines qui fourniront des informations utiles sur son utilisation et sa durabilité. Une étude a été menée à Jui and Allen Town Community, située dans la partie est de Freetown, à l'aide du système de positionnement global (GPS) et d'un dipmètre pour déterminer le schéma d'écoulement des eaux souterraines de la région. Les longitudes, latitudes et élévations de cinquante (50) puits creusés à la main ou emplacements de forage répartis dans la zone d'étude ont été mesurées et enregistrées. Les profondeurs au niveau de l'eau dans les puits creusés à la main ont été mesurées directement à l'aide d'un dipmètre. Un logiciel informatique appelé Surfer a été utilisé pour générer une carte de contour d'élévation de l'eau de la zone d'étude qui a révélé que la direction de l'écoulement des eaux souterraines va de l'ouest à l'est de la zone. Il est donc recommandé que les décharges soient situées dans la partie sud ou sud-est de la zone, tandis que les forages pour l'exploitation des eaux souterraines potable pourraient être situés dans les régions du nord, de l'est et de l'ouest afin de minimiser la contamination des eaux souterraines. D'après les résultats obtenus dans cette étude en relation avec la direction d'écoulement et son implication concernant la vulnérabilité des eaux souterraines à la pollution, on peut voir que les parties est et sud-est de la zone ou de l'aquifère sont plus sensibles à la pollution. Par conséquent, les communautés des régions nord, ouest et sud de Jui et Allen Town Community devraient prendre des mesures pour s'assurer que les activités d'utilisation des terres ne constitueront pas une menace pour la qualité des eaux souterraines. La présente étude sert de guide pour l'exploration future des eaux souterraines, par conséquent, les informations seront utiles à la fois au gouvernement de la Sierra Leone et à d'autres personnes, en particulier celles des industries de l'eau, pour le creusement et l'entretien des forages pour une exploitation optimale des eaux souterraines.

Mots clés

Eaux souterraines, niveau d'eau statique, élévation de la surface, direction de l'écoulement, cartographie.

ACKNOWLEDGEMENTS

First of all, I would like to thank the Allah Almighty, who has walked with me through every step of this journey. Without The Almighty's wisdom, constant guidance and protection, this master thesis would not be accomplished.

Secondly, my special thanks and appreciation goes to the African Union Commission and GIZ for giving the opportunity to be enrolled in this wonderful program and providing all the necessary requirements in terms of financial support to accomplish my master's studies. I thank them so much.

Thirdly, I would like to express my sincere thanks and appreciation to my supervisor Dr. Navneet Kumar and Dr. Mustapha O. Thomas, for having not only reviewed this thesis in details but also provided crucial punctual feedback. They patiently encouraged and guided me to the best of their abilities throughout all stages of this work. I would also like to express my heartfelt gratitude to Mr. Mohamed Juana, Mr. Abu Bakarr Kamara and Miss Grace Kainessie of the National Water Resources Management Agency (NWRMA) for their constant support and encouragement throughout this entire work.

Finally, I am incredibly grateful to my colleagues at PAUWES for the brainstorming sessions, group studies and all the support they provided during this two year period. I send many thanks to my family for their invaluable care, encouragement and support throughout my studies. This work would not have been possible without the love and support of my dear mother, brother and entire family and friends who have always encouraged and believed in me. I received great inspiration from their love and friendship, even from thousands of miles away.

ABBREVIATIONS AND ACRONYMS

DTW	Depth to Water
FAO	Food and Agriculture Organisation
GIZ	German Corporation for International Cooperation
GPS	Global Positioning System
GWP	Global Water Partnership
HH	Hydraulic Head
IWRM	Integrated Water Resources Management
MOWR	Ministry of Water Resources
NMA	National Mineral Agency
NWRMA	National Water Resources Management Agency
NWSP	National Water and Sanitation Policy
PAUWES	Pan African University, Institute for Water and Energy Sciences
PPE	Personal Protective Equipment
SDG	Sustainable Development Goals
SE	Surface Elevation
SWL	Static Water Level
UNEP	United Nations Environment Program
USGS	United States Geological Survey

LIST OF FIGURES

LIST OF TABLES

Contents

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Groundwater is a term that can be used to describe all the waters found beneath the surface of the earth. It can be considered as the most important or major portion of the world's freshwater resources (Elbeih, 2015). According to Global Water Partnership (GWP) in 2010, saltwater (mainly in oceans) represents about 97.2% of the global water resources with only 2.8% available as freshwater. Surface water represents about 2.2% out of the remaining 2.8% whereas the rest of the 0.6% represents groundwater. Groundwater accounts for 26% of the global renewable freshwater resources and less than 1% of this freshwater can be easily accessed for various uses in development right across the world.

The main motive behind the study of groundwater has traditionally been its importance as a resource as it provides water for domestic, agricultural and also industrial uses. Groundwater usage has increased rapidly because of the increase in water demand and the shortage of surface water which is as a result of population growth and the shooting industrialization trend (Ahn & Chon, 1999). Rapid population growth has not only increased groundwater usage but has also threatened the environment through expansion and intensification of agriculture, uncontrolled growth of urbanization and industrialization, and destruction of natural habitats (Ray & Ray, 2011)

The need for both adequate and good quality water has increased extensively due to awareness and also technology and as a result, a good number of people now rely greatly on the exploration and exploitation of groundwater (Anomohanran, 2015).

Groundwater as a resource plays several important roles below the earth's surface such as aiding fault movements, controlling the accumulation and migration of petroleum, earthquake generation and prediction and moving closer to the surface of the earth, groundwater plays an important role in several geomorphological processes such as slope development and stream bed erosion.

The significance of groundwater has long been recognised in indigenous communities and this is being seen in the extra care afforded to those small wells or village springs (Calow et al., 1997).

A groundwater flow system is a set of flow paths with common recharge and discharge areas and groundwater flow mapping is an activity which involves delineating flow directions so we can be able to identify the possible recharge and discharge areas.

In groundwater flow mapping, the depth to the water level is critical as it represents the energy levels or hydraulic heads in moving water particles from one point to another and this varies according to the topography and prevailing climate.

The principal means of groundwater recharge is infiltration of available precipitation on the aquifer (Thomas, 2019) and this groundwater recharge is one of the most complicated aspects of the hydrological cycle as it is difficult to estimate. However, understanding the aspects of groundwater recharge and discharge is essential for the effective management of our groundwater resources (Crosbie, McCallum, & Harrington, 2009).

Groundwater usually flows from points of higher hydraulic heads to points of lower hydraulic heads. This water may flow either towards or away from streams, rivers and boreholes and this groundwater flow in aquifers may not always reflect the flow of the water on the surface. Identifying groundwater recharge and discharge zones within a watershed is very much important for implementing effective strategies for salinity mitigation, both surface and groundwater management and also ecosystem protection. Mapping of recharge and discharge areas is integral to managing water resources and understanding salinization processes (Leblanc et al., 2007).

1.2 PROBLEM STATEMENT

Water is life, access to clean and safe drinking water is one of the main issues in alleviating poverty and this issue is clearly addressed in the Sustainable Development Goal (SDG) number six (6). Groundwater is stored within pore spaces and fractures in rocks. It’s recharge is usually said to happen annually and this mechanism is greatly influenced by a number of factors which include; soil type, land use, total annual rainfall; distribution and intensity of rainfall events (Calow et al., 1997).

In many developed countries in the world, a network of observation of boreholes exists and even though such infrastructure is expensive, it allows the monitoring of groundwater level and also possible recharge. Such an organised system or network of groundwater management is lacking in most developing countries. In most parts of Sierra Leone including our study area, a conceptual model of the area has not been developed so a lot of people lack an understanding of the aquifer system. It is usually difficult to determine the specific contaminant source when contamination problems arise in a water resource. This is as a result of the limited understanding of recharge and sub-surface flow systems in the area.

By definition, any geological material that is sufficiently permeable to yield a significant amount of water to pumping wells can be referred to as an aquifer (Jalloh et al., 2016) and for a geological material to be called an aquifer it should be permeable and porous.

The nature of an aquifer system is highly variable; hence each aquifer system needs to be properly understood as knowledge of similar aquifer cannot be used for another. Identifying groundwater discharge zones and discharge quantity is not only important for determining the dependency of the surface water system, but also the groundwater-surface water interface as this interaction is relevant for a wide range of reasons(Terrestrial & Dependent, 2009).

1.3 RESEARCH OBJECTIVES

1.3.1 Main Objective

The main objective of this study is to investigate the baseline conditions of the existing groundwater in the study area and carry out a mapping exercise to determine the flow pattern or develop a groundwater flow map of the area.

1.3.2 Specific Objectives

- To determine the static water levels and measure the surface elevation of wells being drilled into the aquifer system.
- To generate or develop a contour and other important groundwater maps such as (image, 3D surface, wireframe and vector overlaid map) of the study area.
- To determine groundwater flow direction which also includes the identification of both recharge and discharge areas.

1.4 RESEARCH QUESTIONS

This research is generally looking to address the following questions;

- How is the static water level in wells being measured or determined?
- What is the surface elevation of well positions and possible flow direction of groundwater within the case study area?
- Where can groundwater recharge and discharge areas be located?

1.5 SIGNIFICANCE OF THE RESEARCH

Groundwater is a very important resource, which helps greatly in promoting livelihood as it provides water for domestic, agricultural and industrial purposes and also contributes to economic development. The significant role that groundwater plays in the urban cycle is well established in many countries around the world, both in terms of quantity and quality (Mudd, Deletic, Fletcher, & Wendelborn, 2004). For us to be able to make informed decisions on groundwater allocation and properly manage strategic future planning there is a need to understand its flow direction.

Western areas just as the other regions in Sierra Leone are facing problems of water scarcity. The government has recently embarked on a fundamental reforming process in the water sector and this move included the development of a new National Water and Sanitation Policy (NWSP 2012). This policy document pinpoints the Ministry of Water Resources (MoWR) as the principal authority for the management of the country's water resources, with policy and oversight responsibilities. It provides a framework for Integrated Water Resources Management (IWRM) and also adopts water resources management as the main approach for water security.

A better understanding of the way an aquifer functions and the ability to assess its capacity and recharge patterns is important as it helps in the optimum and sustainable use of groundwater. Here when we say sustainable use of groundwater, we mean when the present day use does not deprive future generations from enjoying the same benefits of the resource.

Groundwater is an important source of freshwater worldwide, and more than two billion people depend on groundwater for drinking water supplies (Liesch & Wunsch, 2019). Although we are not addressing the effects here in detail, but if we can identify the various different land use activities that can pose a threat on our water resources and minimize or put measures in place to stop them, then we may avoid the need for intensive water treatment techniques. This will also reduce the amount of chemicals required for water treatment, as well as improving the overall environmental quality of our water sources.

1.6 RESEARCH CHALLENGES

1.6.1 Scope and limitations

In this research, we needed to measure static water levels for several water points and this needs to be done in the morning for accurate water level measurements. To make work much easier and for our readings to be on point, information was sent the previous day before data collection at a particular water point and the water level measurement was taken the next morning before people start fetching water.

Conducting this research required the permission of certain leading authorities so the approval to carry took some time. A much earlier request or application was sent and constant follow ups were done for approval.

Also, the non-willingness of certain political heads and other stakeholders particularly those at the grassroots to allow me to go ahead with this research was another setback. Therefore sharing certain information was a bit of a problem. Here, consultation was done so the attention of the various stakeholders involved was drawn.

Another limitation which appeared to be the biggest obstacle in this research is the current covid-19 situation that is affecting the world as a whole. My country has recorded high numbers of positive cases and has been on lockdown for quite some time now so movement from one place to another is a big problem.

1.6.2 Chapter Overview

This thesis is made up of five (5) chapters that focus on achieving the purpose of this research and answering research questions. A summary of the chapters is provided below;

Chapter one of this work introduces the background information, statement of the problem, objectives, research questions scope and significance of this work.

Chapter two presents the literature review of the topic in question.

Chapter three describes the materials and methods used to carry out the study and the detailed description of the procedures used to carry out the research to give an understanding of the real situation occurring in the study area.

Chapter four presents the main results and discussions from our groundwater mapping exercise.

Chapter five is made up of the Summary, Conclusions and Recommendation.

This highlights the key results of this study in relation to the overall problems, research and questions.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides a literature review on groundwater mapping and flow dynamics. This literature review explains the concept of groundwater, groundwater mapping, how water flows underground and the various factors that influence groundwater potential. Here, we are also going to look at similar works that have been done on this topic at both national and international level.

2.2 Groundwater

Groundwater is said to be the largest reservoir of liquid fresh water on the planet and it is found in aquifers, porous rocks and sediment with water in between. Water is attracted to the soil particles and capillary action, which demonstrates how water moves through a porous media and moves water from a wet soil to dry areas. Groundwater has been recognized as one of the most precious natural resources, which supports human health, economic development and ecological diversity. Because of its several inherent qualities, it has thus become an immensely important and dependable source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries (Waikar & Nilawar, 2014)

According to USGS, Groundwater can be defined as the water that exists underground in saturated zones beneath the land surface. The upper surface of the saturated zone is called the water table. Contrary to popular belief, groundwater does not form underground rivers. Groundwater fills the pores and fractures in underground materials such as sand, gravel, and other rock, much the same way that water fills a sponge. If groundwater flows naturally out of rock materials or if it can be removed by pumping (in useful amounts), the rock materials are called aquifers.

The movement of groundwater is usually very slow, typically at rates of 7-60 centimetres (3-25 inches) per day in an aquifer. As a result of this slow movement, this water could remain in an aquifer for hundreds or even thousands of years. Groundwater is often called "fossil water" because it has remained in the ground for so long, often since the end of the ice ages.

Looking at one of its main importance, groundwater is a vital natural resource for the reliable and economic provision of potable water supply in both urban and rural communities.

Therefore, it plays a fundamental role in the well-being of humans as well as that of some aquatic and terrestrial ecosystems (Magesh, Chandrasekar, & Soundranayagam, 2012).

2.3 Groundwater Mapping and Monitoring

Groundwater mapping can simply be described as an exercise, which shows how much groundwater is available in an aquifer. It also goes further to explain more about the shape and location of that particular aquifer.

Groundwater can be monitored through the use of wells and water quality samples. Hydro geologists usually install monitoring wells to better understand where water is beneath the surface of the earth and these wells can be drilled deep into the earth, shallow near the surface, or anywhere in between.

Once dug or installed, a well can be used to monitor groundwater and hydro geologists can now be able to measure the distance from the surface of the earth to the water table.

2.4 How Water Flows Underground: Recharge, Permeability and Porosity

Understanding how water travels underground is a very important aspect of hydrogeology. Surface water which infiltrates into the ground is known as Recharge. Water is able to pass through soil pores and pore spaces in rocks, and some of them with great ease; this is so as a result of the permeability of the material.

Water movement in aquifers is highly dependent of the permeability of the aquifer material. Permeable material contains interconnected cracks or spaces that are both numerous and large enough to permit water to move freely. In some permeable materials, groundwater may move several metres in a day and in other places, it moves only a few centimetres in a century. Groundwater moves very slowly through relatively impermeable materials such as clay and shale.

Aquifers can be found at different depths. Some are just below the surface and some are found much deeper below the land surface. It is possible for a region to have more than one aquifer beneath it and even most deserts are above aquifers. The source region for an aquifer beneath a desert is likely to be far from where the aquifer is located; for example, it may be in a mountain area. To be a good aquifer, the rocks present in it must have good porosity and permeability.

2.4.1 Recharge

Recharge is surface water that replenishes groundwater. There are two main sources of recharge. Recharge can either come from precipitation that falls on the ground and percolates or seeps into aquifers. Recharge can also come from surface water (rivers, lakes, streams or wetlands) that percolates into the ground. The type of rock that is being exposed to the earth's surface significantly affects groundwater recharge (Shaban, Khawlie, & Abdallah, 2006). Lithology generally affects groundwater recharge by controlling the percolation of water flow.

2.4.2 Permeability

Permeability is a measure of how easily water can pass through material. Water flows quickly through material with high permeability and flows very slowly through material with low permeability. If you imagine pouring water into a bucket of gravel, the water will flow around the stones rather quickly. If you pour water over a bucket of sand however, the water will move more slowly as it works its way through the gaps between the grains. A bucket of gravel has a higher permeability than a bucket of sand, meaning that the water passes through the material more easily. Almost all materials are permeable. For example, water can pass through dense materials such as clay. However, it can take a long time for this to happen.

2.4.3 Porosity

Porosity is the amount of air space within the grains that make up soils and rocks. A rock with high porosity has a lot of air spaces. If a rock has low porosity, it does not have much air space. Porosity can be a factor in permeability.

The porosity of a geologic material controls the total amount of water available, permeability, in turn, governs both the rate at which water can be withdrawn and the rate at which recharge can occur in an aquifer- rock that holds and transmits enough water to be useful as a source of water. The geologic material may have a high porosity but that does not make it a good source of water e.g. clay.

Gravel and sand have a low porosity, 25-40% and 30-52% respectively compared to clay, 45-55% but their permeability are higher for gravel (1000m/day) and fine sand (0.01-10m/day) to clay less than 0.01 (Data from T. Dunne and L.B. Leopold, 1978). Knowledge of the geology (i.e. the porosity and permeability) of an aquifer, which is a water bearing geological formation; rock or soil, helps to understand the conditions for which a geological formation is supposed to be called an aquifer, in finding groundwater and it is also an important stage in groundwater development and management.

2.5 Factors Influencing Groundwater Potential

There are several factors affecting the occurrence and movement of groundwater in a region including topography, lithology, geological structures, depth of weathering, the extent of fractures, both primary and secondary porosity, slope, drainage patterns, landform, land use/ land cover, and also climate (Jaiswal, Mukherjee, Krishnamurthy, & Saxena, 2003).

2.5.1 Land Use/Land Cover

Land use/Land cover is an important factor in groundwater recharge. This includes the type of soil deposits, the distribution of residential areas, and vegetation cover (Yeh, Lee, Hsu, & Chang, 2009).

The United Nations Convention to Combat Desertification documentation defines land as, “the terrestrial bio-productive system that comprises soil, vegetation, other biogas, and the ecological and hydrological processes that operate within the system” (Haber, 1981).

The terms land use and land cover is often used interchangeably, though they have different meanings. Land use is the purpose for which land is used, whereas land cover refers to the physical characteristics of the surface of the land. A formal description by FAO states that land use is “the arrangements, activities, and inputs people undertake in a certain land cover type to produce, change or maintain it” (FAO and UNEP, 1999).

The role of Land use/ Land cover on groundwater potential is quite obvious and wide. The various types of Land use/ Land cover are forest plantations, crop farms, and open denuded soils surfaces, water bodies like lakes, streams, rivers and settlements. Each Land use/Land cover has a certain influence on groundwater potential indirectly through infiltration, runoff and evaporation (Reghu, Gopinath, Srinivas, Regunath, & Sajan, 2013). Vegetation cover increases the rate of infiltration whilst on the other hand it minimizes evaporation and runoff. Therefore vegetation increases the chances of groundwater recharge and can serve as an indicator for high groundwater potential (Bromley et al., 2002).

Forest plantations require large amounts of water, which they abstract from the vadose zone and in other cases from beneath the water table hence forest plantations indicate high groundwater potential. In settlements and built up areas, infiltration rate is low and this is as a result of roads, pavements and buildings covering the soil surface and consequently, low groundwater potentials are expected (Reghu et al., 2013)

2.5.2 Geomorphology and Slope

Geomorphology is a good proxy for groundwater potential analysis. (Avinash, Jayappa, & Deepika, 2011) demonstrated that the landform and landscape features are well reflected by geomorphology. The slope is a particular type of geomorphologic feature which greatly influences groundwater infiltration and recharge. Where steep slopes are present, groundwater potential is low because there is more surface runoff than infiltration (Fashae, Tijani, Talabi, & Adedeji, 2014). In areas characterised by flatlands and or valleys, the groundwater potential is usually high because it is easier for the water to form pools and infiltrate than to runoff on the surface. In a study carried out by (Youssef, Pradhan, Gaber, & Buchroithner, 2009), geomorphology was the theme with the highest weight of 0.485 in the GIS integration of thematic maps.

2.5.3 Geology

Generally in the field of hydrogeology, it is common knowledge that the geology of a place is a major factor which influences groundwater movement, its storage and subsequently, potential. (Taylor, Krishnamurthy, Kumar, Jayaraman, & Manivel, n.d.) conducted a study on three sites, it was clearly noted that geology was one of the major themes in groundwater analysis. Furthermore, a similar research that was conducted by (Pradhan, 2009) assigned the second highest weight to the geology of all the themes that were used for groundwater zonation in their study area (Bharangi River Basin, India).

Also, the availability of groundwater as a source of water largely depends upon surface and sub-surface geology as well as the climatic condition of that particular area. The porosity and permeability of a geologic formation controls its ability to hold and transmit water. Groundwater is said to be found everywhere beneath the soil surface and can be ever-present in many places if it is being allowed to recharge.

2.5.4 Lineaments

Lineaments can best be described as linear features, which occur on the earth’s surface, distinct from the surrounding features, and reflect what the unseen subsurface can be (Leary, Friedman, & Pohn, 1976). Examples of lineaments include joints, faults, fracture zones, dykes, lithological contacts and foliations (Mogaji, Aboyeji, & Omosuyi, 2011). It has become prominent throughout the last few years to use lineaments studies in the assessment of potential groundwater zones. (Peiffer, 2007) pointed out a number of studies in which the exploration and assessment of groundwater resources were done using lineaments mapping as a core of the exploration. Furthermore, (Morelli & Piana, n.d.) went on to study the correlation between structures mapped in the field and those mapped using the lineament technique. They ended up finding a high correlation, which therefore allows the structures of an area to be indicated by lineaments. Lineaments may be used to infer groundwater movement and storage. (Lattman & Parizek, 1964) were the very first to adopt a lineaments map to exploit groundwater. Thereafter, many scholars have applied this approach in complicated geological regions.

2.5.5 Soil

Infiltration rate and consequently groundwater, is highly dependent on the type of soil and also the texture of that particular. For example, sandy soil has a large particle constituent which makes it have high transmissivity and infiltration values. On the contrary, clay soil comprises of small particle constituents and thus resulting in low transmissivity.

On the aspect of groundwater potential, sandy soils are usually assigned higher weights, clay soils are assigned lower weights whereas loamy soils are assigned intermediate weights (Jha, Chowdary, & Chowdhury, 2010). Soils with high leaching potentials are more sensitive than soils with low leaching potentials. Clay content and organic matter combined control the sorption potential of the soil. Soils with low sorption potentials are more sensitive to groundwater contamination than soils with high sorption potentials. Hence the most appropriate choice for an SAT soil is therefore a compromise, such as a fine sand or sandy loam with relatively little structure (Nagarajappa, Manjunatha, & Manjunath, 2010).

2.5.6 Rainfall

Groundwater recharge mainly comes from rainfall. Rainfall is one of the major hydrological parameters which influences groundwater potential and viability (Avinash et al., 2011). In areas where fossil groundwater is available, rainfall may not indicate groundwater potential but it will indicate sustainability of groundwater exploitation and can be used to estimate optimum water extraction levels. Rainfall is the main source of groundwater recharge in tropic and sub-tropic regions. The slope gradient directly influences the infiltration of rainfall. Larger slopes produce a smaller recharge because water runs rapidly off the surface of a steep slope during rainfall, not having sufficient time to infiltrate the surface and recharge the saturated zone (Yeh et al., 2009).

Several factors such as droughts, seasonal variation in rainfall and pumping affects the height of the underground water levels. If a particular well is being pumped at a faster rate than the aquifer around, it is being recharged by precipitation or other underground flow, and then water levels in the well can be lowered. Although the total rainfall is expected to increase the groundwater level in many places, rainfall variability can put stress on the groundwater availability. High temperatures usually increase evaporation rate and decreases the water levels in lakes, rivers and reservoirs.

2.5.7 Proximity to Drainage

The areas surrounding water bodies such as lakes and rivers usually have high groundwater levels due to the lateral flow of water. Hard rock aquifers close to water bodies might have little groundwater difference from alluvial areas, which are more isotropic in nature. This is so because in hard rock aquifers, the flow of water is dependent on fissures and conduits.

Closer proximity to the drainage network means that the probability of finding groundwater is high (Fashae et al., 2014). Moving away from the drainage, the groundwater potential decreases and the groundwater movement is very slow. Hence at an imaginary threshold proximity to drainage, the influence of the drainage becomes insignificant.

2.6 Previous work

In 2015, a hydro geological account of the Bullom group was given by Lapworth in which he described the unconsolidated sands and clays (inland alluvial and coastal), usually 10 to 20m thick, and can form a moderately productive aquifer with potential borehole yield up to 3L/s. groundwater flow in the sand aquifer is inter-granular attributable to poor consolidation of the sands and storage capacity can be high.

Also in 2015, Adelike provided a simplified hydro geological classification of Sierra Leone. He described the main distinction between the higher permeability and storage of the Bullom Group sands and the relatively low permeabilities of the old, hard rock's of the Precambrian Basement Complex, Sainya Scarp Group, Rokel River Group and Ultrabasic intrusive.

Jalloh, Thomas, & Sasaki, (2017) a case study from the Bullom Group of Sierra Leone revealed that the studied area is composed of Bullom group of sediments and that the formation has undergone various degree of tectonic activities which control groundwater occurrence and accumulation. He continued that based on the interpretation of results and analysis he concluded the groundwater potential of the area could be good to excellent. A transmissivity of 3.34m/day was determined in a borehole pumping at a rate of 130m/day, for a maximum drawdown of 6.13m in the Bullom group.

At international level, similar studies have been done to determine the flow of groundwater. Taking West Africa in particular, various studies using GIS and other mapping tools have been and several contour and other groundwater maps have been produced.

(Otutu, 2011) conducted a study within the Ndowka-East Local Government Area of Delta State wherein The Global Positioning System (G.P.S) was used to measure the longitudes, latitudes and elevations above mean sea level at 11 locations that were evenly spread in the area. The water table contour map that was generated for this region revealed that the groundwater flow direction is moderately towards the south and extensively towards the north-western parts of the area and based on the flow pattern of the aquifer system, it was advised that efforts should be made towards entrenching eco-friendly in the eastern and west Central regions in order to minimize the contamination of groundwater supply to the other regions.

Finally, this study recommended that wells and boreholes for rural and urban water supply should be sited in the south-western through the central onto the eastern regions and not within the North-Western parts of Ndokwa-East local government area.

In other study that was done by (Oseji, 2014), the global positioning system (GPS) was used to measure the longitudes, latitudes and elevations above mean sea level at eight (8) locations that were evenly spread within the major communities in Emu and Ogume kingdom in Nigeria. The water elevation contour map of the study area that was produced revealed that groundwater flow toward the South and South eastern part of Emu and Ogume kingdoms. Three major stages of field procedures were used in this research and the eight holes that were evenly distributed and spaced 7.5 km apart were drilled within the study area.

The depth at which water began to seep into the hole indicated that the surrounding material was saturated with water and this marked the depth to water level in the well. With the aid of a meter rule and tape, the depths to the water level in the hand dug wells were measured and recorded. The Global positioning system (GPS) was used to measure the longitude, latitude and the surface elevations with respect to the mean sea level to the lowest surface within the earth. The values of the static water levels were contoured on the map of Emu and Ogume Kingdoms and these lines represented the water table contours.

A study was also carried out in Utagba-Ogbe Kingdom, Ndokwa west Local Government Area of Delta State in Nigeria using the global positioning system (GPS) and meter tape to determine the groundwater flow pattern of the area. The longitudes, latitudes and elevations of six (6) locations that were evenly distributed within the kingdom were measured and recorded. The depths to the water level in the hand-dug wells were measured directly with the aid of a meter tape.

The water elevation contour map of Utagba-Ogbe Kingdom revealed that groundwater flow direction is toward the Eastern part of the kingdom. This study therefore recommended that dumpsites within the area should be sited within the Eastern part of the kingdom while boreholes for potable groundwater exploitation could be sited in the north, south and western regions of the kingdom to minimize groundwater contamination. In the event of groundwater pollution, the Eastern regions of the study area were densely contaminated. Therefore, communities within the North, West and Southern regions of this region should take steps to ensure that the land use activities will not pose a threat on the quality of groundwater.

The present study act as a guide for future groundwater exploration, hence the information will be useful to both the Government and also individuals especially those in water industries in sinking and maintaining boreholes for optimum groundwater exploitation (Otutu & Oviri, 2010).

2.7 Hydrogeological Units of Sierra Leone

Adelike provided a simplified hydro-geologic classification with four categories corresponding to four geological units in Sierra Leone. Lapworth also provided preliminary concepts of hydrogeology in humid tropics, lateral pathways and water quality related issues in Sierra Leone.

The most important of these units is the basement complex which extends to over 75% of the country and can be further vertically subdivided into upper weathered zone overlying poorly fractured bedrock. The upper zone is widespread and is a primary source of groundwater for hand-dug wells across the country.

A general classification divides Sierra Leone into four hydrogeological units that are being given in the table below. This table better explains the main hydrogeological units and aquifer parameters from various sources in Sierra Leone.

Table 1: The main hydrogeological units and aquifer parameters from various sources in Sierra Leone.

HYDRO GEOLOGICAL UNIITS	AQUIFER TYPE	LAND AREA %	SUB-UNITS	WELL DEPTH (m)	WELL YIELD (l/d)
Pre Cambrian Basement Complex	D	78%	Valley filled deposits Weathered zone (laterized clay-rich) Fractured crystalline bedrock	Up to 15m 37m maximum 35m average (60m max)	Nd 0.3-1.5 l/d 0.3-1.5 l/d
Sainya Scarp/ Rokel River	M	9%	Weathered layer Fractured sediments	Nd Nd	Nd Nd
Bullom Group	C	12%	Unconsolidated sands and clay materials (inland, alluvial and coastal) Interbedded sands and clays	10-20m 30-80m	Up to 3 l/d Up to 6 l/d
Ultrabasic Igneous	D	1%	Fractured Gabbro Weathered and Fractured Dolerite	Nd Nd	Nd Nd

2.8 A Summary of the Geology of Sierra Leone

The Republic of Sierra Leone is located on the West Coast of Africa, between latitudes 7° and 10° north and longitudes 10.5° and 13° west. The Republic of Guinea is to the north and northeast; Liberia is to the east and southeast, and the Atlantic Ocean on the west and south. It has 300 miles of coastline. From an approximate 70-mile coastal belt of low-lying land, the country rises to a mountain plateau near the eastern frontier rising 1219.2 m to 1828.8 m with a rich forest region. The Western Area encompasses the Freetown Peninsula, on which the capital and main commercial centre of Freetown stands; is 24 miles long and 10 miles wide mountainous peninsula which rises in places to 92 m above sea level – one of the few parts of the West African Coast where there is high land so near the sea. The lush green forest spills down hillsides to meet the most beautiful white sandy beaches along the Atlantic Ocean.

This 27,925 square mile (73,326 sq. km) country has a population of approximately seven and a half (7.5) million people. Sierra Leone is divided into four main Provinces, West, North, East and South and there are twelve main districts in the entire country. Most of the country is underlain by rocks of Precambrian age (Archaean and Proterozoic) with a coastal strip about 50 km in width comprising marine and estuarine sediments of Tertiary and Quaternary to Recent Age.

The Precambrian (mainly Archaean) outcrops over about 75% of the country and typically comprises granite-greenstone terrain. It represents parts of an ancient continental nuclei located on the edge of the West African Craton. Regional reconnaissance mapping indicates that the Archaean basement can be subdivided into infracrustal rocks (gneisses and granitoids); supracrustal rocks (containing greenstone belts); and basic and ultrabasic igneous intrusions. The infracrustal gneisses and granitoids were formed and reworked during two major orogenic cycles, an older Leonean episode (~2,950-3,200 Ma) and a younger Liberian episode (~2,700 Ma). The Leonean orogenic episode commenced with the intrusion of a basic igneous suite (the Pre-Leonean amphibolites) and by the formation of a greenstone belt represented by the Loko Group which is now deeply eroded.

2.8.1 The Loko Group

The Loko Group comprises amphibolites, silimanite quartzites and ironstones. It appears to have been formed on a gneiss/granitoid basement in which several granitoid bodies related to an earlier plutonic orogenic episode have been distinguished mainly in the northern part of the country. Only the main deformational phase of the Leonean orogenic episode which resulted in folds and fabrics trending east-west has been distinguished. Minor gold and cassiterite mineralization associated with portions of the Loko Group is probably related to a late Leonean granitization event which accompanied the formation of major shear zones in the craton. Other volcano-sedimentary sequences are preserved within the granites, gneisses and migmatites. Highly folded greenstone belts predominate in the north and central Sierra Leone.

In the southeast, the metamorphic facies increases, first with the Kambui Schists and finally with the Mano-Moa Granulites. Greenstone belts of the Kambui Supergroup are believed to have been deposited upon a post-Leonean basement and accompany by basic to ultrabasic intrusives. The Kambui Supergroup includes most of the schist belts exposed in the Sula Mountains and the Kangari, Kambui, Nimini and Gori Hills; the Marampa Group; and the two small greenstone belts of Serekolia and Sankarama in the northeast. These greenstone belts comprise a lower volcanic unit composed of ultrabasic lavas and basic lavas with pillow layers, overlain by a sedimentary unit comprising tuffs, pelitic and psammitic sediments, with conglomerate layers and ironstone bands.

The greenstone belts are the principal hosts of the gold mineralisation of the country. Other associated mineral deposits include molybdenite, columbite-tantalite, chromite and possible nickel and copper.

2.8.2 The Marampa Group

The Marampa Group bounded on its eastern margin by a tectonic contact, is important for its iron-ore deposits and forms the upper part of the Kambui Group. Late Liberian granitoids, marginal to, and within, the Kambui Supergroup are associated with important zones of shearing and deformation where gold, sulphide and molybdenite mineralization has been concentrated. The Rokel-Kasila Zone bounds the main part of the West African Craton on its west and south-western margin in Sierra Leone, and appears to form part of a north-south orogenic belt. Within this belt, the Marampa Group appears to represent some of the oldest rocks.

2.8.3 The Kasila Group

This is a distinctive group of mafic gneisses and granulites, trending NW–SE, flanking amphibolites emplaced along the western margin of the West African Craton. It comprises the main outcrop of crystalline schists, gneisses and granulites of the Liberian complex. The unit is bounded on the east by intrusive granites whilst on the west; it is overlain by sediments, sands and clays of Pleistocene to recent age. The lithology of the Kasila Group is dominated by fine- to medium-grained basic granulites with minor horizons of quartz magnetite, quartz diopside and silimanite rocks.

The granulites are intruded by deformed gabbros, anorthosites, and ultramafics in which relict igneous textures have survived the Pan- African reworking in zones where shearing was less intense. The Kasila Group comprises of siliceous gneisses with lesser amounts of charnockites, garnet-hornblende gneisses, garnetplagioclase gneisses and minor hornblendite and pyroxenite. Protoliths probably included basalt along with siliciclastic and chemical sedimentary rocks metamorphosed to granulite and almandine–amphibolite facies.

The western portion of the group is predominantly amphibolites, gneisses and metasedimentary migmatites, whereas the eastern portion is metabasic and subordinate metasedimentary granulites containing thin layers and lenses of banded iron formation, quartzite and leucogabbro. The Kasila Group, also considered to be part of the Kambui Supergroup, comprises a high-grade series of granulites, consisting of garnet, hypersthene and hornblende gneisses, quartzites and associated migmatites. When eroded, significant secondary deposition of titanium minerals have been formed from this unit as well as bauxitization which is as a result of weathering process.

2.8.4 The Rokel River Group

A late Precambrian to Cambrian sedimentary and volcanic assemblage, the Rokel River Group, was deposited unconformably on a basement complex. Deposition was probably in a fault-bounded basin of the intracratonic type along the line of the Rokel-Kasila Group following the formation of the tectonic zone at the end of the Liberian or during the Eburnean Orogeny. The Rokel River Group and the Kasila Group to the west were deformed during the Rokelides orogenic episode (~550 Ma). Deformation increased in intensity westwards.

2.8.5 The Sainya Scarp Group

This group forms a small ingression into Sierra Leone in the northwest of the country, and is composed of horizontally-bedded arkoses, grits and shales with intruded dolerite sills. The group appears to belong to that part of the Gres Horizontaux of Guinea which has been classified as Ordovician, based on the discovery of the graptolites Monograptus riccartonensis and Monograptus priodon in shales near Telimele. In Sierra Leone, the Sainya Scarp Group rests on The Rokel River Group. Dolerite intrusions are common as dykes trending mainly east-west within the basement complex, and as extensive sills above the Rokel River Group.

2.8.6 The Freetown Igneous Complex

This complex forms an intrusive body on the coast, with arcuate outcrop concave towards the west. It is composed of a layered complex of gabbro, norite, troctolite and anorthosite. Platinum occurs in the gravels of many of the streams that cut the outcrops of anorthosite and anorthositic gabbro in the noritic gabbro complex of the Freetown Peninsula. The relation of this complex with the other units is obscured by the coastal veneer of Tertiary sediments of the Bullom Group which lies unconformably on the basement. Tertiary and more recent weathering has led to lateritization across a large part of Sierra Leone, affecting mainly the greenstone belts and the extensive dolerite intrusions.

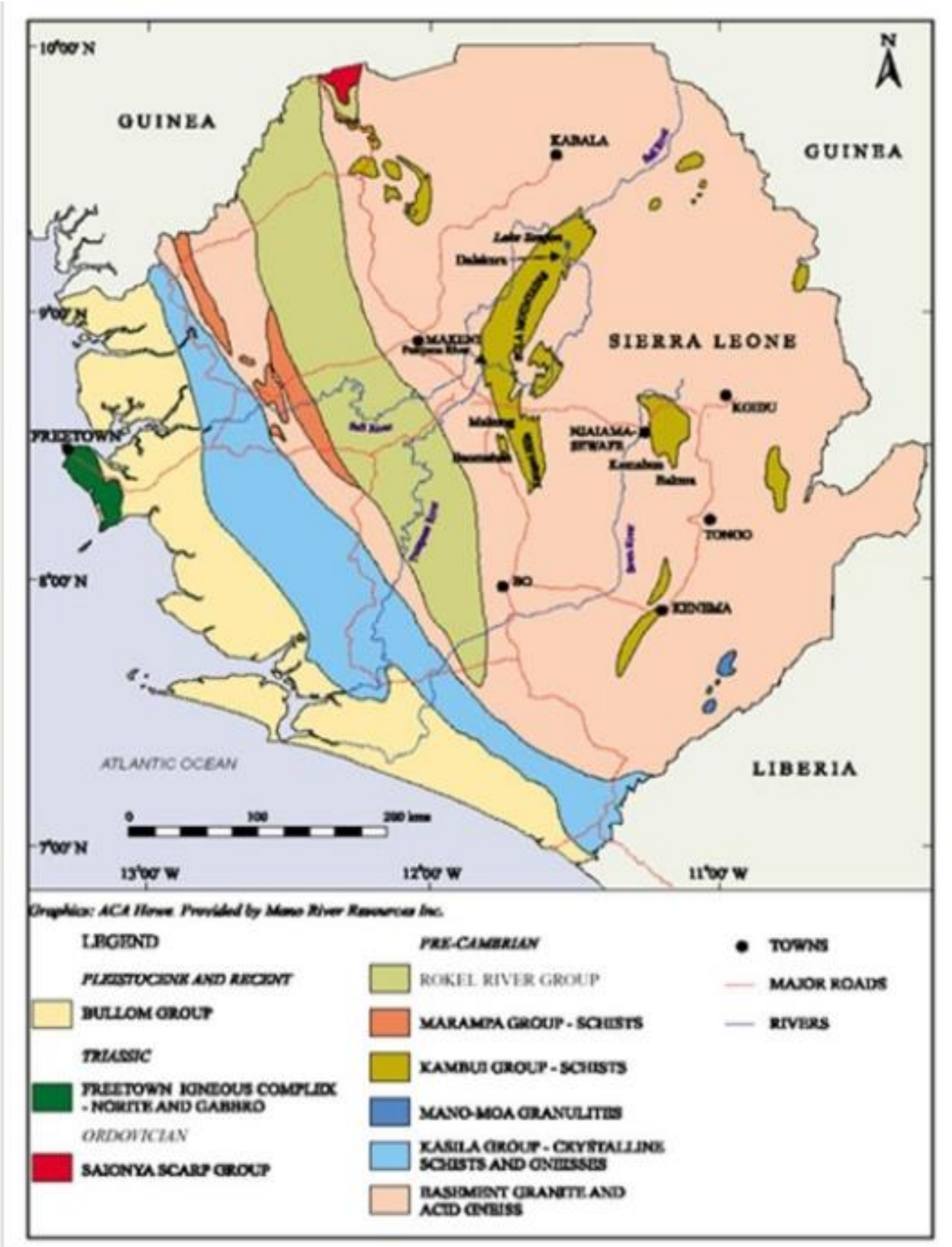

Figure 1 Geological Map of Sierra Leone

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area

The Jui and Allen Town Community are regions within the rural district in the Western Area of Sierra Leone. It is an area located just outside the east end of the country's capital city limit and it is home to a very religiously and ethnically diverse population. There has not been any groundwater mapping of the area and its environs and also prior to the present study, no comprehensive hydrogeological mapping or investigation had been undertaken at national scale. Also, this area is a region entirely underlain by the Bullom group of sediments.

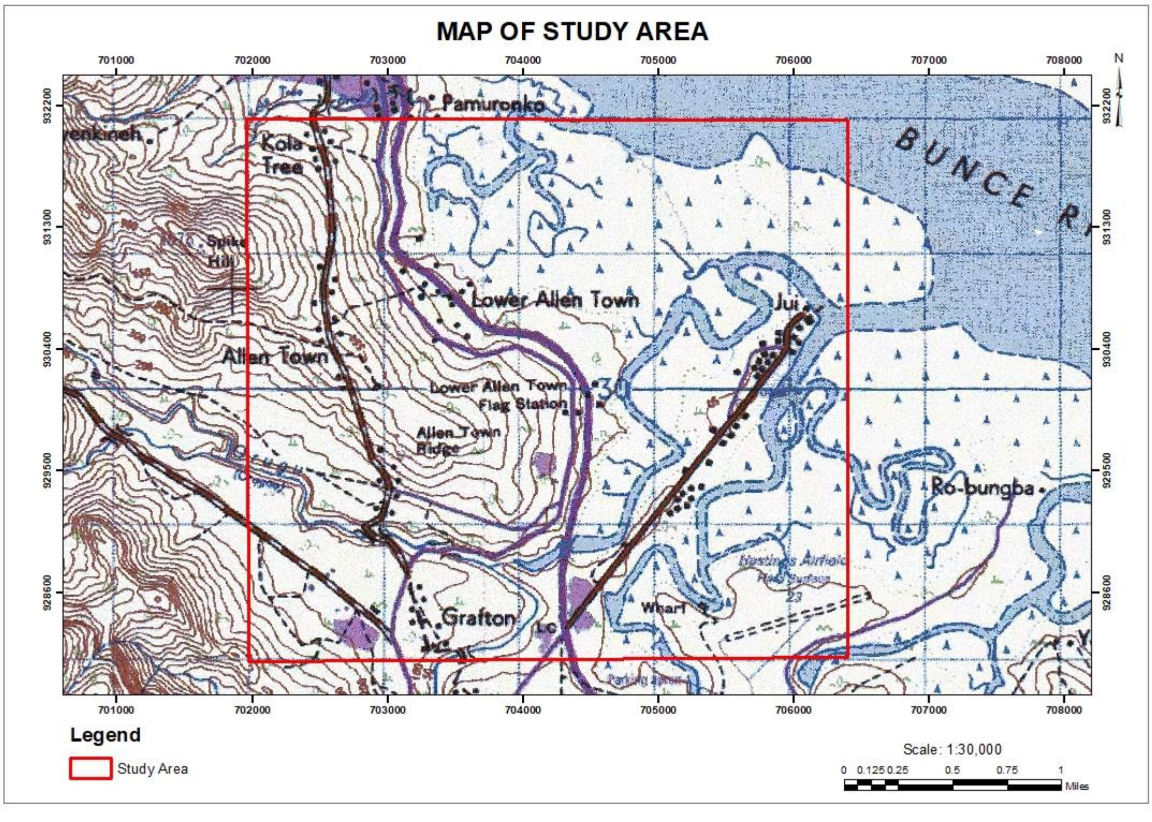

Figure 2 Map of Study Area

The study area lies roughly between longitude 8°25.728' and latitude 13°07.193' in the eastern parts of Freetown. Some major communities in the study area include: Jui Community and Allen town and is bordered to the North-West by Hastings and the North by the Atlantic Ocean. The study area lies within sheet 61 of zone 28 of Sierra Leone. Average air temperature within the study area fluctuates from 27°C in March to 25°C in August (CRU, 2017) and the rainfall varies from 2500-4000 mm/year, with most of the rains falling in August. The study area is relatively low-lying and is characterized by surface streams and groundwater appears to be the major source of drinking water. The area constitutes different physiographic Units, Jui Community is underlain by a relatively low-lying coastal plain. The east and north-east is characterized by undulating lowland dissected by streams and bordered by marshy vegetation and on the western part by two hills dissected by a stream. The coastal plain of the study area increases in altitude westwards towards the Hasting stream.

The study area is a rapidly developing area with high residential exploitation. Unfortunately water supply by Water Corporation is not readily available. The inhabitants rely on the surface water and groundwater extracted from hand dug wells and few boreholes as their main source of water resource. Increased concern for quality and quantity of groundwater has prompted investigations of the pattern of groundwater movement in the study area. It becomes necessary to investigate the pattern in which groundwater is flowing so as to predict the likely pattern of contamination, transportation, hence proffer reliable recommendations.

It is necessary to know the direction of groundwater flow to determine the recharge and discharge zones. Given that water always flows from a region of higher water level, it is found that groundwater use within an area at a higher water level directly affects the quality of water available to people living in regions of lower water levels.

The aquifer system in the study area like most part of Sierra Leone is a multi-aquifer system as reported by various hydrogeology work in the past and occur within clay, sand ,silt and gravel deposited by river and coastal processes. These sediments are distinguished by their geologic characteristics and ages and occur within geologic formation called the BULLOM GROUP (NMA). Groundwater does not usually remain stationary, but moves or flows underground according to the forces acting on the groundwater.

3.2 Geology of the Study Area

The study area and its environs are part of a relatively low-lying coastal plain or swampy coastal strip of the Bullom Group. The coastal plain comprises a poorly consolidated nearly horizontal sediments which rests with marked unconformity upon the Kasila-Marampa and can be located within the vicinity of Freetown upon the layered basic complex. The unconsolidated to poorly consolidated sediments that are found within the project area are typically fluvial, estuarine and are of marine origin.

The sediments of Jui Community and its environs consist of series of iron-stained gravels, coarse feldspathic sands and clays. The area consists of mainly sediments and these sediments were formed as a result of the recent (tertiary) weathering and laterization which even affected a large part of the country; affecting mainly the greenstone belts and the dolerite intrusions. The sediments of the Bullom Group are the youngest litho-stratigraphic unit in the country and it comprises of onshore Cenozoic sediments deposited along the coastal margin.

3.4 Physiography of the Study Area

3.4.1 Topography

The project area is made up of different physiographic units, Jui Community is underlain by a relatively low-lying coastal plain. The East and North-East is characterized by an undulating lowland that is being dissected by streams and bordered by a marshy vegetation and on the west by two hills. The Coastal plain of Jui increases in altitude westwards towards the Hasting stream.

The sediments consist of variable sequence of poorly consolidated, near horizontal, often iron-stained gravels, sands and clays with occasional intra-formational laterites. This colour changes to reddish-brown because of iron-oxides through intensive weathering and erosion processes giving rise to leaching of sedimentary sediments and mineralized proto ores.

The sediments of the Allen Town were consistent with that of the Jui community but were at generally higher elevations as evidenced by the GPS readings and are characterized by similar topographic features. Like the Jui Community, Allen town is a linear settlement and is linear drained with very little tree cover. Generally, these two communities are seen to have a similar topographic design.

3.4.2 Soil

Generally, the dominant soil that constitutes most of the area is the weathered and leached lateritic type. Laterites are soil types that are rich in iron and aluminium oxides and hydroxides. The main factors influencing soil formation in the study area is high rainfall and warm temperatures and these are conducive for deep and intense weathering. The rainfall results in alternating period of deposition and leaching.

The soil type present in our study area possess a distinct reddish-brown colouration that is being formed by the iron oxide present and are developed by long lasting weathering of the underlying parent rock (Forkuor & Cofie, 2011).

The chemistry behind the laterization process involves the going into solution of the soluble minerals in the rock which are mostly those minerals consisting of group I and II elements. This creates room space for the entering of other materials that accelerates weathering process. The iron and aluminium content of the rock which are basically insoluble remains and form their oxides and hydroxides which gives it the characteristic reddish-brown colouration.

3.4.3 Temperature and Climate

The study area and its environs are part of the large area of low-lying coastal plain of the Eastern part of Freetown that lies within a humid tropical climate. Average annual rainfall is approximately twice the average potential evapotranspiration. Rainfall in this region is highly seasonal, with a peak in August and a dry season from December to March. Variation in rainfall is generally small, but there are some extreme rainfall events.

The climate of the area is tropical to most areas of Sierra Leone and temperatures are relatively uniform throughout the year, ranging from 24 to 28℃. The lowest temperatures in this area are observed from July to September which is in the middle of the rainy season and the highest temperatures are in February and March which marks the end of the dry season.

3.4.4 Vegetation

The main vegetation of the study area is a Marshy and Swampy vegetation type which is well-distributed but also there are small portions of agricultural land present. This is only limited to the eastern part of the Jui Community and it extends along a fewer portions to the North; at heights of 15-20m above sea level. The entire Jui Community and some large portions of Allen Town are now extensively been used for buildings and recreational purposes and as a result of this, the tree cover is now sparse or relatively absent. The undulating lowland on the eastern part of Jui hosts the Coastal Swampy and the Marshy Vegetation and widely scattered shrubs close to the boundary separating Jui and Allen Town Communities.

3.4.5 Drainage

Drainage can simply be defined as the natural or artificial run-off of water from an area by rivers or streams. The project area is traversed by two streams with the one on the eastern part emptying into the Atlantic Ocean. The drainage network particularly the large east-end stream flow principally to the tectonic direction of the area i.e. the drainage network is controlled by the topography of the area.

During the dry season, the volume of the streams decreases and this could best be explained in terms of less rainfall. These streams are perennial and are possibly discharge areas (topographically low areas). The elevation is a bit higher along the Allen Town area but the Jui community is well-drained as the streams remove a greater portion of water from the land and also the soils are porous and permeable.

3.5 Data Collection

A groundwater flow system is a set of flow paths with common recharge and discharge areas. The conceptualization of how and where water originates in the groundwater flow system and how and where it leaves the system is critical to the development of an accurate model. As it is pointed out by different researchers, the groundwater flow system of an area is mainly controlled by extensive faults and fractures.

The local flow system is controlled by the topography and geology and degree of fracturing. For us to accurately determine groundwater flow direction, hydraulic head information and head measurements are required.

Figure 3 Field Images Showing Data Collection

In this study, both primary and secondary data were used. Once a well was located in the field, before data collection could commence permission to gather well data was obtained from the residents.

3.5.1 Determining the Static Water Levels in Wells

With the aid of a Dipmeter, metre rule and tape, the depth to the water level in fifty (50) boreholes or hand-dug wells were measured between the months of May and June. The Global positioning system (GPS) Garmin 550 was used for measuring the longitude, latitude and the surface elevation (with respect to the mean sea level) of each of the selected borehole or hand-dug well site in a UTM coordinate system within the study area.

The hydraulic head at various locations will be obtained by subtracting the static water level (SWL) from the elevation (E) obtained from the GPS reading with respect to the mean sea level.

Mathematical Model for Groundwater Flow

Groundwater is not static, it flows in an aquifer and its flow can be described using partial differential equation and associated initial-boundary conditions (Naji, Tawfiq, & Jabber, 2016).The simplest mathematical model of groundwater flow is Darcy's law which is an equation that describes the flow through a vertical section of an aquifer can be calculated using Darcy' law;

$$\boldsymbol{Q}= \frac{\boldsymbol{KA\,(h1-h2)}}{\boldsymbol{L}}$$

Where; $\boldsymbol{Q}$= flow (m3/day)

$\boldsymbol{K}$= hydraulic conductivity averaged over the height of the aquifer (m/day) A= area (m2)

(h1- h2)= difference in hydraulic head (m)

L= distance along the flow path to the point where h1 and h2 are measured (m)

In order to determine the hydraulic head of each well, certain parameters measured in the field were used to calculate for the hydraulic head value derived from the formulae;

HH= (SE-DTW)

Where; ***HH***= hydraulic head (m), ***SE***= surface elevation (m), ***DTW***= depth to water (m).

Let ***DHDW*** = the depth from the surface of the earth to the water level in the hand-dug well (Direct Bore hole logging), ***E*** = the surface elevation with respect to the mean sea level, ***Swl*** = the true or uniform water level otherwise known as the static water level in the case of an unconfined aquifer then***(Swl = E – DHDW).*** The values of the static water levels were contoured on the map of Jui and Allen Town Community.

3.5.2 Mapping of Groundwater Flow Direction

In constructing or studying groundwater flow direction, hydraulic head measurement or information is required. These hydraulic head measurements are also needed to establish initial conditions for numerical groundwater modelling and for model calibration in groundwater studies that requires the use of a model.

On the aspect of mapping the groundwater flow direction; significance in advance of groundwater flow direction was analysed using Arc GIS and Surfer 11 software. The Surfer 11 software was used to translate the XYZ data into clear surface and contour map. The observed static ground water level data was being used as input in this software to produce 3D Maps, Contour maps, Vector grid maps etc.

The contouring program require that the groundwater level data be organized as XYZ files where X and Y are plane coordinates of the measuring points and Z is a function of the elevation of the water table or piezo metric surface above a chosen reference level, usually the mean sea level. The significance in advance of groundwater flow direction was analysed using Arc GIS 9.3 and Surfer 11 program. The three (3D) surface, wireframe, image and vector overlaid maps generated with Surfer is very much clear and straight forward as this particular software is known for its clarity, colour and accuracy and the flow lines and equipotential lines (i.e. groundwater contours) were digitized by Arc GIS to create the shape files features of water wells.

3.5.3 Identification of Groundwater Recharge and Discharge Areas

In order to prepare sound land-use planning and management approach, analysis of groundwater flow system which connects recharge and discharge areas is very much important. The recharge and discharging zones of the study area were identified with the help of Surfer 11 program and Arc GIS. Based on the groundwater flow direction in a contour map, the convergence and divergence zone of the study area were clearly identified and a water table contour map was used to identify groundwater recharge and discharge areas. The flow line on a flow net tends to diverge from recharge areas and are seen converging towards to discharge areas.

Topography is a major factor which has to be taken into consideration for delineating the recharge and discharge zones; high land areas are an indicator of recharge areas and low land areas are an indicator for discharge areas. Generally, the divergence and convergence of vector flow lines is an indicator of the recharge and discharge areas respectively.

3.6 Field Equipment Used In Collecting Groundwater Data

The various different equipment used in the field for collecting groundwater data and their directives are briefly explained below;

3.6.1 Dip Meter

This is an instrument that is used to measure the Static Water Level (SWL) in hand dug wells. This device can also be referred to as an In-Situ rugged Water Level Tape (Water Level Tape) as it provides accurate water level measurements in wells or boreholes. It is simple to use, portable and can be used at many different locations. It has a tape design which prevents it from sticking to wet surfaces such as the lining of boreholes and thus ensuring accurate measurements.

Attached to this instrument is a stainless steel probe fitted to a flexible graduated cable which is being wound on to a hand reel containing a transistorised switched circuit, an audio (buzzer) and visual (LED light) indicators and a battery.

3.6.2 Compass

A compass is an instrument that is used for navigation and orientation which shows directions that are relative to the geographic cardinal directions. It determines direction as by means of a freely rotating magnetized needle that indicates magnetic north.

3.6.3 GPS (Global Positioning System)

The “Global Positioning System” GPS is a satellite navigation system that is being used to determine the ground position of an object. This instrument works in any weather conditions, anywhere in the world, 24 hours a day, with no subscription fees or setup charges. In this study, the GPS was used to measure the elevations above sea level and also assign or provide the easting and northing values for each well position in our study area.

3.6.4 Safety Gears

Safety or personal protective equipment (PPE) are protective gears designed to protect the user or wearer's body from injury or infection. They were worn during the field exercise for safety reasons and also for identification purposes. These included stuffs like a safety boot, reflective gear or vest and other small items like safety glasses or googles and face masks as the covid-19 situation required the use of this particular item.

3.7 Using the Surfer Software for Data Analysis

Using the software package for analysis involves various different steps. Some of which are stated here;

3.7.1 Gridding Data

The data file that is to be used as input for the Surfer Software is supposed to be gridded in the very first place. If the data file has XYZ data in it, then one can go directly to the Grid Data menu and continue. If you are unsure about the column layout or spatial distribution of your data file, there are a number of ways to familiarize yourself with the data. In our case here, the data file was already prepared in XYZ format so it was directly converted to Grid Data.

3.7.2 Gridding Methods

Unless you have specific information about your data set, it is recommended to use the default gridding methods provided by the software. However, this method doesn't always produce the desired result with every data set, so it sometimes pays to consider the other gridding methods which are being stated below;

Inverse Distance - This is a method which uses a "simple" distance weighted averaging method to calculate grid node values. This method does not extrapolate values beyond the values that are found in the data file, but it tends to draw circles or bulls-eyes around each data point.

Kriging Method - The kriging method uses trends in the map to extrapolate into areas of no data, sometimes resulting in minimum and maximum Z values in the grid that are beyond the values in the data file. This could be acceptable in a structure map or topography map but not in an isopach map where the extrapolation produces negative thickness values.

Minimum Curvature - The minimum curvature method attempts to fit a surface to all the data values using an iterative approach. One drawback to this method is a tendency to "blow up", or extrapolate extremely large or small values, in areas of no data. Minimum curvature can extrapolate values beyond your data's Z range.

The modified Shepard's method - is a method that attempts to combine the inverse distance method with a spline smoothing algorithm. It tends to accentuate the bulls-eye effect of the inverse distance method. It can extrapolate values beyond your data's Z range.

Natural Neighbour - The natural neighbour gridding method uses a weighted average of the neighbouring observations. This method generates good contours from data sets containing dense data in some areas and sparse data in other areas. It does not generate data in areas without data and does not extrapolate Z grid values beyond the range of the data.

3.7.3 Creating Contour Maps

After the grid file has been created, the contours maps can be easily created and edited. The software package provides numerous other functions for editing or personalising the contour map that has been created such as filling in contours, displaying colour scale, smooth the contours and also specify properties for blanked regions and fault lines.

The contour lines can also be edited to change individual grid node values in a grid file so as to change a contour shape, but this method tends to be very labour intensive unless limited to small changes.

3.7.4 Digitizing contours and gridding

In order to use contours created in software other than Surfer, the contours have to be recorded in a digital format and converted to the XYZ file format that Surfer can use. Tablet digitizing and onscreen digitizing a scanned image are two ways of recording data in a digital format.

Tablet digitizing requires a piece of equipment called a digitizing tablet, and software to use with the tablet. The Golden Software Didger software works with a digitizing tablet to store the XYZ coordinates along a contour in an ASCII data file format which you can use for gridding.

3.8 Expected Results from the Surfer Software.

A Contour Map - This is a groundwater map with contours showing lines connecting points of equal water level elevation (hydraulic head). This map can be used to explain different factors such as change in hydraulic gradient, identify regions of both high and low elevation and also used to show groundwater flow.

A Vector Overlaid Map - A vector Overlaid map is a map obtained by superimposing a vector map on a water table contoured map. This map show contour values which are representations of hydraulic head values measured in meters and also show arrows indicating flow directions. These arrows cluster on the map to indicate a groundwater discharge zones and the diverging arrows represents zones of groundwater recharge

An Image Map - An image map is also one of the products that can be obtained from this map producing software. The Image map basically shows high points which are translated as groundwater recharge areas and depressions are identified as discharge areas.

A 3D Surface Map - A 3D surface map is also another product that can be obtained from this groundwater mapping tool. This map basically gives a 3D view or representation of the surface.

A Wireframe Map - A wireframe map is a map which provides an impressive three dimensional display of the data. This map uses different colour zones and different combinations of X, Y and Z lines to produce exactly the desired surface you are looking for.

3.9 Spatial Distribution of Groundwater or Wells Locations

A GIS map was also generated and it showed important features such as settlements, roads, streams etc. of the study area and went further to incorporate or display all the fifty (50) different well positions measurements that were taken during the field visits using GPS.

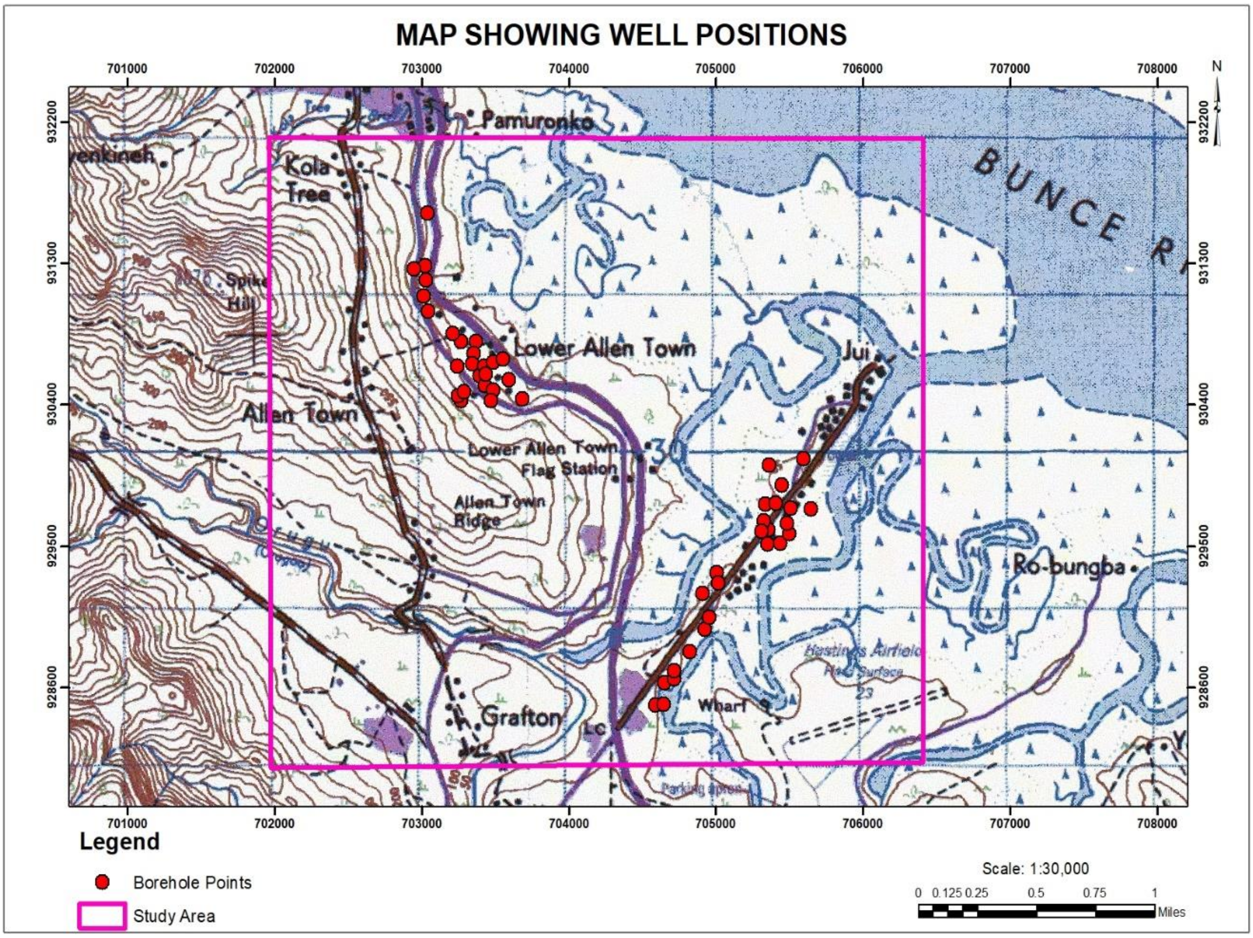

Figure 4 Spatial Distribution of Groundwater or Well Locations

CHAPTER FOUR

RESULTS AND DISCUSSIONS

This chapter presents the results and discussions that were gathered from this research. In this study, the depth to water level of fifty (50) different boreholes in the study area was measured and The Global positioning system (GPS) was used for measuring the longitude, latitude and the surface elevation of each of the well or borehole sites in the area.

The hydraulic head measurement at each location was obtained by subtracting the static water level (SWL) from the elevation (E) that was derived from the GPS reading with respect to the mean sea level.

4.7 Measurements Obtained from Groundwater Mapping Exercise

The observations or measurements from our groundwater mapping exercise which was done to basically estimate hydraulic heads are given in the table below;

Table 2: Measurements Obtained from Groundwater Mapping Exercise

NO	WELL ID	(X) CORDINATES	(Y) CORDINATES	SURFACE ELEVATION (M)	DEPTH TO WATER (M)	HYDRAULIC HEAD	UTM
1	JW1	704585	928490	31	14.8	16.2	28
2	JW2	704641	928493	17	6.7	10.3	28
3	JW3	704647	928631	26	9	17	28
4	JW4	704710	928656	16	7	9	28
5	JW5	704712	928709	21	13.3	7.7	28
6	JW6	704820	928829	20	13.3	6.7	28
7	JW7	704921	928971	21	14.5	6.5	28
8	JW8	704949	929047	20	13.8	6.2	28
9	JW9	704906	929201	17	9.6	7.4	28
10	JW10	705003	929334	12	4.2	7.8	28
11	JW11	705014	929268	18	12.9	5.1	28
12	JW12	705349	929513	19	12.9	6.1	28
13	JW13	705434	929522	20	11.1	8.9	28
14	JW14	705495	929579	19	9.2	9.8	28
15	JW15	705477	929645	20	12.2	7.8	28
16	JW16	705641	929739	10	3.5	6.5	28
17	JW17	705506	929741	21	14.3	6.7	28
18	JW18	705353	929605	17	11.9	5.1	28
19	JW19	705320	929663	10	2.4	7.6	28
20	JW20	705308	929595	6	2.4	3.6	28
21	JW21	705330	929770	7	3	4	28
22	JW22	705401	929772	18	13.2	4.8	28
23	JW23	705442	929893	19	14.9	4.1	28

24	JW24	705355	930016	21	11.9	9.1	28
25	JW25	705589	930058	22	15.2	6.8	28
26	ATW1	703365	930804	48	12.4	35.6	28
27	ATW2	703353	930727	57	13.2	43.8	28
28	ATW3	703339	930665	59	15.8	43.2	28
29	ATW4	703389	930589	56	14.8	41.2	28
30	ATW5	703421	930645	54	11.8	42.2	28
31	ATW6	703483	930673	48	11.4	36.6	28
32	ATW7	703548	930693	38	12.2	25.8	28
33	ATW8	703428	930525	58	13.1	44.9	28
34	ATW9	703431	930597	53	12.8	40.2	28
35	ATW10	703485	930496	54	12.2	41.8	28
36	ATW11	703679	930438	49	10.7	38.3	28
37	ATW12	703589	930560	46	10.1	35.9	28
38	ATW13	703470	930431	61	13.7	47.3	28
39	ATW14	703262	930427	89	15.4	73.6	28
40	ATW15	703242	930461	87	15.5	71.5	28
41	ATW16	703283	930486	75	14.1	60.9	28
42	ATW17	703240	930649	68	15.1	52.9	28
43	ATW18	703262	930807	55	16.8	38.2	28
44	ATW19	703207	930854	57	15.4	41.6	28
45	ATW20	703039	930997	66	13.5	52.5	28
46	ATW21	703009	931092	61	9.6	51.4	28
47	ATW22	703024	931196	44	9.5	34.5	28
48	ATW23	703022	931287	50	17.5	32.5	28
49	ATW24	702942	931265	61	15.5	45.5	28
50	ATW25	703038	931623	43	14.3	28.7	28

After processing and inputting the groundwater data that was generated, the following results were obtained;

4.1 A Contour Map

This is a groundwater map with the contours showing lines connecting points of equal water level elevation (hydraulic head).

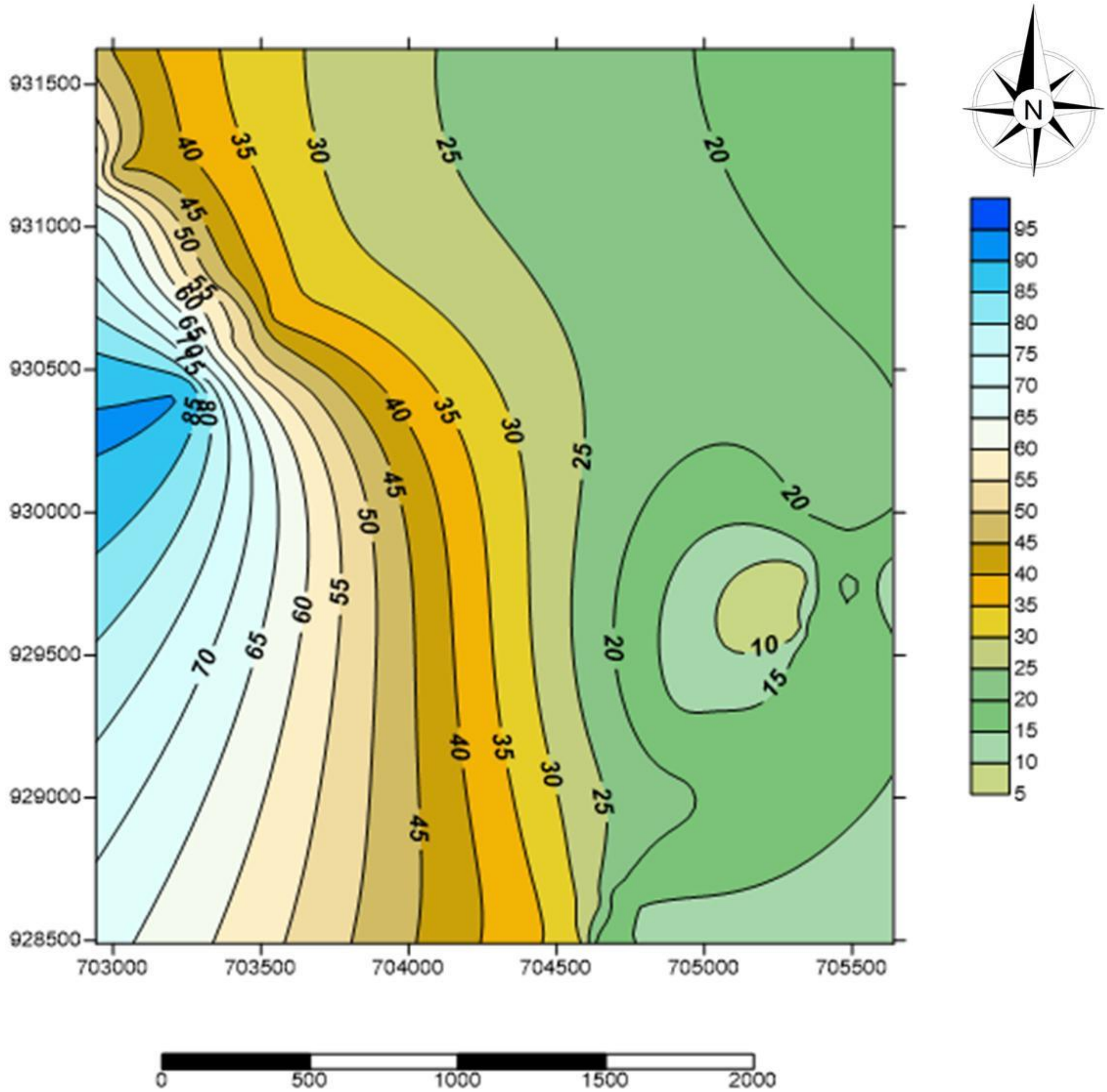

Figure 5 Contour Map of Study Area

Figure 5 above shows the contour map of the study map. It can be seen that the clustered contours with high values can be seen on the left hand side (western part of the study area) and these values are indicating areas of higher elevation whereas moving towards the east or right hand side the values are decreasing. This tells us that the water is moving from the region of high elevation (western) towards the lowland or flat areas (eastern) part of the study area.

4.2 A Vector Overlaid Map

Figure 6 below shows a vector Overlaid map of the study area. The contour values that are seen on this vector map are a representation of hydraulic head values measured in meters and the arrows indicate flow directions. The areas on the map where the arrows are seen clustering or coming together depicts a groundwater recharge zones, while the diverging arrows represents a zone of groundwater discharge.

The figure shows a clear representation of a vector map overlaid on the groundwater contour map. The arrows indicate the direction of groundwater flow and also identifies recharge and

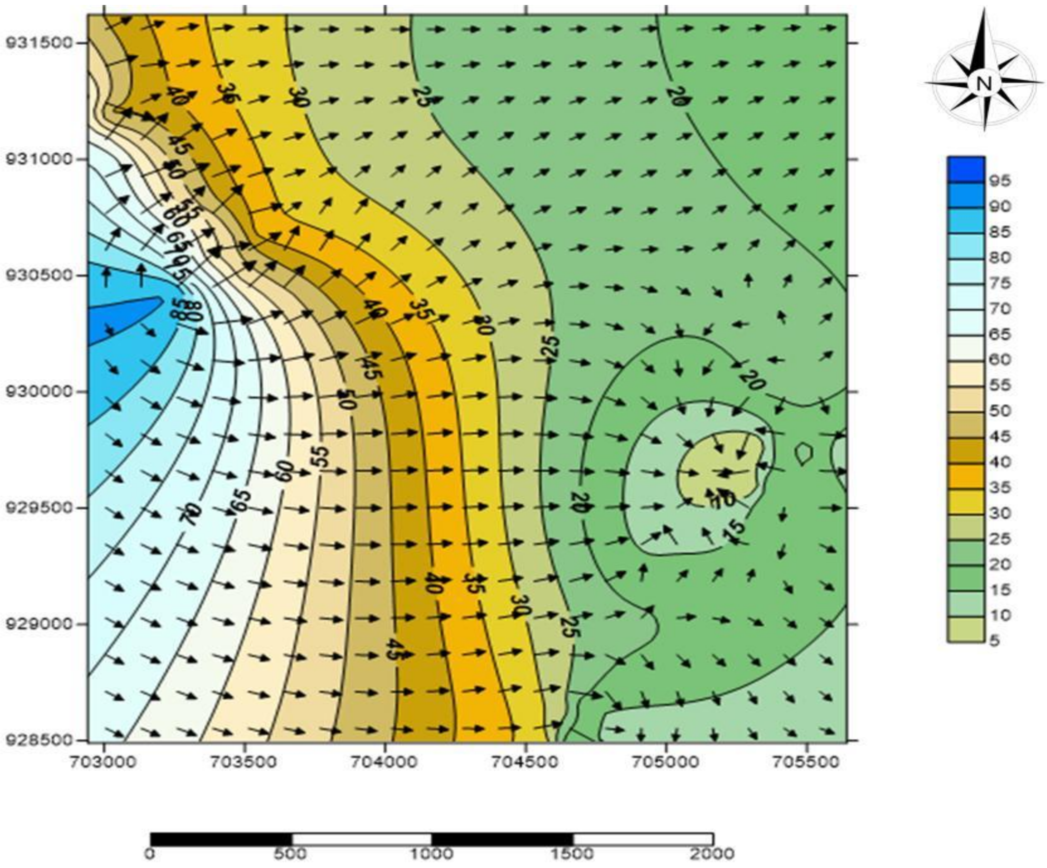

Figure 6 Vector Overlaid Map of Study Area

discharge areas. The arrows seen here are clearly showing movement of groundwater from the west to the eastern region of the study area.

4.3 An Image Map

The Image map basically shows high points which are translated as groundwater recharge areas and depressions are identified as discharge areas. Figure 7 below is a representation of the image map of our study area.This map is basically a simple image representation of the

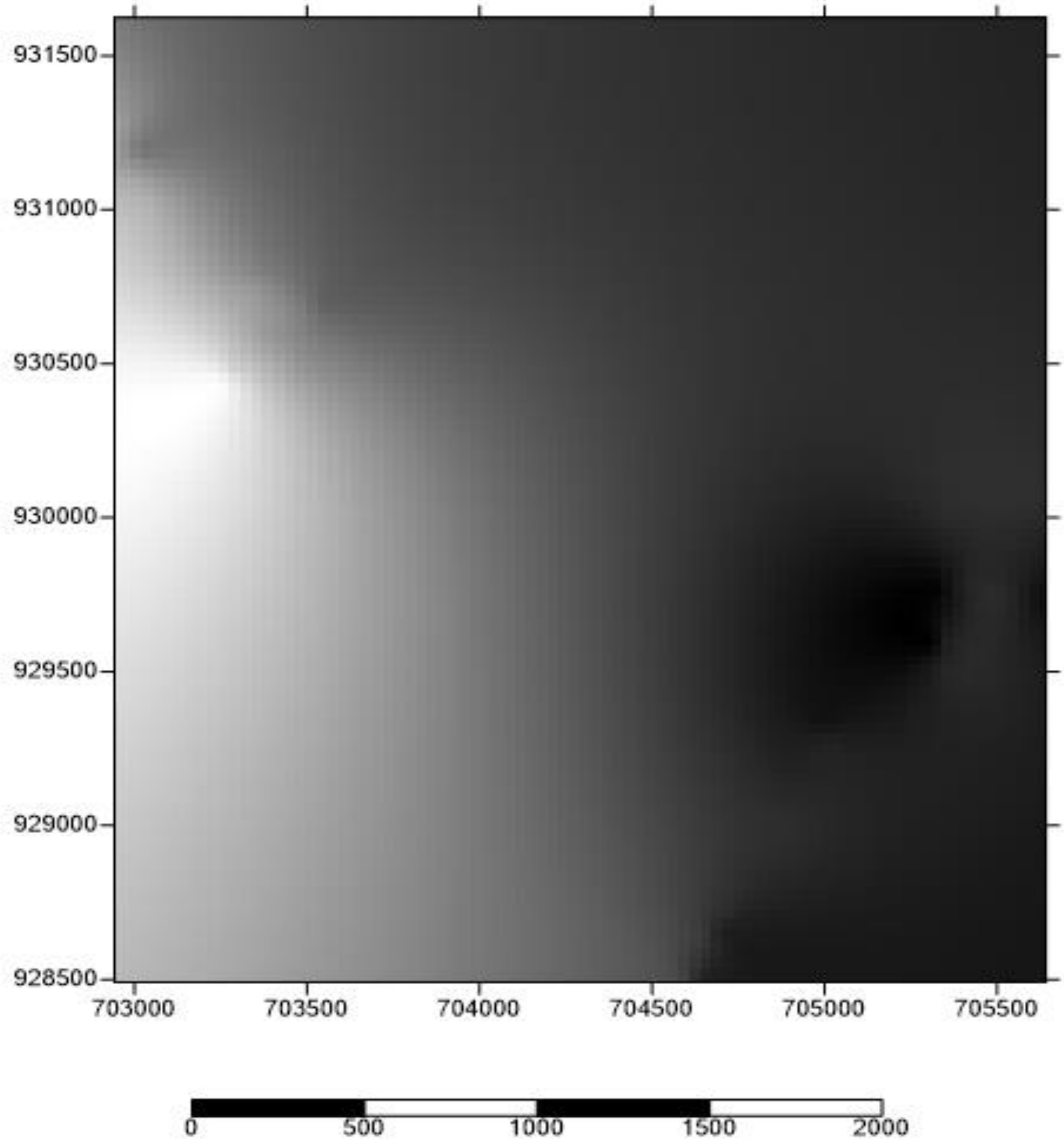

Figure 7 Image Map of Study Area

study area. Looking closely at this map you can observe that some areas are indented and these can be interpreted as discharge areas. On the other hand, some areas are seen pointing out sharply or out dented and they are translated as recharged areas. The colour variation also explains the difference in elevation. Areas appearing to be thicker or darker in colour depict low elevation whereas the lighter regions show higher elevation.

4.4 A 3D Surface Map

A 3D surface map was also generated and this map basically gives a 3D view or representation of the surface.

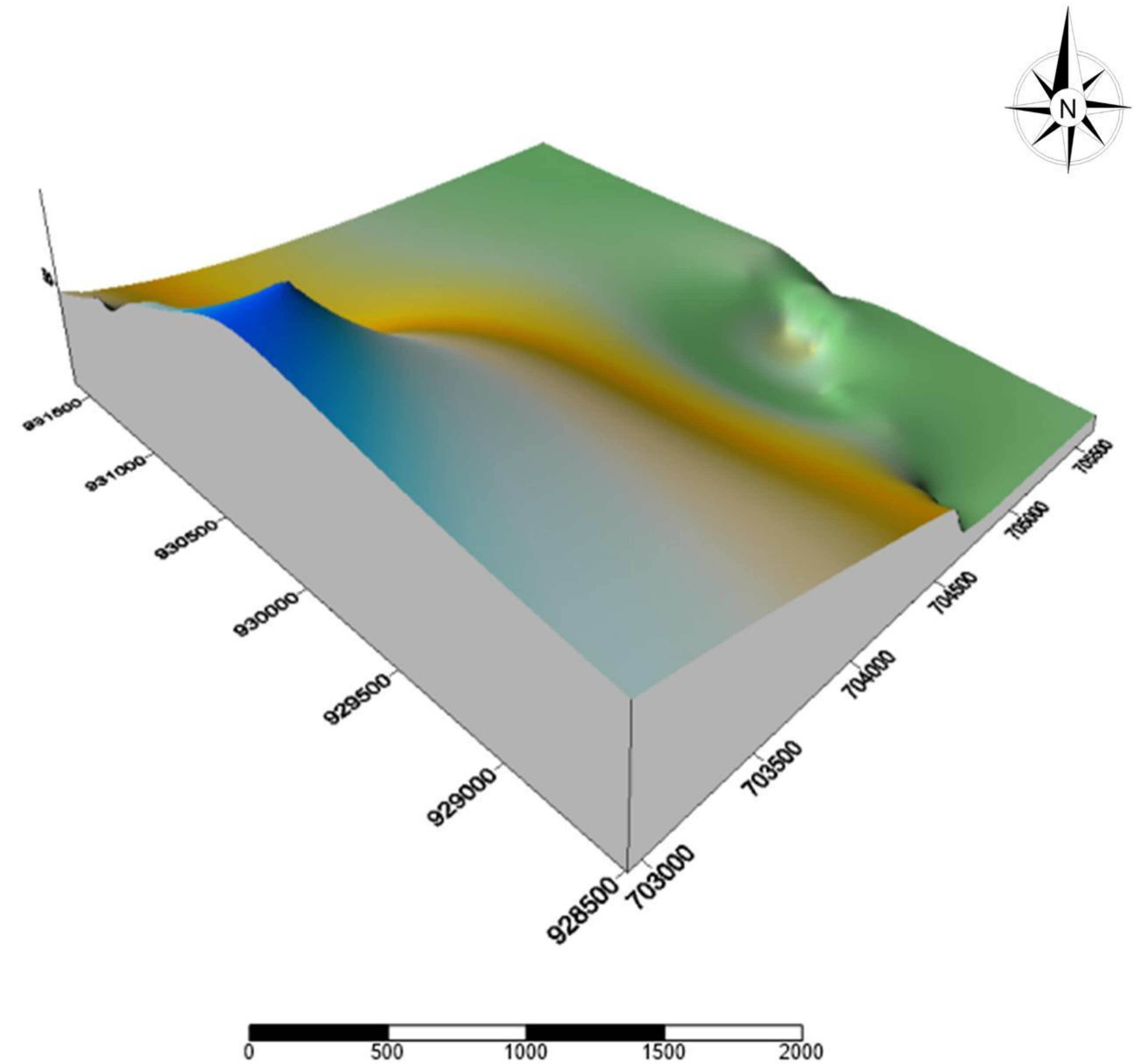

Figure 8 3D Surface Map of Study Area

As seen in Figure 8, the 3D surface map uses shadings and colour to emphasize the various different data features that are being represented. It specifies the surface colour gradation, shininess, base fill and line colour. This 3D map of the study area uses XY data limits or specifies a subset of the map and it adds colours scales to explain the data value that is corresponding to each colour. This map also produces a detailed report of the grid statistics of the study area.

4.5 A Wireframe Map

A wireframe map produced by surfer provides an impressive three dimensional display of your data.

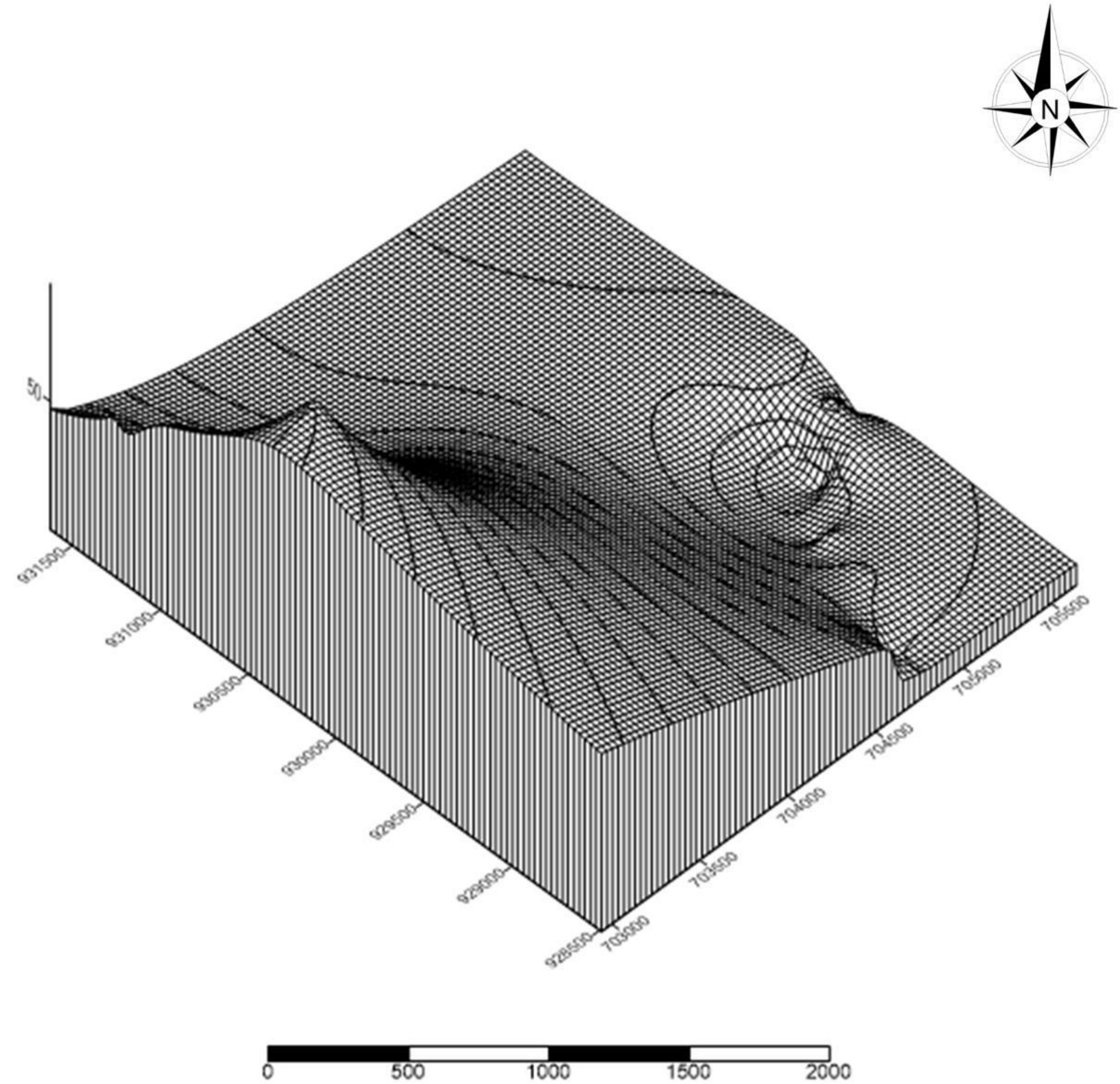

Figure 9 Wireframe Map of Study Area

This map also uses colour zones, independent X, Y and Z scaling, orthographic or perspective projections at any tilt or rotation angle and different combinations of X, Y and Z lines to produce exactly the desired surface you are looking for. Figure 8 above is the 3D wireframe map of the study area.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

This chapter is the last of this research and it concludes the findings that have been made and made some few recommendations for groundwater management within the Jui and Allen Town Community.

5.1 Conclusion

In this research, the water table contour map generated from the computer based program or mapping tool, Surfer, suggested or revealed lateral flow i.e. groundwater in the area is moving from west to east.

The spacing of the contours on the water table map generated by the Surfer package shows a clear indication of the hydraulic gradient. Some areas were seen to have a characteristic of steep hydraulic gradients where flow seems to be appreciable and where the hydraulic gradients are milder, the flow is expected to be rather sluggish. Also from the groundwater map, some zones were identified within the study area where flow seems to be diverging and these areas can be interpreted as possible recharge areas, and where the component of flow is downward.

This research has clearly pointed out the need for a national groundwater monitoring system which will, among other things, assist in characterizing the groundwater flow mechanism derived from the analysis of the groundwater table contour map. The mapping tool that was used in this study has enabled us to better understand the spatial relationship that is existing between groundwater recharge and discharge in the study area.

This mapping tool has also enlightened us on various other aspects of groundwater such as its flow directions, future pumping regimes, and other land use practices that can affect both the quantity and quality of groundwater. The methodology that was employed in this research or groundwater mapping exercise is relatively simple to use and could be replicated in other areas that contain similar hydro geological characteristics.

The water elevation contour map of the study area revealed that groundwater flows from the west to east and the implication of this with respect to the vulnerability of groundwater to pollution is that the east and south eastern part of the area or aquifer is more susceptible to receive transported contaminants or materials from the west and north western part of our study area.

5.2 Recommendations

The water elevation contour map of Jui and Allen Town Community revealed that groundwater flows from western to the eastern part of the region. Based on the groundwater flow pattern of the aquifer system in the study area, it is therefore recommended that dumpsites should be located within the south or south-eastern part of the area and none in the north, east and western regions of the land in order to minimize the contamination of groundwater.

This research did not only pave way for a clear picture of the flow system in area but also went further to recommend that boreholes for potable water supply could be sited within the north, east and western part of the area.

It is recommended that the government of Sierra Leone and other stakeholders in the water sector should ensure that inhabitants in the study area are enlightened on the importance of ensuring clean and sustainable environmental practices. The main aim of this is to reduce the contamination of the groundwater resources available within the study area particularly in the west and north western parts because if these areas are polluted it could easily spread throughout the aquifer system.

In minimizing pollution and other practices that will lead to groundwater contamination, it is recommended that Land Use maps of the study area should be considered and studied carefully so that the people residing within this region will have a clear understanding of the real situation on ground.

It is also advised that groundwater should be managed as part of a much broader integrated approach that includes water quality, surface water, conservation, environmental stewardship, reuse and other water management strategies. Reliable hydro geological data, particularly the amount, location, its availability and demand upon groundwater resources is very important to make informed management decisions, determine acceptable levels of groundwater impact, its anticipated use and establish a baseline state.

REFERENCES

Ahn, H. I. L., & Chon, H. T. (1999). Assessment of groundwater contamination using geographic information systems. *Environmental Geochemistry and Health*, *21*(3), 273–289. https://doi.org/10.1023/A:1006697512090

Anomohanran, O. (2015). Hydrogeophysical and hydrogeological investigations of groundwater resources in Delta Central, Nigeria. *Journal of Taibah University for Science*, *9*(1), 57–68. https://doi.org/10.1016/j.jtusci.2014.06.003

Avinash, K., Jayappa, K. S., & Deepika, B. (2011). Prioritization of sub-basins based on geomorphology and morphometricanalysis using remote sensing and geographic informationsystem (GIS) techniques. *Geocarto International*, *26*(7), 569–592. https://doi.org/10.1080/10106049.2011.606925

Bromley, J., Taylor, C. M., Gash, J. H. C., Favreau, G., Leduc, C., & Schroeter, P. (2002). Comment on "Long-term rise in a Sahelian water-table: The Continental Terminal in South-West Niger" by Leduc, C., Favreau, G., Schroeter, P., 2001. Journal of Hydrology 243, 43-54. *Journal of Hydrology*, *255*(1–4), 260–262. https://doi.org/10.1016/S0022-1694(01)00516-9

Calow, R. C., Robins, N. S., Macdonald, A. M., Macdonald, D. M. J., Gibbs, B. R., Orpen, W. R. G., … Appiah, S. O. (1997). Groundwater management in drought-prone areas of Africa. *International Journal of Water Resources Development*, *13*(2), 241–262. https://doi.org/10.1080/07900629749863

Crosbie, R. S., McCallum, J. L., & Harrington, G. A. (2009). Estimation of groundwater recharge and discharge across northern Australia. *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences, Proceedings*, (July), 3053–3059.

Elbeih, S. F. (2015). An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. *Ain Shams Engineering Journal*, *6*(1), 1–15. https://doi.org/10.1016/j.asej.2014.08.008

FAO, & UNEP. (1999). *The Future of Our Land: FACING THE CHALLENGE- Guidelines for Intergrated Planning for Sustainable Mnanagement of Land Resources*. 1–88.

https://doi.org/9251043669

Fashae, O. A., Tijani, M. N., Talabi, A. O., & Adedeji, O. I. (2014). Delineation of groundwater potential zones in the crystalline basement terrain of SW-Nigeria: an integrated GIS and remote sensing approach. *Applied Water Science*, *4*(1), 19–38. https://doi.org/10.1007/s13201-013-0127-9

Forkuor, G., & Cofie, O. (2011). Dynamics of land-use and land-cover change in Freetown, Sierra Leone and its effects on urban and peri-urban agriculture - a remote sensing approach. *International Journal of Remote Sensing*, *32*(4), 1017–1037. https://doi.org/10.1080/01431160903505302

Haber, M. (1981). Exact significance levels of goodness-of-fit tests for the hardy-weinberg equilibrium. *Human Heredity*, *31*(3), 161–166. https://doi.org/10.1159/000153199

Jaiswal, R. K., Mukherjee, S., Krishnamurthy, J., & Saxena, R. (2003). Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development - An approach. *International Journal of Remote Sensing*, *24*(5), 993–1008. https://doi.org/10.1080/01431160210144543

Jalloh, Y., Sasaki, K., & Thomas, M. O. (2016). The Influence of Local Geology on the Groundwater Potential of Kunike Sanda and Barina Chiefdoms Tonkolili District Northern Sierra Leone. *Hydrology: Current Research*, *07*(04). https://doi.org/10.4172/2157-7587.1000262

Jalloh, Y., Thomsa, M. O., & Sasaki, K. (2017). Groundwater Assessment through an Integrated Approach Using GIS and Electrical Resistivity Technique: A Case Study from the Bullom Group of Sediments in Sierra Leone. *Journal of Environmental & Analytical Toxicology*, *07*(06). https://doi.org/10.4172/2161-0525.1000523

Jha, M. K., Chowdary, V. M., & Chowdhury, A. (2010). Groundwater assessment in Salboni Block, West Bengal (India) using remote sensing, geographical information system and multi-criteria decision analysis techniques. *Hydrogeology Journal*, *18*(7), 1713–1728. https://doi.org/10.1007/s10040-010-0631-z

Lattman, L. H., & Parizek, R. R. (1964). Relationship between fracture traces and the occurrence of ground water in carbonate rocks. *Journal of Hydrology*, *2*(2), 73–91. https://doi.org/10.1016/0022-1694(64)90019-8

Leary, D. W. O., Friedman, J. D., & Pohn, H. A. (1976). Geological Society of America Bulletin Lineament , linear , lineation : Some proposed new standards for old terms. *Geological Society of America Bulletin*, *87*(10), 1463–1469. https://doi.org/10.1130/0016-7606(1976)87<1463

Leblanc, M., Favreau, G., Tweed, S., Leduc, C., Razack, M., & Mofor, L. (2007). Remote sensing for groundwater modelling in large semiarid areas: Lake Chad Basin, Africa. *Hydrogeology Journal*, *15*(1), 97–100. https://doi.org/10.1007/s10040-006-0126-0

Liesch, T., & Wunsch, A. (2019). Aquifer responses to long-term climatic periodicities. *Journal of Hydrology*, *572*(March), 226–242. https://doi.org/10.1016/j.jhydrol.2019.02.060

Magesh, N. S., Chandrasekar, N., & Soundranayagam, J. P. (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. *Geoscience Frontiers*, *3*(2), 189–196. https://doi.org/10.1016/j.gsf.2011.10.007

Mogaji, K. A., Aboyeji, O. S., & Omosuyi, G. O. (2011). *Mapping of lineaments for groundwater targeting in the basement complex region of Ondo State , Nigeria , using remote sensing and geographic information system (GIS) techniques*. *3*(August), 150–160.

Morelli, M., & Piana, F. (n.d.). *International Journal of Remote Comparison between remote sensed lineaments and geological structures in intensively cultivated hills (Monferrato and Langhe domains , NW Italy)*. (December 2014), 37–41. https://doi.org/10.1080/01431160600784200

Mudd, G. M., Deletic, A., Fletcher, T. D., & Wendelborn, A. (2004). A review of urban groundwater in Melbourne: Considerations for WSUD. *Water Sensitive Urban Design Conference*, 428–438.

Nagarajappa, D. P., Manjunatha, K., & Manjunath, N. . (2010). *Effects of Soil Types on Performance of Soil Aquifer Treatment (SAT) System*. (1), 1–4.

Naji, L., Tawfiq, M., & Jabber, A. K. (2016). Global Journal of Engineering Science and Researches Mathematical Modeling of Groundwater Flow. *C) Global Journal Of Engineering Science And Researches*, *3*(10), 2348–8034.

https://doi.org/10.5281/zenodo.160914

Oseji, J. (2014). *DETERMINATION OF GROUNDWATER FLOW DIRECTION AT EMU AND OGUME DETERMINATION OF GROUNDWATER FLOW DIRECTION AT EMU AND OGUME KINGDOMS / NIGERIA*. (December 2010).

Otutu, O. J. (2011). *Groundwater flow direction in Ndokwa-East local government area of Delta state , Nigeria*. *3*(February), 21–24.

Otutu, O. J., & Oviri, O. M. (2010). Determination of Groundwater Flow Direction in Utagba-Ogbe Kingdom, Nokwa Land Area of Delta State, Nigeria. *Online Journal of Earth Sciences*, *4*(1), 32–34. https://doi.org/10.3923/ojesci.2010.32.34

Peiffer, S. (2007). *Groundwater management and development by integrated remote sensing and geographic information systems : prospects and constraints*. 427–467. https://doi.org/10.1007/s11269-006-9024-4

Pradhan, B. (2009). Groundwater potential zonation for basaltic watersheds using satellite remote sensing data and GIS techniques. *Central European Journal of Geosciences*, *1*(1), 120–129. https://doi.org/10.2478/v10085-009-0008-5

Ray, S., & Ray, I. A. (2011). Impact of Population Growth on Environmental Degradation: Case of India. *Journal of Economics and Sustainable Development*, *2*(8), 72–77. Retrieved from www.iiste.org

Reghu, S., Gopinath, G., Srinivas, R., Regunath, R., & Sajan, K. (2013). Demarcation of groundwater prospective zones in humid tropical river basin: A geospatial approach. *Iranian Journal of Earth Sciences, 5*(1 A), 13–20.

Shaban, A., Khawlie, M., & Abdallah, C. (2006). Use of remote sensing and GIS to determine recharge potential zones: The case of Occidental Lebanon. *Hydrogeology Journal*, *14*(4), 433–443. https://doi.org/10.1007/s10040-005-0437-6

Taylor, P., Krishnamurthy, J., Kumar, N. V., Jayaraman, V., & Manivel, M. (n.d.). *International Journal of Remote Sensing An approach to demarcate ground water potential zones through remote sensing and a geographical information system*. (December 2014), 37–41. https://doi.org/10.1080/01431169608948744

Terrestrial, M., & Dependent, G. (2009). *5 Identification of GDEs*. 21–24.

Thomas, M. O. (2019). *Groundwater Flow Mechanism at a proposed mining site in South-western Sierra Leone*. *35*(1), 20–25. Retrieved from www.journalresearchijf.com

Waikar, M. L., & Nilawar, A. P. (2014). *Identification of Groundwater Potential Zone using Remote Sensing and GIS Technique*. *3*(5), 12163–12174.

Yeh, H. F., Lee, C. H., Hsu, K. C., & Chang, P. H. (2009). GIS for the assessment of the groundwater recharge potential zone. *Environmental Geology*, *58*(1), 185–195. https://doi.org/10.1007/s00254-008-1504-9

Youssef, A. M., Pradhan, B., Gaber, A. F. D., & Buchroithner, M. F. (2009). Geomorphological hazard analysis along the Egyptian Red Sea coast between Safaga and Quseir. *Natural Hazards and Earth System Science*, *9*(3), 751–766. https://doi.org/10.5194/nhess-9-751-2009