# ESTIMATION OF BOREHOLE YIELD USING VERTICAL ELECTRICAL SOUNDING DATA: A CASE STUDY FROM KWABRE DISTRICT

By:

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A Thesis submitted to the Department of Geological Engineering, College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, in partial fulfilment of the requirement for the degree of

MASTER OF SCIENCE

MAY, 2017

# DECLARATION

I hereby declare that that this thesis is my own work towards perusing a Master of Science in Geophysical Engineering, and that to the best of my knowledge, it contains no previously published material by another person nor material that has been accepted for the award of any other degree of the University, expect where due acknowledgement has been made in the text.

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# ABSTRACT

Groundwater has been identified as the world's largest resource that can be easily accessed especially when confronted with water shortages as a result of low river discharges. Successful execution of groundwater exploration using geophysical methods requires knowledge on the relationships that exist between hydrogeological and geophysical parameters. This makes data interpretation and delineation of groundwater zones easier, thereby avoiding the drilling of marginal holes. This study was carried out in the Kwabre District and was aimed at establishing a relationship between airlift yields and electrical resistivity parameters. Three methods, viz. borehole log analysis, cumulative resistivity method and the drilling rate with respect to formation analysis, were employed to obtain resistivity (rho) and thickness of the saturated zones from borehole logging and vertical electrical sounding data. The obtained resistivity and saturated thickness were used to compute transverse resistance (Tr) and longitudinal conductance (Sc). Each of these parameters (i.e. Tr and Sc) including the resistivities of the saturated zones were further correlated with airlift yields of the boreholes to evaluate their relationships. Also, the airlift yields were used to create a yield map of the district. Correlation results obtained from the borehole log analysis and cumulative resistivity method suggest there is no relationship between the airlift yield and the resistivity parameters. On the other hand, results obtained from the drilling rate with respect to formation analysis showed that the yield versus resistivity, longitudinal conductance and transverse resistance are related by 60.85%, 57.16% and 50.25% respectively. However, validations of the associated models were very poor in predicting measured airlift yield values. Thus, further studies may be required to improve and validate the method. This study also provided useful information on the variation of airlift yields in the district.

# ACKNOWLEDGEMENTS

My thanks and appreciation go to the Almighty God for this uncountable grace, mercy, strength and his wisdom, knowledge and understanding throughout my program.

My gratitude goes to USAID, University of Michigan, EHELD, Division of Engineering and the Department of Geology of the University of Liberia for their financial and moral support through this study period and for the opportunity afforded me to achieve higher education.

My deepest appreciation goes to my supervisor, Dr. Emmanuel Kwame Appiah-Adjei for coming up with the report. Many appreciation and thanks go to Dr. Frederick Owusu-Nimo for his time, patience, support and effort towards this study.

Many thanks go to my family and all those who directly and indirectly supported me throughout my studies; may God bless you all.

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

Groundwater is known to be the world's largest accessible storage of fresh water. It is considered as the logical resource to turn to when faced with water shortage which may arise from low and variable river discharges (Ifabiyi *et al.*, 2016). The convenient nature and occurrence of groundwater have rendered it less expensive for treatment when exploited and could be developed at a desired location and at a reasonable cost.

The demand for adequate, good-quality water has increased extensively due to awareness and technology. Therefore, many people rely on the exploration and exploitation of groundwater, which is one of the valuable natural resources for sustenance of life. Its quality is good for human consumption; hence, it is the most preferred choice in various households and communities.

In the Kwabre District of Ashanti Region, groundwater has proven to be the most reliable source of water for household, agricultural and some industrial purposes. It has over the years, conveniently, served the inhabitants of the district during the dry seasons when surface water runs out. Groundwater consumption in the district has saved the inhabitants from contracting some water-borne diseases that could be obtained from the consumption of surface water, which is usually exposed to the glare of potential pollution. As the occurrence of groundwater depends on the nature and type of aquifer, the shallow aquifer system in the district permits groundwater to be easily tapped by hand-dug wells and boreholes.

Due to the growing needs of groundwater in most areas including Kwabre District, many methods have been used for its exploration. These methods include water witching (dowsing), fracture mapping, direct drilling, borehole logging and the use of geophysical techniques. Today, one of the most efficient ways of identifying groundwater is the use of geophysical methods. These methods include but not limited to, electrical resistivity, seismic, electromagnetic, gravity and magnetic. Out of all the methods, the direct current resistivity method is a common tool used in groundwater survey. This method can be successively employed for groundwater exploration where a good electrical resistivity contrast exists between the saturated and unsaturated layers. The vertical electrical sounding with dipole-dipole array as a low-cost technique and as an authentic tool in groundwater exploration, is more suitable for hydrogeological surveys in both sedimentary and hard rock terrains. It has been used to successfully map vertical variations in resistivity with depth, determine the depth to the water table, thickness of the saturated zone, delineate structures that serve as hosts for groundwater accumulation, map overburden thickness, determine the depth to bedrock and provide an understanding of the geometry of aquifers (Ifabiyi *et al.*, 2016). This technique employs collinear arrays of electrodes designed to input a 1-D vertical apparent versus depth model at a specific observation point. Using this technique, a series of potential differences are acquired at successful greater electrode spacing while maintaining a fixed central reference point. The potential difference measurements are propositional to the changes in the deeper subsurface (Cardimona, 2002). Vertical electrical sounding (VES) technique for groundwater exploration has proven reliable in many areas. For instance, it was used in delineating groundwater zones in an arid region in Iran (Nejad *et al.*, 2011). It has proven very popular with groundwater prospecting and engineering investigation due to the simplicity of the technique and has been used to map groundwater bodies in many places in Nigeria (Jatau *et al.*, 2013).

Although VES has proven useful and shown to be one of the most reliable techniques for groundwater siting, unsuccessful and marginal holes are still encountered; hence there has been studies trying to improve on the success rate. Like many others, this study is investigating the use of VES data to estimate the yield prior to drilling by creating a model that relates yield to VES data. This model is to show that, results obtained from VES survey can further be used to estimate the potential yield of boreholes and, therefore, enhance selection of VES points for drilling. In so doing, it would help improve the success rate in drilling boreholes and cut down the losses from drilling dry and marginal holes.

## 1.2 Purpose and Specific Objectives

The main purpose of this research is to establish a possible relationship between borehole yield and some electrical resistivity parameters. The specific objectives are to:

1. Develop a yield map of the area,
2. Determine resistivity of the saturated zone,
3. Determine transverse resistance and longitudinal conductance of the saturated zone, and
4. Establish correlation between the yield and electrical resistivity parameters

## 1.3 Scope of Study

The research is limited to Kwabre District of Ashanti Region and concentrated on creating models that relate yield to vertical electrical sounding data. Secondary data consisting of dipole-dipole siting data, borehole logs and borehole construction data were used. The ArcGIS software was used to produce the yield distribution map of the area. Comparing the VES data with the borehole logs, resistivity and thickness of the saturated zones were obtained and used to compute transverse resistance and longitudinal conductance. Also, airlift yields obtained from the borehole logs were correlated with each of the electrical resistivity parameters to determine the relationship between them.

This thesis comprises five chapters. The background, problem statement, justification and scope of work are presented in chapter 1. Chapter 2 includes a review of literature on previous studies done in relation to the study while Chapter 3 provides a brief description of the study area and explains the methods employed in the study. The study results and discussion are presented in Chapter 4. Lastly, conclusion and recommendations based on findings from the study are provided in Chapter 5.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Importance of Groundwater

Groundwater is water beneath the earth's surface, filling pore spaces in soils, voids in rocks and fractures of various rock formations and constituting about 21% of the world's fresh water supply, which is about 0.61% of the world's water including the oceans and permanent ice. Global groundwater storage is known to be approximately equal to the total amount of freshwater stored in the snow and ice pack, including those in the north and south poles. This makes it an important resource that can be considered as a natural storage to substitute surface water in times of shortage or drought (Columbia Water Center, 2009). It is replenished by surface water and precipitation, when the water table is recharged.

Groundwater is useful in many aspects of human life. It can be used in agriculture, for industrial purposes, municipal water supply, etc. The abstraction of groundwater for these purposes are usually done through the construction and operation of wells.

Yield is an important feature in assessing an aquifer. It is a characteristic of an aquifer's ability to release groundwater. It is known as the volume of water released from storage during pumping. It involves determining the amount of dewatered material in a depressed cone during pumping test (Ramsahoye and Lang, 1961). The yield of an aquifer is less than its porosity since, due to capillary retention, not all water drains from the pore spaces during abstraction.

## 2.2 Geophysical Methods in Groundwater Exploration

Geophysical methods can aid in the delineation of subsurface structures that serve as potential hosts to groundwater resources. Exploration for groundwater therefore requires the use of geophysical methods to map out these potential zones. The various geophysical methods used in groundwater exploration are electrical resistivity method, seismic method, magnetic method, gravity method, electromagnetic method and the magnetic resonance method. The choice of any of these methods for use depends on in-situ subsurface conditions and their ability to properly detect and determine the potential groundwater zones.

In the Seismic method, acoustic energy of the wave propagating through a medium is measured. The velocity of the acoustic energy, which is in the form of compressional and shear waves, is related to the dynamic elastic modulus and density of the material through which the wave is travelling. Seismic method for groundwater exploration relies on the seismic refraction technique, which makes use of the compressional wave and shows increase in velocity with density (Haeni, 1988). This technique is used because it investigates an approximate depth of about 200m, which is within the depth range for the existence of groundwater in some rock formation in Ghana.

Gravity survey involves measuring variations in the earth's gravitational field caused by difference in subsurface densities (Rivas, 2009). It provides an indirect investigation of the subsurface by reviewing physical properties (density, magnetization) of rocks. The presence of water beneath the surface changes the density of the material in the area and therefore can be detected by gravity method. Due to the wide range of density variation among various rock types, geophysicists are able to tell the presence of water beneath the subsurface using the gravity method.

Similarly, magnetic method measures the remnant magnetic field associated with various geologic structures and artificial objects. The method has been used to map regional structures since the early 1900's, mainly in the hydrocarbon and mineral industries, but has not been used much in groundwater exploration except in mapping large scale structures and/or basins that serve as host for groundwater (Aubert *et al*., 1984). Also it has proven substantial in the mapping of bedrock topography and possible groundwater reservoirs in crystalline hard rock (igneous and metamorphic) terrains (Babu *et al*., 1991).

On the other hand, the electromagnetic method has proven to be one of the best geophysical methods in groundwater investigation. For the past years, the method has been used to map the conductivity of lateral and vertical structures, which are sometimes associated with groundwater. There are basically two types of electromagnetic survey; they are the time domain and the frequency domain electromagnetic surveys. In groundwater studies, the interest lies in the frequency domain since it can be used to measure lateral and vertical conductivity variations along a profile either as single line or grids of data (Richard *et al*., 1996).

## 2.3 Electrical Resistivity Method

The electrical resistivity method (ERM) is the method commonly used in groundwater exploration. Its application in groundwater exploration began as far back as in the World War II and aims at delineating vertical and horizontal boundaries with electrical contrast. It is mostly used because of its efficiency and economic method of determining the presence of groundwater (Anomohanran, 2014).

During an electrical resistivity survey, an artificial source of energy is introduced into the subsurface via a set of current electrodes and the resultant potential difference is measured by another set of potential electrodes in a four-electrode system. In this system, the resistivity is measured using the pattern of the current and potential electrodes. During this process, the source detector separation can be changed to achieve the optimum separation, which effectively controls the depth of measurement.

When two current electrodes (A and B) are used and the potential difference are measured via another sets (M and N), the total potential at M due to A and B is given as:

$$\mathbf{V_M^{A,B}} = \frac{\boldsymbol{\rho}\mathbf{I}}{\mathbf{2\pi}} \left(\frac{\mathbf{1}}{\mathbf{AM}} - \frac{\mathbf{1}}{\mathbf{BM}}\right) \tag{1}$$

The total potential at N due to A and B is given as;

$$\mathbf{V_N^{A,B}} = \frac{\boldsymbol{\rho}\mathbf{I}}{\mathbf{2\pi}} \left(\frac{\mathbf{1}}{\mathbf{AN}} - \frac{\mathbf{1}}{\mathbf{BN}}\right) \tag{2}$$

Therefore the net potential difference is given as;

$$\Delta\mathbf{V_{M,N}^{A,B}} = \mathbf{V_M^{A,B}} - \mathbf{V_N^{A,B}} = \frac{\boldsymbol{\rho}\mathbf{I}}{\mathbf{2\pi}} \left(\frac{\mathbf{1}}{\mathbf{AM}} - \frac{\mathbf{1}}{\mathbf{BM}} - \frac{\mathbf{1}}{\mathbf{AN}} + \frac{\mathbf{1}}{\mathbf{BN}}\right) \tag{3}$$

Rearranging the equation to solve for resistivity ($\rho$), we get;

$$\boldsymbol{\rho} = \left(\frac{\mathbf{2\pi}}{\frac{\mathbf{1}}{\mathbf{AM}} - \frac{\mathbf{1}}{\mathbf{BM}} - \frac{\mathbf{1}}{\mathbf{AN}} + \frac{\mathbf{1}}{\mathbf{BN}}}\right) \frac{\Delta\mathbf{V}}{\mathbf{I}} \tag{4}$$

This is the equation for direct-current electrical survey. From the equation (4) the geometry factor, K, is given as:

$$\frac{2\pi}{\frac{1}{AM}-\frac{1}{BM}-\frac{1}{AN}+\frac{1}{BN}} = K \qquad (5)$$

Therefore, apparent resistivity is given as:

$$\rho = K\frac{\Delta V}{I} \qquad (6)$$

Equation (6) represents the apparent resistivity for an inhomogeneous, and/or anisotropic medium, because the resistivity of the earth is determined by inhomogeneous lithology and geological structures. This apparent resistivity is dependent upon the geometry of the electrode array, the true resistivity and other characteristics of the subsurface materials such as layer thickness, angle of dips, etc. ( Zohdy, 1974).

In groundwater exploration, the inverse of resistivity “conductivity” is of interest. Zones of low resistivity “high conductivity” becomes the areas where detailed investigations are concentrated. Conduction of electricity occurs not only by the movement of ions through the bulk saturating electrolyte, but also by the movement of absorbed ions along the interface of pores and cracks. Conductivity of a fully saturated rock is related to its porosity, pore geometry, and the nature of the surface of the mineral grains lining the pores, as well as the dielectric property of the mineral grains and pore fluid. It also depends on its hydraulic permeability, which describes how the pores are interconnected, the amount and composition of colloids (clay content) etc. (Zohdy, 1974). These things are properly investigated during the delineation of groundwater zones as they reduce the resistivity of subsurface materials. Thus the more saturated the material, the less resistive it becomes.

In geophysical investigations for ground water exploration, depth to bedrock determinations, sand and gravel exploration, etc., the electrical resistivity method can be used to obtain quick and economic details about the location, depth and resistivity of the subsurface (Arshad *et al*., 2007). The ERM is generally used for groundwater studies in determining the quality and quantity of groundwater, the extents of contaminant plumes, used to map fresh water lenses, and also to investigate salt water intrusions. In other places, it has been used to determine the depth, thickness and boundary of an aquifer, determine the interface of saline and fresh water, the hydraulic conductivity, transmissivity and specific yield of aquifers (Choudhury *et al*., 2001). The use of geophysical methods for groundwater resource mapping and for water quality evaluation has dramatically increased over the years in many parts of the world due to rapid advances in microprocessor and associated numerical modeling solutions (Arshad *et al*., 2007).

### 2.3.1 Electrode Configurations

There are various electrode configurations that can be used in resistivity surveying. The electrode configurations are the Wenner array, Schlumberger array the Dipole-Dipole array, Pole-Dipole array, Square array, etc. For each array type, there is a geometry factor "**K**" that describes the geometry of the configuration used. Among all the electrode configurations, Wenner, Schlumberger and Dipole-Dipole are frequently used for groundwater exploration.

In the Wenner configuration, the electrodes are uniformly spaced in a line. For groundwater exploration, the array is usually used for profiling. This is done as an initial step to obtain the lateral changes in resistivity of the subsurface. During this practice, a fixed electrode spacing is chosen (based on the objective of the survey and in studying the result for sounding) and the entire spread is moved along a profile after each measurement is done. In investigating a specific depth, such as the depth to the water table, the electrodes are expanded about a fixed center, increasing the electrode spacing as you move along (Telford *et al*., 1990; Zohdy *et al*., 1974).

In the Schlumberger configuration, the distance between the current electrodes are much further apart than the distance between the potential electrodes. In exploration for groundwater, this array is used either for profiling or vertical sounding. In vertical sounding, the potential electrodes are kept at a fixed distance while the current electrodes are expanded symmetrically about the center of the spread, and the vertical variations in resistivity with depth are obtained. This procedure is more convenient than the Wenner because only two electrodes are moved and the effect of shallow resistivity variations is constant with fixed potential electrodes (Telford *et al*., 1990).

The Diploe-dipole array is important because of its ability to probe deeper. In the dipole-dipole array, the distance between the current electrodes ($I_1I_2$) and the distance between the potential electrodes ($P_1P_2$) are smaller than the center (r) of the two dipoles (Zohdy, 1974). The array has mostly been used due to its low electromagnetic coupling between the current and potential electrodes. From sensitivity analysis, the dipole-dipole is most sensitive to change in resistivity between the electrodes in each dipole pair. The array is very sensitive to horizontal changes in resistivity, but less sensitive to vertical changes in resistivity (Loke, 2000). This means the method is good at mapping vertical structures, but relatively poor in mapping horizontal structures. Figure 2.1 shows the configuration of the dipole-dipole array.

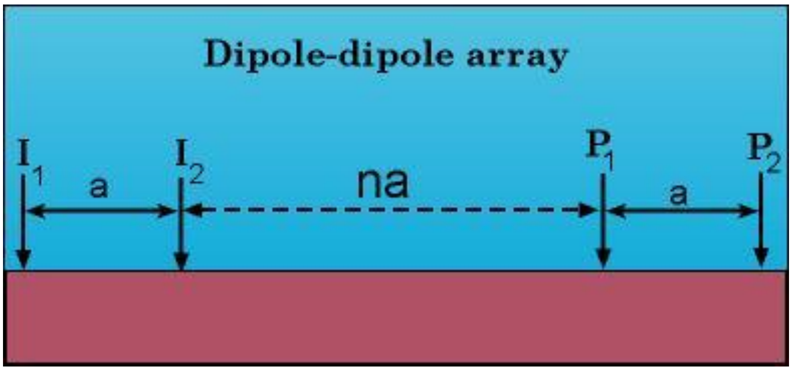



**Figure 2.1. Configuration of the dipole-dipole array (Loke 2000)**

In this configuration, the spacing between the current electrodes ($I_1I_2$) is **a**, which is the same as the distance between potential electrodes ($P_1P_2$). In the arrangement, **na** represents the ratio of the distance between the $I_1P_1$ electrodes to the $I_2P_2$ dipole separation **a**. During a survey, the **a** separation is kept constant from the initial while the **na** is changed along the line. This **na** separation is increased from one, two, and three up to six in order to maximize the depth of investigation (Loke, 2000). These arrays have been used to characterize groundwater aquifer in Kangonde Area, Machakos, Kenya (Lucy *et al*., 2016), to delineate groundwater zones in the Gulf of Suez, Egypt (Galil *et al*., 2014), to determine the lithology and groundwater quality in Pakistan (Arshad *et al*, 2007), to investigate for groundwater in Etroro-Akoko, Southwestern Nigeria (Cyril *et al*., 2014), etc.

## 2.4 Use of Dar-Zarrouk Parameters in Groundwater Exploration

Dar-Zarrouk parameters play many important roles in geoelectrical resistivity soundings and groundwater prospecting (Orellano 1963; Singh 2004). In case of a stratified conductor, certain parameters are significant both in terms of interpreting and understanding the geological model. These parameters, termed as Dar-Zarrouk parameters by Maillet (1947), are related to the resistivity and thickness of each layer in the model. They have been used to compute the distribution of surface potential in a section consisting of **N** fine layers with thicknesses $\mathbf{h_1}$, $\mathbf{h_2}$, $\mathbf{h_3}$, ......$\mathbf{h_n}$, and resistivities $\boldsymbol{\rho_1}$, $\boldsymbol{\rho_2}$, $\boldsymbol{\rho_3}$, ......$\boldsymbol{\rho_n}$. The Dar-Zarrouk parameters "Longitudinal Conductance (Sc) and Transverse Resistance (Tr)" are defined by:

$$\mathrm{Sc} = \frac{\mathrm{h}}{\rho} \tag{7}$$

$$\mathrm{Tr} = \mathrm{h}\rho \tag{8}$$

Where, **h** is the thickness of the saturated layer in meter, **ρ** is the resistivity in ohm-m, **Tr** is transverse resistance "resistance normal to the face" and **Sc** is the longitudinal conductance "conductance parallel to the face" for a unit cross sectional area (Henriet 1972).

For groundwater exploration, the resistivity (ρ) and thickness (h) of the saturated zone are the parameters of interest. Groundwater flow through an aquifer is not governed by hydraulic conductivity (K) alone but the bulk parameter called transmissivity, which is the product of K and h (Utom *et al*., 2012). Dar-Zarrouk parameters which are also bulk parameters considering the relationship between hydraulic conductivity and resistivity, can also be related to the transmissivity of aquifer (Utom *et al*., 2012). These parameters are related to various subsurface layers and can be used to delineate groundwater settings and determine some geological conditions (Batayneh, 2013). The parameters have proven significant in many areas and have been discussed by many authors. For instance, they were estimated and used in the Gulf of Aqaba coastal aquifer system to explore for quality affecting the aquifer (Batayneh 2013), used to differentiate between fresh and saline groundwater aquifers of Sinjar plain area (Al-yasi et al., 2013), applied to aquifer protection studies (Braga et al., 2006), used to estimate hydraulic conductivity using direct current sounding in Nile Delta, Egypt (Attwa et al., 2014), and used to estimate aquifer transmissivity in Enugu Town (Utom *et al*., 2012). The parameters have also been used by several authors (Henriet 1972; Singh et al. 2004; Utom et al. 2012) for different groundwater characterization and geological conditions.

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Description of Study Area

### 3.1.1 Location and Size

The study area Kwabre District is located in Ashanti Region and lies between longitudes $6^{o}39'30''$ to $6^{o}59'30''$ North and latitudes $1^{o}27'30''$ to $1^{o}40'30''$ West. It is bounded to the North by Sekyere District, to the South by Kumasi Metropolis, to the West by Atwima Nwabiagya District and to the East by Ejisu Juaben District. It covers a total area of 532.4 $km^2$ constituting about 1.91 % of the total land area of Ashanti Region. According to the 2010 Population and Housing Censes, the district's population stands at 251,696 with a higher percentage of this number being males (Ghana Statistical Service, 2014; District Planning Coordinating Unit, 2012). The district is known for its cultural heritage as well as its endowment in unique craftworks and natural resources. It is described as an ultimate tourist destination in the Ashanti Region. Figure 3.1 shows the map of the study area indicating communities, rivers and geology.

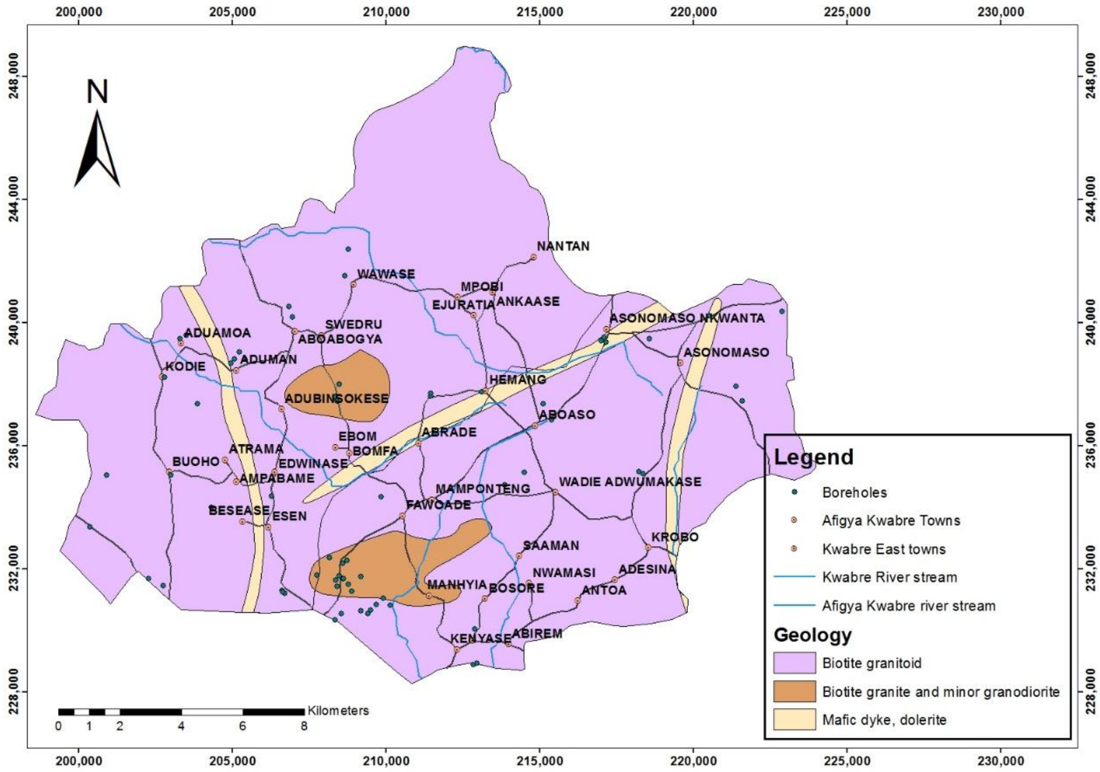



**Figure 3.1: The Kwabre District with distribution of study boreholes**

### 3.1.2 Climate

The district is characterized by wet semi-equatorial climate with double rainfall pattern. The first rainy season is from April to June with more rain falling during the month of June and the second rainy season is from September to October. The double rainfall maxima in the district contributes immensely to agriculture as cultivation of both vegetable and food crops are done twice a year.

The relative humidity of the area is 75 - 80 % during the rainy season and 70 - 72 % during the dry season. The average annual rainfall is between 125 mm and 175 mm. The mean annual temperature is about 30 ℃ with the lowest occurring around 26 ℃ (Ghana Statistical Service, 2014; District Planning Coordinating Unit, 2012).

### 3.1.3 Geology

The main rock types in the district are biotite granite and granodiorites. These rocks have weathered in some areas such as Antoa, Abira, Sakora Wonoo, Adwumakase and Kenyase forming fine texture granitic soil. Biotite gneiss and biotite granite outcrop in Kenyase and Aboaso. Highly complex soils are found in the district. They include the Kumasi-Offin and Bomso-Offin compounds associations, Boaman Simple Association and Nyanoa-Tinkong Simple Association (Ghana Statistical Service, 2014; District Planning Coordinating Unit, 2012).

Lower Birimian-phyllite and coarse-grained Voltaian sandstone with several soil associations and/or mapping units have developed over their parent materials. The soil types are grouped into associations, ranging from the Kumasi-Offin Compound Association, Bomso-Offin Association, Jamasi Simple Association, Boamang Simple Association, Bediesi-Sutawa Association and the Yaya-Primpimson Association. A portion of the area contains disserted plateau with heights ranging from 1200 m above sea level. This 1200 m above sea level elevation is mainly located in the north and at some isolated hills south around Buoho community. The undulating nature of the relief in this area creates the easy flow of water. Rivers, valleys and waterlogs are found in the district. The district is drained by three main rivers and tributaries; the rivers are the Offin, Oyon and Abankro.

At Sakora Wonoo and on the bank of the Bomonwe stream at the outskirts of Adanwomase, there exist low-grade alluvial gold deposits. Diamonds have also been sited at Safo and Kasaam, northeast of the district. Sand and clay deposits have been found in the central portion of the district (Ghana Statistical Service, 2014; District Planning Coordinating Unit, 2012).

## 3.2 Data Collation

The study began with a desk study on the entire Kwabre district. This provided easy understanding of the geology, groundwater conditions, the aquifer system and the selection of favorite sites for the running of the electrical resistivity survey.

Secondary data consisting of electrical resistivity data, borehole logs and borehole construction totaling 120 data sets were later obtained from the Community Water and Sanitation Agency, Kumasi and used for the study. The data was from a groundwater project undertaken in 2010. The project was done in two phases; the first phase was geophysical siting undertaken over the entire area to determine favorable groundwater points; whereas the second phase was on drilling of the boreholes for community water supply.

Information obtained from the secondary data included:

- Dipole-Diploe sounding data with details on how the siting was done, the maximum depth investigated, and how the subsurface resistivities vary with depth. These were compared with borehole logs to obtain the resistivity and thickness of the saturated zones.
- Location coordinates of the boreholes in the UTM format.
- Borehole construction details such as the maximum construction depth, the drill penetration rate, location of plain and screened PVC pipes and the position of gravel pack.
- Borehole logs detailing the different subsurface formations encountered at different depths, thickness of each layer, and the airlift yield. Pumping test yields were not available; therefore, the airlift yields were used for all the analysis in this study.

To ensure data quality, field visit was done to verify some of the coordinates and positions of boreholes. Boreholes without GPS coordinates and those with wrong coordinates that could not be verified were discarded. In some boreholes, PVC screens were not placed, therefore, the aquifer zones could not be identified. After the quality checks, data from 88 boreholes were found to be valid for the study.

## 3.3 Yield Distribution Map

Airlift yield data from the 88 valid boreholes were used in creating the yield distribution map of the district. Ten (10) of these boreholes were dry holes, 4 had marginal yields (yield < 10 l/min) and 74 were successful holes (yield > 10 l/min). Data was scarce in the extreme north and east portions of the study area.

The yield distribution map was prepared to have an understanding of groundwater yield distribution in the study area. This was done by arranging the data in Microsoft Excel with their respective coordinates, converting the coordinates from degree-minute to decimal and inputting the data into ArcGIS. In ArcGIS, the area maps were imported and the coordinates of both dataset were set in conformity with the geographical location of the area. The yield distribution map was generated using Inverse Distance Weight (IDW) interpolation method in ArcGIS. This method, basically indicates that yield values being mapped decrease in influence with distance from their borehole locations.

## 3.4 Estimation of Layer Thicknesses and Assigning Electrical Resistivity Parameters

The electrical resistivity sounding was done to determine the depths to the saturated zones, the thicknesses of the aquifer/saturated zones, the resistivities of the saturated zones and the depth at which possible fractures exist.

In all instances, results of sounding and profiling are affected by the vertical and horizontal variations in resistivities of the subsurface. If for example the subsurface comprises horizontal homogeneous and isotropic layers, the resistivity sounding would reflect only the variation in resistivity with depth (Zohdy, 1974). But in practice, it is not so; as the data from electrical resistivity sounding are a result of both vertical and horizontal heterogeneities. It was based on this theory that the surveys, the processing and interpretation of the data from various sites were done so that one could easily distinguish the horizontal variation from the vertical variation.

Results from the electrical resistivity “dipole-dipole” sounding provided the basis for drilling of the 120 boreholes in the district. It indicated the depth and resistivity of groundwater based on the geology of the area. Since the objective of the thesis is to establish empirical relationships between yield and electrical resistivity parameters, many emphasis were not placed on the groundwater conditions of the area, the geometry of the aquifer etc., but on determining the resistivities and thicknesses of the saturated zones. Having obtained the resistivity and thickness of the saturated zone, Dar-Zarrouk approach was used to calculate longitudinal conductance (Sc) and transverse resistance (Tr). Values of airlift yield were obtained from the borehole logs and correlated with longitudinal conductance (Sc), Transverse resistance (Tr) and resistivity of the saturated zones.

Three methods were used to determine the thicknesses of the saturated zones and resistivity values within the depth range of those thicknesses were assigned to each of them for the purpose of establishing empirical relationships between the airlift yield and geophysical parameters. The methods used are the borehole log analysis, cumulative resistivity analysis, and the drilling rate analysis.

### 3.4.1 Borehole Log Analysis

This method was done in accordance with the number of subsurface layers indicated in the borehole logs. In preforming this method, it is important to have an idea of the layer that hosts the zone of saturation. The second and third layers were targeted as the layers that could possibly host the aquifer zone. The first layer was not considered because the dipole-dipole sounding did not account for it and the aquifer zone could not be in the first layer that have an approximate thickness of 8 m. The sounding started from the depth of eight (8) meter ignoring the first layer. Depths to the top and bottom of each layer in the logs were taken and compared to the depths on the dipole-dipole siting data. From that depth range on the dipole-dipole siting data, the point of low resistivity was picked and assumed to be the resistivity of the saturated zone in case a saturated zone exists within the layer. Based on the geology of the area, the zone with the lowest resistivity value was taken as zone that hosts the groundwater.

It is important to reference the geology in picking the resistivity of the aquifer zone because groundwater is not the only conductive subsurface material. Subsurface conductivity can also be caused by the presence of clay and other conducting minerals. Figure 3.2 is one of the borehole log showing the different layers, their depths and thicknesses.

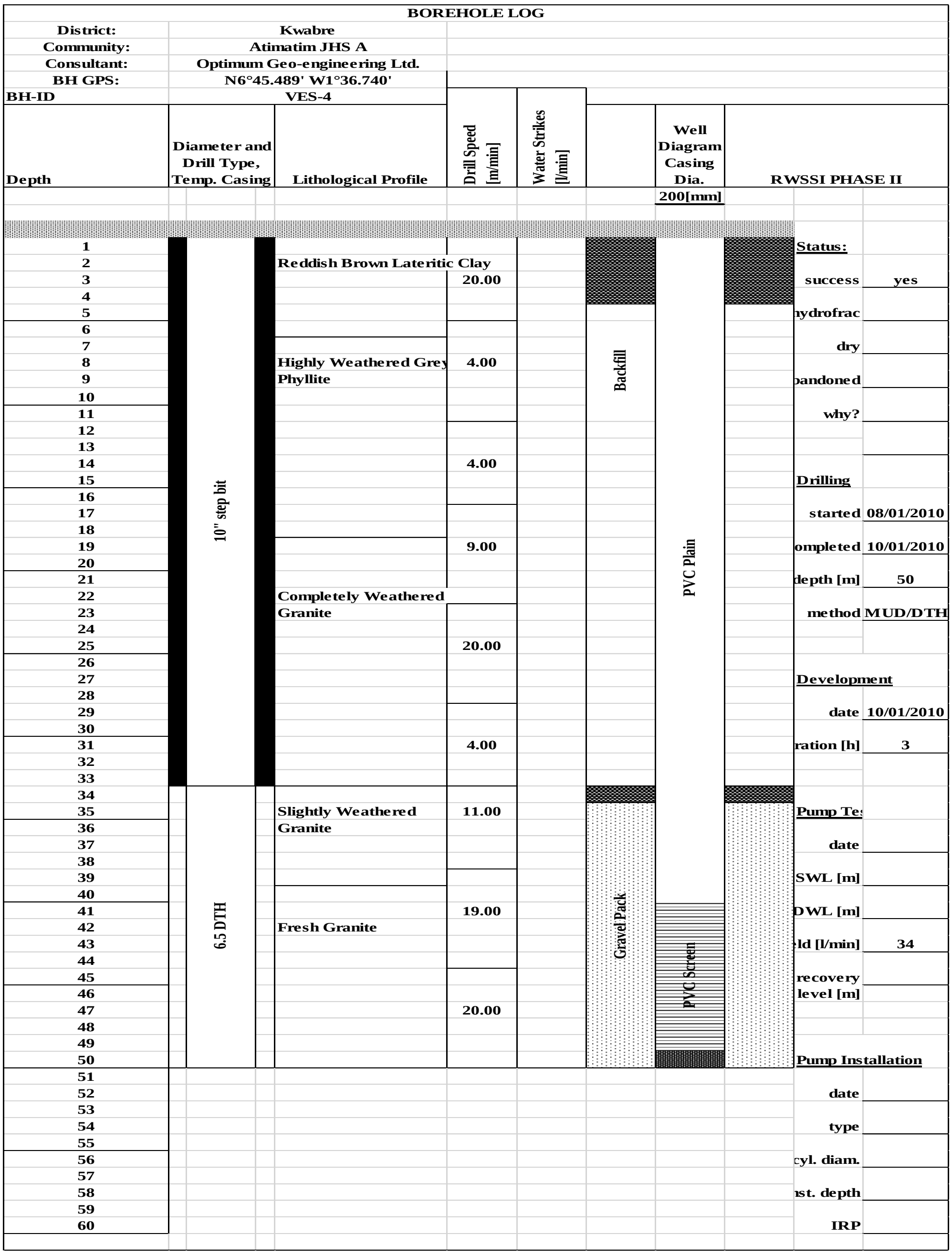



**Figure 3.2: Borehole log with borehole construction data**

Once the subsurface layers and formations are known, one can precisely pick the resistivity and thickness of the saturated zone. The thicknesses of each layer was used. The lowest resistivity value within the second and third layers and their thicknesses were used to compute longitudinal conductance and transverse resistance. Each of the electrical resistivity parameters was correlated with airlift yield to understand how the airlift yield could possibly be related to the resistivity, longitudinal conductance and transverse resistance of the area. Because the R-squared values for the third layer was higher than the second, the third layer was assumed to be the layer hosting the aquifer zone. Its results was presented in the report while the results for the second method was discarded. Low resistivity of the layer was obtained from the dipole-dipole sounding data indicated in Table 3.1. The low resistivity was picked from the sounding data by comparing the depth range of the layer (e.g. layer one, 7 - 18 m) in the log with that depth range (e.g. 7 – 18 m) on the sounding data. Within that depth range on the sounding data, the low resistivity was picked and assumed to be the resistivity of the saturated zone.

**Table 3.1: Dipole-dipole sounding data**

| | | |
|---|---|---|
| Community: Atimatim JHS A | | |
| District : Kwabre | | |
| Survey No.:VES4 | | |
| Depth (m) | App-rho | Cum-rho |
| | (ohm-m) | (ohm-m) |
| 2 | | |
| 4 | | |
| 6 | | |
| 8 | 238.41 | 238.41 |
| 12 | 404.53 | 642.94 |
| 16 | 383.30 | 1026.24 |
| 20 | 425.96 | 1452.20 |
| 25 | 476.01 | 1928.21 |
| 30 | 575.98 | 2504.19 |
| 35 | 540.30 | 3044.49 |
| 40 | 452.39 | 3496.88 |
| 45 | 426.32 | 3923.20 |
| 50 | 510.04 | 4433.24 |
| 60 | 666.16 | 5099.40 |
| 70 | 668.85 | 5768.25 |
| 80 | 741.76 | 6510.00 |
| 90 | | |
| 100 | | |

### 3.4.2 The Cumulative Resistivity Analysis

This method was done by determining the cumulative sum of resistivities from the apparent resistivities provided by the siting data. The cumulative sum resistivities were plotted against the dipole-dipole electrode spacing to obtain the cumulative resistivity curve. This was done by plotting the first point as per the value with the second point being the sum of the first and second data point respectively. A tangent line was placed across values of resistivities making up a specific layer (Fig. 3.3). The resistivity values falling within a tangent line was able to distinguish one layer from the other. The essence of the method is to determine the number of subsurface layers, the depth to each subsurface layer, and use each layer to determine the necessary parameters to be correlated. Figure 3.3 is the cumulative plot showing the number of subsurface layers.

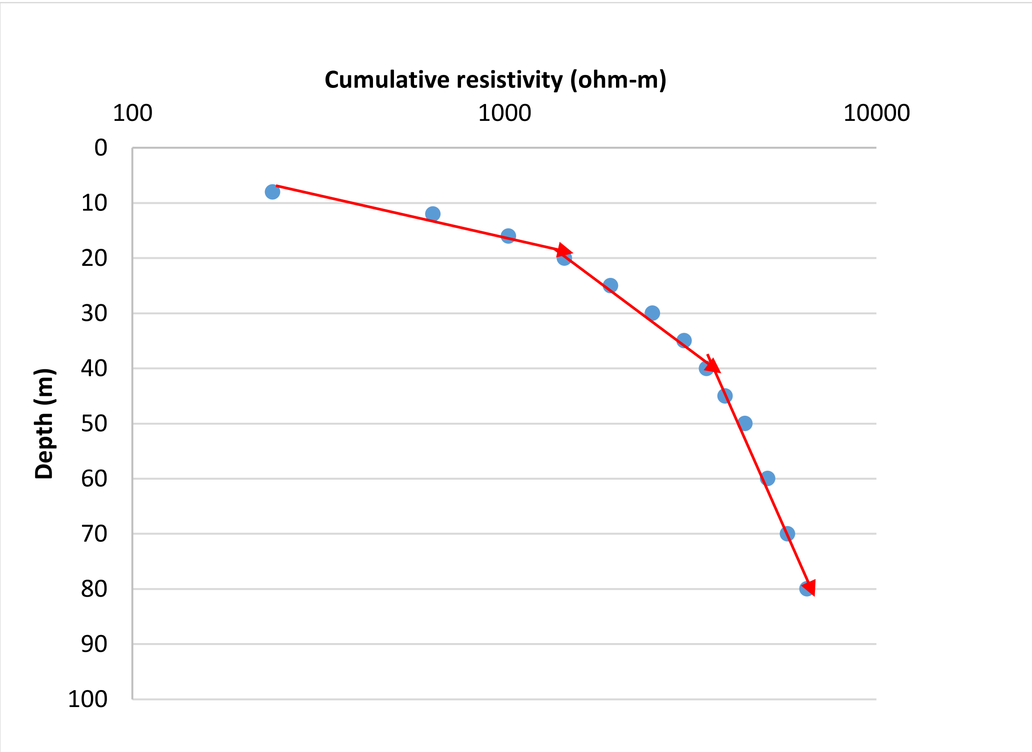



**Figure 3.3: Cumulative resistivity plot showing number of subsurface layers**

The cumulative resistivity method is based on the assumptions that equipotential hemispheres with a given radius are established around each current electrode. As the electrodes are expanded to increase the depth, the bottom of the hemispheric zones may involve layers of differing electrical resistivity, which produces a trend towards the lower or higher resistivity (Lucy et al., 2016).

From the cumulative resistivity plot, a specific depth range obtained from the top and bottom of each layer was compared to that depth range on the siting data. Within that range, the point of low resistivity was chosen as the resistivity of the saturated zone. Also, from the depth range, the thicknesses of the layers were obtained. From the resistivity and thickness of the saturated zone, longitudinal conductance and transverse resistance were computed and correlated with airlift yield.

### 3.4.3 The Drilling Rate with Respect to Formation Analysis

This was done by referencing the drill speed with respect to the penetrated formations. It is known that, based on the type of subsurface formation and the level of competence or degree of compaction of that formation, drilling may be slow or fast. Drilling rate is usually low in compacted formations or massive rock formations and high in loose, weathered and/or saturated formations. Based on this principle, the saturated zones were identified in the logs to be the zones of high drilling rate between zones of low drilling rates. For each borehole logs, layer or formation with low drilling speed at the top of the zone of high drilling speed was considered the upper confining layer while the one at the bottom was considered the lower confining beds.

Drilling rate was observed from the beginning of the second layer to the end of the third layer. The area where high drilling rate was observed between areas with low drilling rates was considered the aquifer zone. Thickness of the saturated zone was determined from the depth at which the drilling speed started to increase at the top to the depth it started to decrease at a higher depth. This depth interval was compared to similar depth range on the resistivity data, and the point of low resistivity was chosen as the resistivity of the saturated zone. The resistivity and thickness of the saturated zone from this approach were used to compute longitudinal conductance and transverse resistance, which were each correlated with the airlift yield obtained from the borehole construction data.

## 3.5 Validation

In each method, some outliers were removed from the data to improve the correlation model during the correlation. Overall, a total of 57 out of the 88 valid boreholes were used in all the correlation analysis. This is because the dry, marginal and high yielding boreholes were excluded since they mainly appeared as outliers in the analysis; most of the yield values used were in the range of 12 to 60 l/min. Each of the electrical resistivity parameters was plotted against the airlift yield, trendline was added, and equations and R-squared ($R^2$) values were displayed using Microsoft Excel. This process was repeated as the outliers were removed. The empirical relationship for each parameter against yield was changed from exponential, linear, logarithmic, polynomial, and power considering the increase in coefficients of determination ($R^2$), and the behavior of the trendlines in relation to the data. The best trendline and model were chosen based on the highest value of coefficient of determination.

Based on the coefficients of determination obtained from correlating each of the parameters with yield, using the drilling rate with respect to formation analysis, each model was validated to test its accuracy. This was done by using the generated models equations to predict the yield for comparison with measured yield values from the field. In so doing, the predicted values were plotted against the measured and a linear $45^0$ line placed between the data as the line of best fit.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 Lithological Analysis

Comparing the cumulative resistivity curves with the borehole logs, the area can be generally interpreted as a three to four region down to the depth of investigation. The layers begin with a top soil consisting of lateritic gravelly to light brownish clay, a second layer of highly to slightly weathered granitic layer and a fresh granitic third layer. In some places, few depths below the fresh granitic layer is a highly fractured granitic layer. Layer thickness is not uniform throughout the study area. It varies from one location to the other.

Resistivity of the layers varies from one site to the other, therefore, the resistivities are given as a range of values. Layer two ranges between 75 - 600 ohm-m with thicknesses between 3 - 32 m, and a 500 – 1000 ohm-m third layer with thicknesses greater than 20 m. In places where fractured granitic layers are below the fresh granitic basement rock, the fractured layer has a resistivity between of 200 – 300 ohm-m with a thicknesses between 5 - 10 m. Resistivities of the saturated zones in the area are in the range of 75 – 400 ohm. From the borehole logs, the saturated zones were identified to be in the highly to moderately weathered and fractured granitic layer.

The aquifer zone in the area is confined and varies in thickness from 6 to 7 meter respectively. The granitoid is the dominant formation in the area and, therefore, the formation that hosts the aquifer zones.

## 4.2 Generated Yield Map

Figure 4.1 is the generated map of the district indicating the distribution of the airlift yield. The yields were grouped into five classes, with borehole yielding <10 l/min being regarded as low or marginal, between 10 - 35 l/min being regarded as yields suitable for household water supply, 35 - 60 l/min and 60 – 85 l/min as yields whose boreholes could be mechanized and those greater than 85 l/min can be mechanized for community water supply. The classes are based on the regulations provided for point source boreholes and piped system where point source boreholes are fitted with hand pumps and are required to sustain a minimum yield of 10 l/min for six-hours constant pumping while the piped system requires a minimum 85 l/min during pumping test and can be mechanized and distributed to individual houses or stand pipes erected within a community (CWSA, 2010a; CWSA, 2010b).

The map shows areas like Kodie, Abuohai Newsite, Bronkong, Wawase Ahodwo, Medoma Zongo, Ahwiaa, Holy Quran School, Aboaso, etc. are located within the southwestern and central portion of the map as those producing high yields. The map shows that boreholes yielding < 10 l/min cover about 90 % of the study area, those between 10 – 35 l/min cover about 6 % of the study area, those with yield between 35 – 85 l/min cover about 3.5 % of the study area while those > 85 l/min cover about 0.5 % of the area.  The interpolation and classes show that boreholes covering about 90% of the area are suitable for household supply while the remaining 10% could be mechanized and some used for community water supply.

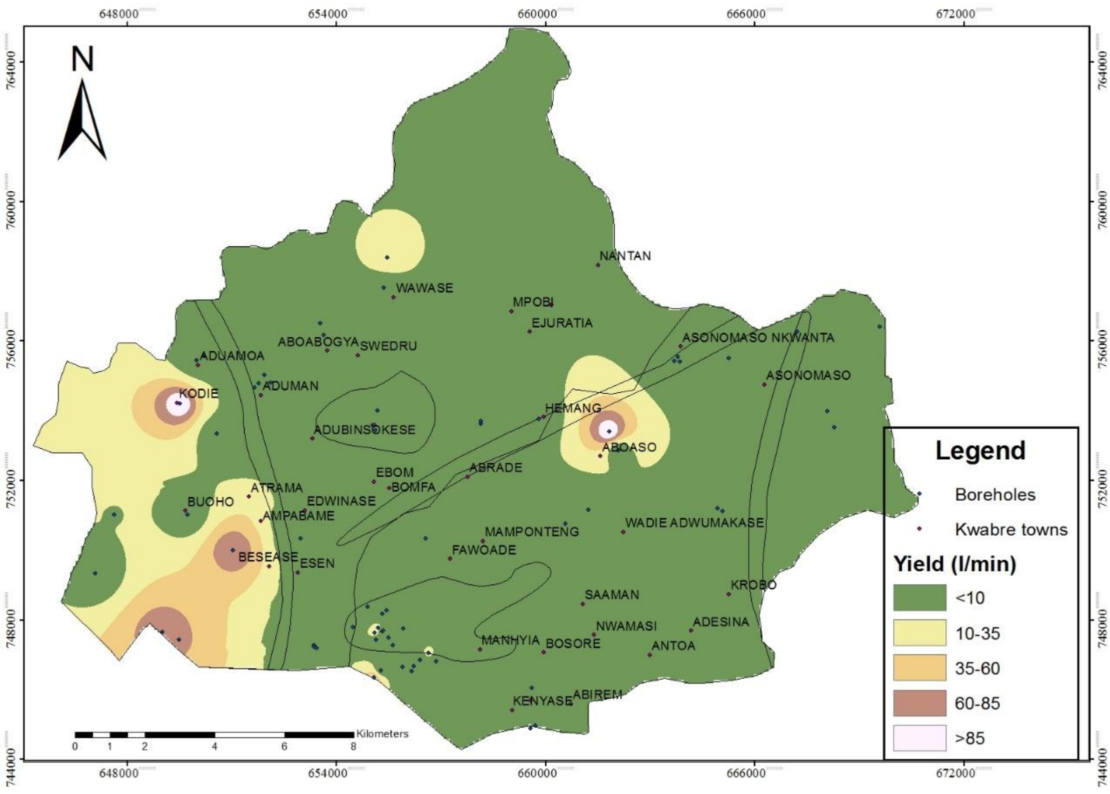



**Figure 4.1: Generated yield map of Kwabre District**

## 4.3 Airlift Yield Correlation with Electrical Resistivity Parameters

Figure 4.2 shows the results of the correlation between airlift yield and electrical resistivity parameters obtained using the Borehole log analysis method. The result shows that airlift yield is poorly related to all of the electrical resistivity parameters. The best fitted models established using logarithmic relationships gives poor coefficients of determination ($R^2$) and indicate that the models can explain about 10.5%, 9.33% and 4.04% of the variability in the data between the yield against resistivity, transverse resistance, and longitudinal conductance respectively. Thus suggesting that the models are not good for prediction.

This is based on the fact that $R^2$ is the percentage of the response variable variation that is explained by the model. 0 % indicates that the model explains none of the variability of the response variable around its mean while 100 % indicates that the model explains all the variabliity of the response data around its mean. In general, the higher the $R^2$, the better the model fits the data (Frost, 2013).

The correlation of airlift yields and electrical resistivity parameters using the cumulative resistivity method are shown in Figure 4.3. Correlation results of this method is similar to that produced by the resistivity versus lithological analysis method. The fitted models suggest that airlift yields and resistivity, longitudinal conductance, and transverse resistance have relationships of 8.09%, 4.62% and 8.86% respectively. This results suggest that very insignificant amount of variability in the data can be explained by the models. All of the coefficients of determination ($R^2$) values indicate that the models cannot be used for estimation of the yield and does not meet the objective of the research

Figure 4.4 shows the results of the correlation between airlift yields and electrical resistivity parameters obtained using the drilling rate method. The results shows there is some statistical correlation between yield and resistivity, longitudinal conductance and transverse resistance. It shows that resistivity is the major parameter that controls aquifer yield in the area followed by transverse resistance. The empirical models suggest that electrical resistivity has about 60% relationship with yield.

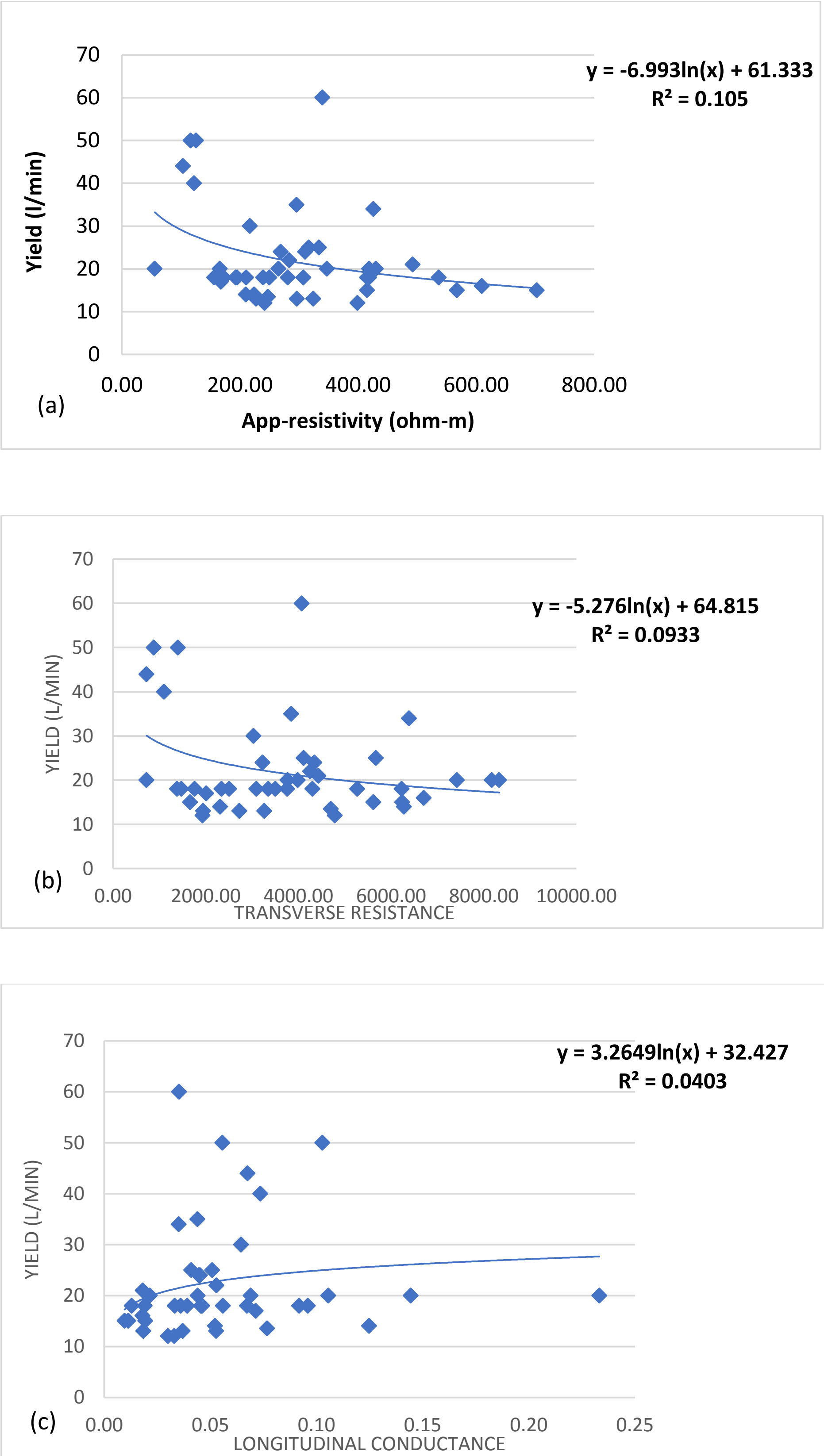
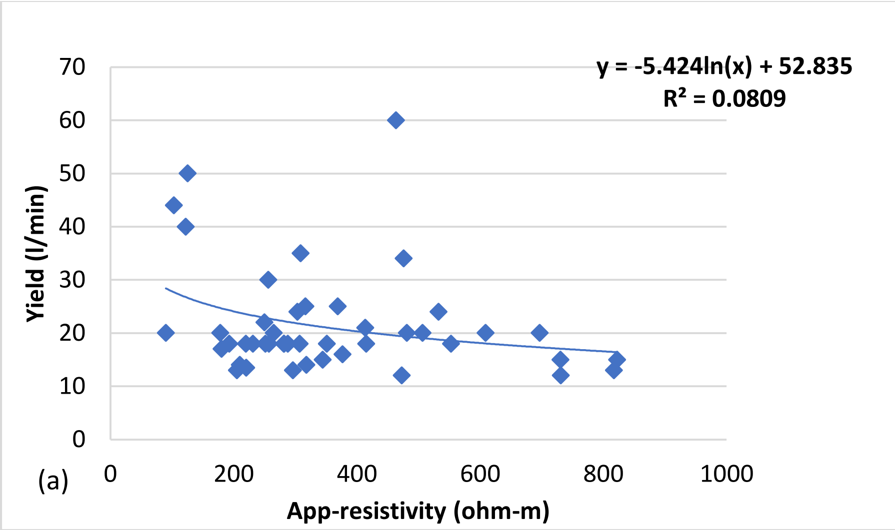
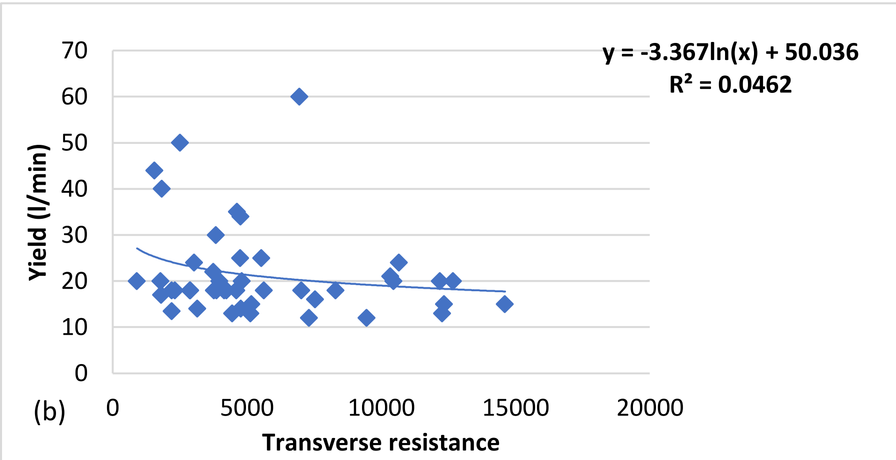



**Figure 4.2: Airlift yield versus (a) resistivity, (b) transverse resistance, and (c) longitudinal conductance for the borehole log analysis method**



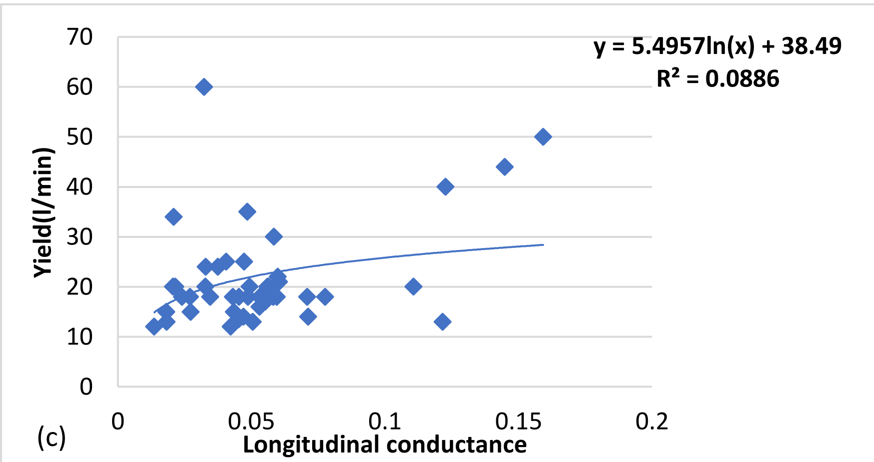




**Figure 4.3: Airlift yield with (a) resistivity, (b) transverse resistance and (c) longitudinal conductance using the cumulative resistivity method**

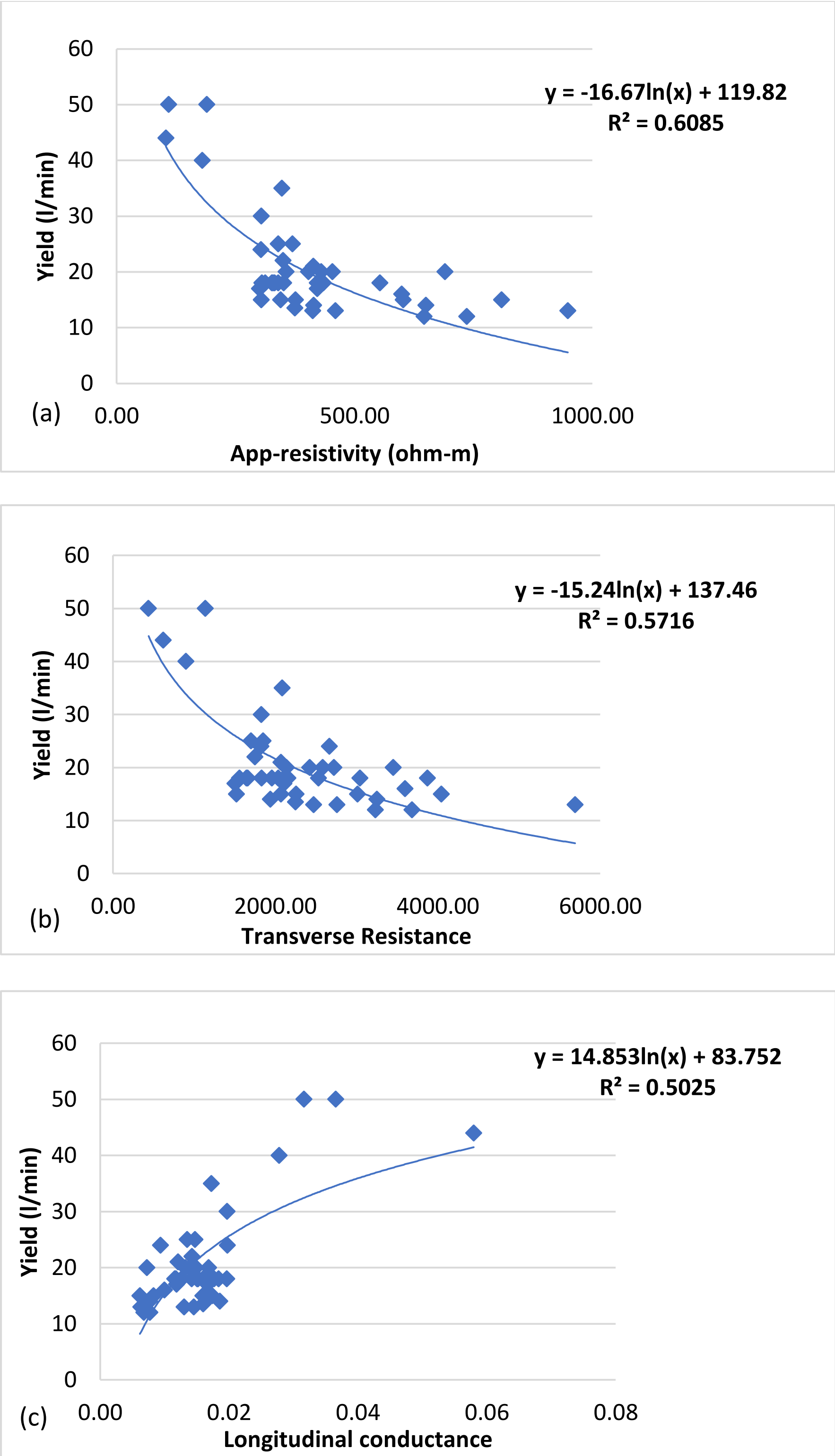



**Figure 4.4 Airlift yield correlation with (a) resistivity, (b) transverse resistance and (c) longitudinal conductance using the drilling rate analysis**

The fitted models show that yield is related to resistivity by 60.85%, yield and longitudinal conductance have 57.16% relationship, while yield and transverse resistance are related by 50.25%. Each of the models can be used to explain over 50 % of the variability in each data set. Validation of each of the models shows that the models are not good for prediction since on each of the plots, the data were far from the line of best fit. If the coefficients of determination for each module was greater than 90%, the models would have been good for prediction because the predicted and observed yield values would have fallen directly or close to the fitted line. Based on the behavior of the data with the fitted line, the established models are not good for predicting groundwater yield from electrical resistivity data.

# CHAPTER FIVE

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

Dipole-Dipole siting data, borehole logs and borehole construction data obtained from Kwabre District have been evaluated under this study with the creation of a yield distribution map. This was done by collating the data and inputting them into ArcGIS. Inverse Distance Weight (IDW) interpolation software in ArcGIS was used to create the map. This was done to understand the spatial distribution of groundwater yield in the area. The map shows that boreholes yielding < 10 l/min cover about 90 % of the study area, those between 10 – 35 l/min cover about 6 % of the study area, those with yield between 35 – 85 l/min cover about 3.5 % of the study area and those > 85 l/min cover about 0.5 % of the area.

After reviewing the borehole logs, several subsurface layers were identified with the aquifer zones being located in the highly to moderately weathered and fractured granitic layer. Resistivities of the saturated zones in the area are in the range of 75 – 400 ohm. The area is dominantly composed of granitic materials with few constituent of clay and laterite serving as overburden materials.

Results from the three methods, viz. borehole log analysis, cumulative resistivity method and the drilling rate with respect to formation analysis, used in determining the resistivity parameters (i.e. saturated zone resistivity, longitudinal conductance and transverse resistance) for correlation evaluation with the airlift yield indicate that the first two methods are not suitable for determining relationships between yield and the electrical resistivity parameters. Thus, their models cannot be used to estimate aquifer yield from electrical resistivity data. The last method, on the other hand, showed that each of the resistivity parameters has some correlation with the yield and their fitted models had $R^2$ values of more than 50%. However, validation results from the associated models suggested that they were not good enough for predicting the yield.

## 5.2 Recommendations

Out of the three methods used, the results from the drilling rate with respect to formation analysis showed that some relationships exist between the yield and electrical resistivity, longitudinal conductance and transverse resistance but the validation results showed that models are not good for prediction. Therefore, it is recommended that this method be explored further to realize its potential.

Secondly, further studies could be done using other approaches to explore whether a better relation could be established between the aquifer yield and the electrical resistivity parameters. In doing so, accurate airlift yield and resistivity data should be used since there were some challenges with the accuracy of the data employed in this study.

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# APPENDIX

Table A1: Resistivity versus lithological analysis

| YIELD (l/min) | Resistivity (ohm-m) | Transverse resistance = hρ | Longitudinal conductance = h/ρ |
|---|---|---|---|
| 50 | 125.60 | 879.22 | 0.06 |
| 13.5 | 247.59 | 4704.19 | 0.08 |
| 15 | 415.52 | 1662.09 | 0.01 |
| 17 | 167.93 | 2015.11 | 0.07 |
| 20 | 55.73 | 724.49 | 0.23 |
| 18 | 195.43 | 1758.88 | 0.05 |
| 18 | 239.50 | 5269.00 | 0.09 |
| 18 | 210.46 | 1473.19 | 0.03 |
| 18 | 307.49 | 4304.90 | 0.05 |
| 18 | 419.08 | 3352.62 | 0.02 |
| 18 | 537.06 | 3759.41 | 0.01 |
| 20 | 166.21 | 3988.94 | 0.14 |
| 13 | 296.75 | 3264.22 | 0.04 |
| 44 | 103.49 | 724.42 | 0.07 |
| 14 | 224.24 | 6278.69 | 0.12 |
| 18 | 415.55 | 6233.18 | 0.04 |
| 34 | 425.96 | 6389.42 | 0.04 |
| 15 | 567.48 | 6242.23 | 0.02 |
| 13 | 324.29 | 1945.71 | 0.02 |
| 24 | 310.46 | 4346.45 | 0.05 |
| 12 | 241.89 | 1935.12 | 0.03 |
| 35 | 296.07 | 3848.96 | 0.04 |
| 40 | 122.26 | 1100.30 | 0.07 |
| 20 | 347.37 | 8336.86 | 0.07 |
| 18 | 172.87 | 1382.94 | 0.05 |
| 13 | 227.51 | 2730.10 | 0.05 |
| 50 | 116.65 | 1399.82 | 0.10 |
| 30 | 216.85 | 3035.96 | 0.06 |
| 60 | 339.60 | 4075.24 | 0.04 |
| 25 | 333.85 | 5675.48 | 0.05 |
| 25 | 316.67 | 4116.74 | 0.04 |
| 20 | 265.18 | 7424.93 | 0.11 |
| 20 | 430.32 | 8176.08 | 0.04 |
| 18 | 193.09 | 2510.20 | 0.07 |
| 18 | 281.15 | 3092.61 | 0.04 |
| 18 | 156.33 | 2344.94 | 0.10 |
| 22 | 283.68 | 4255.14 | 0.05 |
| 16 | 609.78 | 6707.55 | 0.02 |
| 14 | 210.43 | 2314.75 | 0.05 |
| 18 | 250.08 | 3501.15 | 0.06 |
| 21 | 492.81 | 4435.28 | 0.02 |
| 15 | 702.72 | 5621.74 | 0.01 |
| 20 | 418.85 | 3769.63 | 0.02 |
| 12 | 399.25 | 4791.02 | 0.03 |
| 24 | 269.02 | 3228.20 | 0.04 |

Table A2: Cumulative resistivity versus borehole logs analysis

| Yield (l/min) | Resistivity (ohm-m) | Thickness (m) | Longitudinal Conductance = hρ | Transverse Resistance = h/ρ |
|---|---|---|---|---|
| 50 | 125.60 | 20.00 | 0.16 | 2512.06 |
| 14 | 220.71 | 10.00 | 0.05 | 2207.08 |
| 15 | 344.73 | 15.00 | 0.04 | 5170.97 |
| 17 | 180.91 | 10.00 | 0.06 | 1809.07 |
| 20 | 90.27 | 10.00 | 0.11 | 902.72 |
| 18 | 220.09 | 10.00 | 0.05 | 2200.90 |
| 18 | 251.89 | 15.00 | 0.06 | 3778.34 |
| 18 | 257.58 | 15.00 | 0.06 | 3863.63 |
| 18 | 307.49 | 15.00 | 0.05 | 4612.40 |
| 18 | 553.25 | 15.00 | 0.03 | 8298.68 |
| 18 | 351.43 | 20.00 | 0.06 | 7028.54 |
| 20 | 178.40 | 10.00 | 0.06 | 1783.98 |
| 13 | 296.75 | 15.00 | 0.05 | 4451.21 |
| 44 | 103.49 | 15.00 | 0.14 | 1552.32 |
| 14 | 318.21 | 15.00 | 0.05 | 4773.21 |
| 18 | 415.55 | 10.00 | 0.02 | 4155.45 |
| 34 | 476.01 | 10.00 | 0.02 | 4760.11 |
| 15 | 822.83 | 15.00 | 0.02 | 12342.47 |
| 13 | 817.78 | 15.00 | 0.02 | 12266.63 |
| 24 | 303.64 | 10.00 | 0.03 | 3036.40 |
| 12 | 731.27 | 10.00 | 0.01 | 7312.66 |
| 35 | 308.95 | 15.00 | 0.05 | 4634.25 |
| 40 | 122.26 | 15.00 | 0.12 | 1833.83 |
| 20 | 609.39 | 20.00 | 0.03 | 12187.84 |
| 18 | 231.71 | 10.00 | 0.04 | 2317.13 |
| 13 | 205.51 | 25.00 | 0.12 | 5137.85 |
| 30 | 256.37 | 15.00 | 0.06 | 3845.51 |
| 60 | 463.61 | 15.00 | 0.03 | 6954.09 |
| 25 | 369.37 | 15.00 | 0.04 | 5540.48 |
| 25 | 316.67 | 15.00 | 0.05 | 4750.08 |
| 20 | 265.18 | 15.00 | 0.06 | 3977.64 |
| 20 | 506.79 | 25.00 | 0.05 | 12669.80 |
| 20 | 481.44 | 10.00 | 0.02 | 4814.44 |
| 18 | 193.09 | 15.00 | 0.08 | 2896.38 |
| 18 | 288.35 | 10.00 | 0.03 | 2883.54 |
| 18 | 281.73 | 20.00 | 0.07 | 5634.62 |
| 22 | 250.39 | 15.00 | 0.06 | 3755.90 |
| 16 | 376.99 | 20.00 | 0.05 | 7539.80 |
| 14 | 210.43 | 15.00 | 0.07 | 3156.48 |
| 18 | 282.19 | 15.00 | 0.05 | 4232.78 |
| 21 | 413.71 | 25.00 | 0.06 | 10342.75 |
| 15 | 730.53 | 20.00 | 0.03 | 14610.60 |
| 20 | 697.11 | 15.00 | 0.02 | 10456.61 |
| 12 | 473.08 | 20.00 | 0.04 | 9461.50 |
| 24 | 533.10 | 20.00 | 0.04 | 10662.04 |

Table A3: Drilling rate analysis

| Borehole Id | Yield (l/Min) | Resistivity (Rho) | Sat-Thickness (m) | Longitudinal Conductance = h/ρ | Transverse Resistance = hρ |
|---|---|---|---|---|---|
| VES-7 | 50 | 189.69 | 6 | 0.03 | 1138.16 |
| VES-2 | 13.5 | 374.62 | 6 | 0.02 | 2247.70 |
| VES-9 | 15 | 344.73 | 6 | 0.02 | 2068.39 |
| VES-5 | 17 | 300.48 | 5 | 0.02 | 1502.41 |
| VES-7 | 20 | 403.64 | 6 | 0.01 | 2421.86 |
| VES-1 | 18 | 430.94 | 5 | 0.01 | 2154.68 |
| VES-6 | 18 | 434.71 | 7 | 0.02 | 3042.98 |
| VES-3 | 18 | 339.48 | 6 | 0.02 | 2036.85 |
| VES-2 | 18 | 331.97 | 5 | 0.02 | 1659.86 |
| VES-4 | 18 | 553.25 | 7 | 0.01 | 3872.72 |
| VES-2 | 18 | 351.43 | 6 | 0.02 | 2108.56 |
| VES-1 | 13 | 460.00 | 6 | 0.01 | 2760.00 |
| VES-3 | 44 | 103.49 | 6 | 0.06 | 620.93 |
| VES-2 | 14 | 414.00 | 6 | 0.02 | 1940.06 |
| VES-1 | 18 | 326.38 | 6 | 0.02 | 1958.30 |
| VES-2 | 15 | 809.07 | 5 | 0.01 | 4045.34 |
| VES-2 | 13 | 948.28 | 6 | 0.01 | 5689.68 |
| VES-3 | 24 | 303.64 | 6 | 0.02 | 1821.84 |
| VES-4 | 12 | 646.50 | 5 | 0.01 | 3232.50 |
| VES-2 | 35 | 347.57 | 6 | 0.02 | 2085.40 |
| VES-5 | 40 | 180.02 | 5 | 0.03 | 900.09 |
| VES-4 | 20 | 690.39 | 5 | 0.01 | 3451.96 |
| VES-1 | 18 | 424.81 | 5 | 0.01 | 2124.03 |
| VES-2 | 13 | 412.17 | 6 | 0.01 | 2472.99 |
| VES-5 | 50 | 109.44 | 4 | 0.04 | 437.74 |
| VES-3 | 30 | 304.29 | 6 | 0.02 | 1825.73 |
| VES-2 | 15 | 304.17 | 5 | 0.02 | 1520.87 |
| VES-2 | 25 | 369.85 | 5 | 0.01 | 1849.23 |
| VES-8 | 25 | 339.85 | 5 | 0.01 | 1699.23 |
| VES-7 | 20 | 453.37 | 6 | 0.01 | 2720.20 |
| VES-3 | 20 | 430.32 | 6 | 0.01 | 2581.92 |
| VES-5 | 18 | 312.17 | 5 | 0.02 | 1560.83 |
| VES-1 | 18 | 305.21 | 6 | 0.02 | 1831.24 |
| VES-1 | 15 | 376.21 | 6 | 0.02 | 2257.26 |
| VES-2 | 18 | 421.68 | 6 | 0.01 | 2530.06 |
| VES-2 | 22 | 350.12 | 5 | 0.01 | 1750.59 |
| VES-6 | 16 | 599.53 | 6 | 0.01 | 3597.15 |
| VES-2 | 14 | 650.17 | 5 | 0.01 | 3250.87 |
| VES-3 | 18 | 329.21 | 5 | 0.02 | 1646.07 |
| VES-6 | 21 | 413.71 | 5 | 0.01 | 2068.55 |
| VES-9 | 15 | 602.28 | 5 | 0.01 | 3011.40 |
| VES-3 | 17 | 421.58 | 5 | 0.01 | 2107.92 |
| VES-3 | 20 | 356.14 | 6 | 0.02 | 2136.85 |
| VES-2 | 12 | 736.33 | 5 | 0.01 | 3681.66 |
| VES-2 | 24 | 533.10 | 5 | 0.01 | 2665.51 |

Table A4 Validation data set

| YIELD & RES. MODULE | | | YIELD & SC. MODULE | | | YIELD & TR. MODULE | | |
|---|---|---|---|---|---|---|---|---|
| **SAT-RESISTIVITY** | **Observed** | **Predicted** | **Sc** | **Observed** | **Predicted** | **Tr** | **Observed** | **Predicted** |
| **226.346** | 15 | 29.43 | 0.03 | 15 | 29.83 | 1358.08 | 15 | 27.52 |
| **224.825** | 20 | 29.55 | 0.03 | 20 | 29.93 | 1348.95 | 20 | 27.62 |
| **128.796** | 18 | 38.83 | 0.05 | 18 | 38.21 | 772.78 | 18 | 36.11 |
| **575.979** | 34 | 13.86 | 0.01 | 34 | 13.25 | 2879.90 | 34 | 16.07 |
| **194.155** | 16 | 31.99 | 0.03 | 16 | 32.11 | 1164.93 | 16 | 29.86 |
| **642.75** | 26 | 12.04 | 0.01 | 26 | 14.33 | 3856.50 | 26 | 11.62 |
| **608.634** | 30 | 12.95 | 0.01 | 30 | 15.14 | 3651.80 | 30 | 12.45 |
| **579.275** | 40 | 13.77 | 0.01 | 40 | 13.17 | 2896.38 | 40 | 15.98 |
| **390.579** | 35 | 20.34 | 0.02 | 35 | 21.73 | 2343.47 | 35 | 19.21 |
| **401.63** | 13 | 19.87 | 0.01 | 13 | 18.61 | 2008.17 | 13 | 21.56 |
| **323.34** | 14 | 23.49 | 0.02 | 14 | 25.65 | 1940.06 | 14 | 22.09 |