

**BOREHOLE YIELD ESTIMATION FROM ELECTRICAL
RESISTIVITY MEASUREMENTS – A CASE STUDY OF
GARU TEMPANE AND BAWKU WEST DISTRICTS,
UPPER EAST REGION, GHANA**

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fulfilment of requirements for the award of the degree of

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CERTIFICATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any other educational institution, except where due acknowledgement is made in the thesis.

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ABSTRACT

Electrical resistivity survey has proven to be an effective tool for groundwater exploration and has been widely embraced to help reduce the drilling of unsuccessful wells. Currently, information from electrical resistivity survey is often used in locating points for drilling, but it does not give indication of the yield of the borehole. The lack of this information therefore sometimes results in the drilling of dry and marginal wells. This study therefore looks at the possibility of using resistivity data, which is readily available from electrical resistivity surveys for groundwater exploration, for estimating the yield of yet to be drilled borehole. The study was limited to the Garu Tempane and Bawku West districts. Secondary data on vertical electrical sounding (VES) and drill logs for 49 boreholes in the selected districts were used. The thicknesses, apparent resistivities, longitudinal conductance and transverse resistance of the various subsurface layers of the boreholes were determined from drill logs and VES data. Correlations between borehole yields and the third layer apparent resistivity, longitudinal conductance and transverse resistance were then investigated to develop regression models for estimation of the borehole yields. The results showed that the third layer is fractured and contributes significantly to borehole yields in the area; hence the fractured subsurface layer is of primary interest to be considered in groundwater exploration and estimating potential borehole yield from VES data. The results obtained further indicated that apparent resistivity, longitudinal conductance and transverse resistance had good exponential and positive linear relationships with borehole yield.

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LIST OF ABBREVIATIONS AND ACRONYM

AC	Alternating Current
BW	Bawku West
C1 and C2	Current electrodes
CUM	Cumulative
DC	Direct Current
G	Accumulated Groundwater
GI-WASH	Ghana Integrated-Water, Sanitation and Hygiene
GPS	Global Positioning System
GT	Garu Tempane
I	Electrical Intensity
K	Permeability of an aquifer
LC	Longitudinal Conductance
Oe	Effective Porosity
P1 and P2	Potential Electrodes
PA	Apparent Resistivity
pH	Power of hydrogen
R ²	Correlation Coefficient
TR	Transverse Resistance
UER	Upper East Region
V1 and V2	Potential Electrodes
VES	Vertical Electrical Sounding
ΔV	Potential Difference
Y	Groundwater Yield

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CHAPTER 1: INTRODUCTION

1.1 Background

The high cost associated with borehole drilling has necessitated for extensive detailed subsurface investigation before selected sites are chosen for eventual drilling to reduce the number of unsuccessful wells. Electrical resistivity survey has demonstrated to be an effective means for groundwater exploration. Geophysical methods application has commonly proved to be highly effective for water content estimation and locating of the depth to water table and bedrock (Hubbard and Rubin, 2002). Successes have also been attained using the resistivity method for siting wells in areas underlain by crystalline rock terrains (Ballukraya, 2001; Gupta *et al.*, 2000; Patangay *et al.*, 1977; Satpathy and Kanungo, 1976). Mazac *et al.* (1985) assessed the correlation between aquifer and geoelectrical parameters in both the saturated and unsaturated zones of the aquifers. VES is ideal for ascertaining the depth, thickness, and boundary of an aquifer (Zohdy, 1969; Young *et al.*, 1998) and the water content of aquifer (Kessels *et al.*, 1985). But still dry and marginal wells are recorded even after groundwater investigations are conducted. There is therefore the need to augment the groundwater investigation to improve the success of drilled holes and to cut down the cost of drilling unsuccessful wells.

Garu Tempane and Bawku West districts are two districts with serious water challenges in Upper East region. The districts rely mostly on dugouts, dams, hand-dug wells and some boreholes for their water supply needs. The preferred water supply alternative in the area is groundwater because it is usually present even in drought situations and of comparatively good quality. The groundwater is not only viable but also the most cost effective means of potable water for these rural and scattered settlements (Gyau-Boakye and Dapaah-Siakwan, 1999).

Although boreholes have been drilled to complement surface water supplies in Garu Tempane and Bawku West districts, some of these boreholes have been abandoned as a result of low yields. Conventionally, the yield of a borehole is determined after drilling and carrying out pumping test. The borehole is declared unsuccessful and abandoned if the yield is below 13 liters per minute according to Community Water and Sanitation Agency (CWSA, 2014) standard.

Hence it would be beneficial for the yield of an intended borehole to be estimated from electrical resistivity data obtained from geophysical exploration survey which is conducted to aid in selecting drilling sites. This would help to reduce the drilling of dry and marginal wells.

This study therefore explores the possibility of estimating borehole yield from electrical resistivity data by developing models relating borehole yield to electrical resistivity parameters. The resultant models will, hopefully, help to improve on selection of potential sites for drilling and reduce the drilling of unsuccessful wells. This will enable the limited financial resources in developing countries to be channelled into providing boreholes with substantial yields.

1.2 Research Objective

The primary objective of the study is to investigate the possibility of estimating borehole yield from sub surface electrical resistivity data in Garu Tempane and Bawku West districts in Upper East Region of Ghana. The specific objectives of the study are:

- To assess the relationship between individual subsurface layer apparent resistivities and borehole yield within the study area.
- To determine the relationship between longitudinal conductance and borehole yield.
- To determine the relationship between transverse resistance and borehole yield.
- To assess the reliability of estimating borehole yield from individual layer apparent resistivities, longitudinal conductance and transverse resistance.

1.3 Scope of the thesis

The study is limited to Garu Tempane and Bawku West districts. Basically secondary VES data, drill logs and air lift yield of boreholes in these two districts were acquired for the study. Thicknesses and apparent resistivities of various subsurface layers were determined using drill logs alone first and secondly from the VES data. Longitudinal conductance and transverse resistance were the main electrical

properties focused on. Correlation relationships between the borehole yield and the third layer apparent resistivity, longitudinal conductance and transverse resistance were investigated. Regression models were developed and used to estimate yield in these two districts.

The thesis comprises of five chapters. Chapter one is the background of the thesis, research objectives and scope of the study. Chapter Two deals with review of literature and study area focusing on: crystalline bedrock aquifers, groundwater storage and flow in basement complex rocks and relations between electrical resistivity and yield. Chapter Three describes data acquisition and the methods used in the study. Chapter Four presents and discusses the results from the study. Finally, Chapter Five presents the conclusions and recommendations on results of the study.

CHAPTER 2: LITERATURE REVIEW

2.1 Groundwater Storage, Yield and Flow in Basement Complex rocks

Basement bedrock (hard rock) aquifer refers to igneous or metamorphic rocks such as granites, basalts, metaquartzites or gneisses. The intergranular pore spaces in such rocks are insignificant and all groundwater flow usually takes place through the cracks and fractures in these rocks (Banks and Robin, 2002). The presence of groundwater in areas underlain by mainly impermeable basement igneous and metamorphic rocks is usually as a result of the development of secondary porosity and permeability resulting from weathering and fracturing (Olayinka, 1992).

Rocks have distinct porosity and permeability qualities, which mean that water does not flow in similar way in all rocks beneath the ground surface because of these varying characteristics. An aquifer is a geological formation that stores and transmits water to wells, springs and streams. Wells can be drilled into these aquifers and water can be pumped out from them. Precipitation adds water (recharge) into the porous rock of the aquifer. The recharge rate is not similar for all aquifers and this must be taken into consideration when pumping water from a well (U.S Geological Survey Water Science School, 2016). Too much pumping of water quickly draws down the water level in the borehole and causes a well to yield less and less water and eventually run dry. Actually, pumping a well too much can even cause a neighbour's well to run dry if both boreholes are pumping from the same aquifer.

The availability of joints and fractures within the bedrock may lead to the development of a high permeability which can supplement a productive well. The groundwater in Basement rocks are used as a supplement to surface water for domestic and industrial uses. The fractured and or saturated weathered zones constitute the prime aquifer unit (Satpathy and Kanungo, 1976; Olorunniwo and Olorunfemi, 1987). The clayey sand horizon overlying the weathered section may also contain considerable quantity of groundwater.

A much asked question is will a borehole always have the same yield continually over time? The answer is "No". The water yield may vary depending on the time of the year, the number of new boreholes in the neighbourhood, the annual rainfall

changes and the local effects of transpiration (Hose Solutions, 2010). It is for these reasons that very large safety margins are admitted when installing the correct pumping systems. Groundwater is a very valuable natural resource and hence should not be wasted. Pumping test is a controlled experiment in which a borehole (well) is pumped at a controlled rate and water-level response (draw down) is measured (U.S Geological Survey Water Science School, 2016). It is important to determine a borehole yield for many reasons: to establish the safe yield of the borehole and to determine the borehole safe yield duty period that it can be operated indefinitely, without endangering the aquifer (U.S Geological Survey Water Science School, 2016).

The groundwater volume (G) within the weathered/fractured zone is dependant on the effective porosity (O_e) of the aquifer (from equation 1). The groundwater yield (Y) is a function of the amassed groundwater volume (G) and the permeability of an aquifer (K) (from equation 2). Both G and K are dependant on porosity; hence logically Y is indirectly related to effective porosity (O_e) (from equation 3) (Olorunfemi *et al.*, 1991).

$$G = f(O_e) \quad (1)$$

$$Y = f(G + K) \quad (2)$$

$$Y = f(O_e) \quad (3)$$

2.2 Electrical Resistivity Survey

Usually, measuring the resistivities of subsurface strata requires four electrodes. An electrical current of intensity I is introduced between a pair of electrodes, referred to as current electrodes. These current electrodes may be identified as C1 and C2 (also as A and B and sometimes as +I and –I representing source and sink respectively) (Reynolds, 2011).

The potential difference generated as a result of the current flow is measured with the aid of another pair of electrodes called potential electrodes or probes. The potential electrodes may be denoted as P1 and P2 (or as M and N and sometimes as V1 and

V2). Given the potential difference as ΔV , the apparent resistivity (ρ) measured can be calculated by:

$$\rho = G * (\Delta V/I) \quad (4)$$

Where G signifies a geometric factor or configuration constant in the expression. There are a number of electrode arrays which are in use and they have relative advantages and disadvantages. Some of the well-known electrode arrays are presented in section 2.2.1.

The instruments needed for the resistivity surveys include the following (Reynolds, 2011):

- (a) A power source
- (b) Resistivity meters to measure current and potential or a combination to read resistance directly
- (c) Electrodes and
- (d) Cable

The power may be Direct Current (DC) or low frequency Alternating Current (AC). The use of DC power is desirable for the measurement of DC resistivity. The DC measurements have certain difficulties and necessary precautions have to be taken (Reynolds, 2011). The first is the use of non-polarizing electrodes. When the metal electrodes come in contact with the ground, they produce potential because of the moisture in the ground acting as electrolyte.

The other factor that affects the DC resistivity measurement is the self-potential (SP). There may exist some potential difference between the points on the ground because of mineralization potentials, potentials created due to fluid streaming, varying electrolytic concentrations in ground water, geochemical actions and telluric fields. To eliminate the influence of this unidirectional SP effect on resistivity measurements, it is either noted first before switching on the power or subtracted from the potential reading or it is compensated. The DC polarity should be reversed (commutated periodically either by a mechanical commutator or with an electronic device). In this process, the metal to solution potential (self-potentials) which are usually unidirectional during short time interval get cancelled in measurement,

because the readings get average during positive and negative cycles. The use of alternative or commutated current eliminates the use of non-polarizing electrodes and SP compensating system and also offers advantage of amplification of signal by use of narrow band tuned amplifiers to get high signal to noise ratio.

2.2.1 Electrode Configurations

In general, the electrode arrangements have been named after the persons who originally proposed the arrangement or by denoting the essential features in the arrangement (Reynolds, 2011). The arrangements may be classified broadly into two categories:

- (1) Those in which all the four electrodes are positioned in a straight line, for example, Wenner, Schlumberger , etc. and
- (2) Those in which the pairs of current and potential electrodes are separated and four electrodes are not necessarily along a straight line, for example Dipole-Dipole system.

The choice of array in the field is dependent on:

- The data type required. For example, the location of only a target, or if it is necessary to characterize the target details.
- The sort of model (either 1D, 2D, or 3D) most likely to be used for interpretation.
- The economics of the condition. Since wires must be connected to all electrodes, and the electrodes must be firmly fixed in the ground, surveys covering large areas in cumbersome ground with hard or gravelly surface materials can become very costly.

Several three dimensional array types exist, in which electrodes are not in line. Examples include:

- Equatorial dipole-dipole array which is used mainly for very shallow work such as archaeological probes.
- Twin probe configuration (a Wenner Gamma essentially, but with a separation more like dipole-dipole) is used primarily for very shallow probes such as archaeological work.

- The E-Scan method is a pole-pole configuration. However, it is organized by placing firmly a large number of electrodes over the whole zone of interest, without attempting to stay on a grid or on lines. Measured potentials are taken at all electrodes and one is used as a current source. A new electrode then turns a current source, and all potentials are recorded. Once an electrode is used as a source, it is never used again. This large data set should be inverted so as to obtain interpretable information. The E-Scan technique is costly but it has been employed in the exploration for geothermal energy and mineral exploration.

Several other proprietary or experimental electrode array types are also designed for 3D interpretation. Azimuthal arrays are used to probe the horizontal electrical anisotropies near the surface. Electrode configurations are most often one of the linear configurations (Wenner, dipole-dipole, etc.). Rather than moving the array along a line (profiling), or spreading it about a central point (sounding), the array is rotated about a central location so that resistivity as a function of azimuthal direction can be plotted.

Figure 1 shows some of the configurations (arrays) which are mostly used:

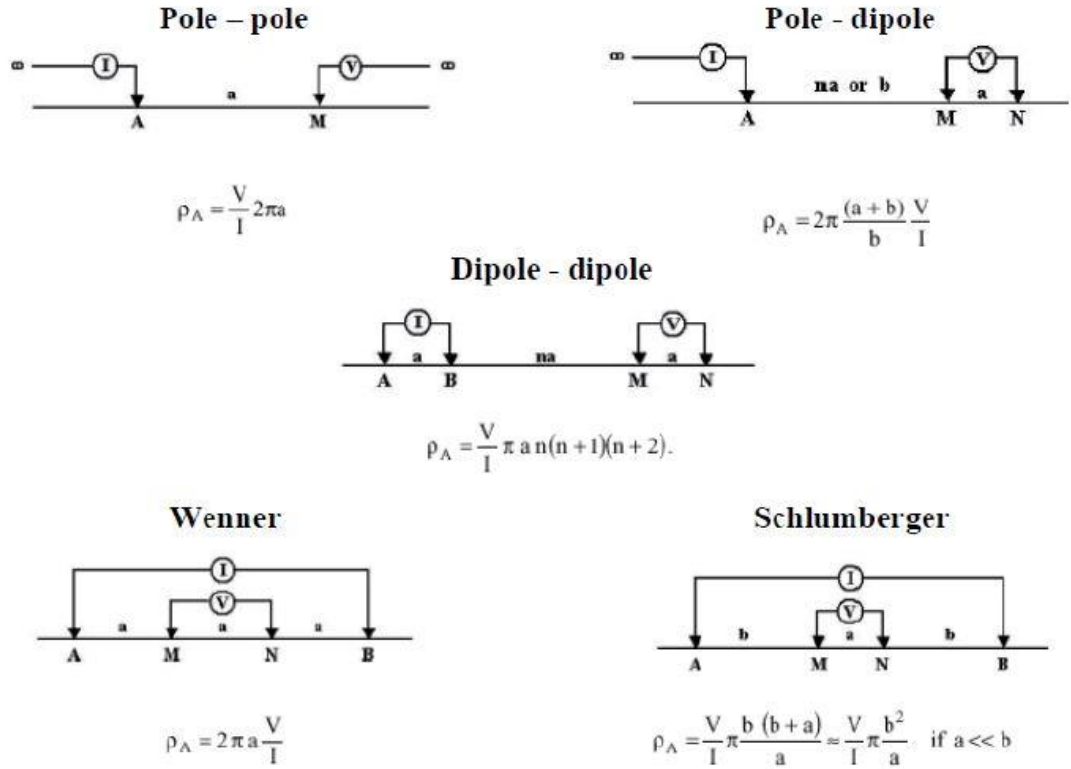


Figure 1: Electrode arrays for resistivity surveys

Some advantages and disadvantages of these different electrode arrays are presented by Ward (1990) and Shendi (2008). The dipole-dipole is the commonest profiling configuration in which numerous potential measurements are recorded for each transmitter station. The spacing between the current source and the potential dipole can be expanded virtually indefinitely, being affected only by instrumental sensitivity and noise whereas the increase of electrode separation in the Wenner and Schlumberger arrays is restricted by cable lengths. It measures the largest anomalies as compared to other array types, but has low signal-to-noise ratio which restricts its application. It has good lateral resolution. Pole-Dipole as compared to dipole-dipole is more effective (as only one source electrode is moved), has deeper penetration, but lower spatial resolution. Pole-Pole is relatively more efficient, but has lower spatial resolution and penetrates much deeper in comparison to pole-dipole. Gradient array provides insufficient depth information nevertheless rapid reconnaissance of large areas comparatively to the other arrays.

Schlumberger's distance "a" is one tenth of distance "b". During soundings, "b" can remain constant, provided $a \ll b$, and measured potentials are powerful enough to record. It is less sensitive to lateral variations in resistivity due to the effect of near surface inhomogeneity in their vicinity. It is slightly faster in field operation and requires less physical movement of electrodes than the normal Wenner array since only the current electrodes must be moved between readings. The potential electrodes only occasionally moved, while in a Wenner sounding the potential and the current electrodes are moved after every recording. In Wenner the three distances between electrodes remain the same for all measurements taken. During soundings all electrodes must be moved for every fresh datum. Wider spacing of the potential electrodes with Wenner results in larger potential differences. This translates into less severe instrumentation requirements for a given depth capability.

2.2.2 Vertical Electrical Sounding (VES)

In resistivity sounding, resistivity variation with depth is investigated. In this, the center of the configuration is kept fixed and the measurements are made by successively increasing the electrode spacing (Reynolds, 2011). The values of apparent resistivities (measured in ohm-meters) along with the depths at which the measurements are taken are recorded. The recorded apparent resistivity values with increasing values of electrode spacing are used to appraise the thicknesses and resistivities of the subsurface formation. Through this, the measured resistance values at the surface mirror the vertical distribution of resistivity values in a geological section. The apparent resistivity is then plotted against the depth.

In dipole-dipole arrays, 4 electrodes (A, B, M and N) are placed on the ground, with A, B on one side and M, N on another side, each pair having a constant mutual separation (a) as shown in figure 1. Electric current is passed between current electrodes and voltage between potential electrodes measured. Voltage, current and separation distance (na) is recorded. With the (a) spacing remaining constant, increase the separation between the electrode pairs about a fixed center. The configuration factor is $\pi n(n+1)(n+2)a$ and the apparent resistivity can be obtained as (Reynolds, 2011):

$$\rho_a = \pi n(n+1)(n+2)a \times \Delta V/I \quad (5)$$

Where (a_n) is the distance between the two innermost electrodes, one current electrode and the other potential electrode.

2.3 Electrical Resistivity and Groundwater Yield

Geophysical surveys can furnish information on the depth to bedrock, alterations in subsurface layering and lithology, the extent of saturation and porosity of the regolith and the places of steeply dipping structures such as faults and dykes. The factors which influence the electrical resistivity of rocks include the amount and salinity of the water present, the volume and configuration of the pore spaces, the matrix conductivity and resistivity of the rock grains. Usually the resistivity of a water-bearing formation decreases as the quantity of water available increases (Olayinka, 1992). The formation of secondary porosity by jointing and fracturing causes a further reduction in the resistivity. A lower extent of weathering, with a corresponding lesser domination of clay materials is to be anticipated in granitic areas (Olayinka, 1992). Several attempts to correlate resistivities with well yield have been made. McDowell (1979) disclosed that in the basement regions of Botswana, the low yield boreholes are characterised by a usually higher resistivity levels for the intermediate layer (i.e. weathered basement/saprolite).

A comparable conclusion was also arrived at from a part of southwestern Nigeria (Olayinka, 1992). Since the yield of boreholes also associates to some extent with bedrock fissuring, it is not unexpected that high yields could be obtained from places of both shallow and deep weatherings. This probably partly manifests the low correlation coefficient supposedly observed between the depth to bedrock and the well yield (Lewis, 1990; Olotu, 1990). In instances of productive wells situated at places where the basement is shallow, water is derived mostly from fractures in an otherwise "fresh" rock. Here, the bedrock resistivity is usually less than 1000 ohm-m (Verma *et al.*, 1980; White *et al.*, 1988). A high density of water-filled fracture zones may at times yield a measurable response as a low resistivity anomaly. McDowell (1979), Palacky *et al.* (1981) and Olorunfemi *et al.* (1986) have proven that over Precambrian crystalline areas of Botswana, Burkina Faso, and Southwestern Nigeria, these resistivity lows correspond to fractured bedrock. Moreover, such section of weakness are more likely to be related to the deeply-weathered basins than in the

adjacent country rocks where weathering is much thinner. The fracture pattern in crystalline rocks can be inferred from radial soundings in which for a sounding point apparent resistivities are recorded along different azimuths (Mallik *et al.*, 1983; Olorunfemi and Opadokun, 1987; Shemang *et al.*, 1990).

In hard rocks such as in granite, the rock porosity soaked with water is the controlling factor that affects the hydraulic and electrical conductivities. The current flow within the subsurface is fundamentally formed by two phenomena: electronic and electrolytic conductions (Keller and Frischknecht, 1966). Electronic conduction (i.e. the current flow through the free electrons available in the minerals which constitutes the rock) in the granite is negligible due to the high resistivity of the minerals and as such the water in the fissures is the main factor controlling the current flow (i.e. electrolytic conduction). Thus the electrolytic conduction is the prevalent phenomenon.

Since ions flow through some similar paths as water, the electrical resistivity and hydraulic conductivity of aquifer are anticipated to be influenced by similar variables. Fluid (i.e. groundwater) and electric currents flow from higher potential to lower potential locations and their flow rates are dependent upon hydraulic and electric potential gradients, respectively. The potential gradients occurrence could be spontaneous as well as artificially imposed while carrying out tests. For example hydraulic potential gradient is artificially imposed while carrying out a pumping test and likewise electric potential gradient is unnaturally imposed while carrying out a geoelectrical investigation. If the hydraulic potential gradient exists (naturally), groundwater moves by its own towards low potential site. The flow of groundwater generates self-potential current (electrokinetic or streaming potential) (Lowrie, 1997). While carrying out the pumping test, groundwater moves more or less horizontally towards the pumping well from the surrounding environments (Marechal *et al.*, 2004). Likewise, the current moves more or less horizontally in the aquifer from source towards sink current electrodes while executing the vertical electrical sounding using Schlumberger array. This is totally applicable in cases of hard rock, in which the aquifer horizon is at quite deeper level and needs enough inter-current electrode separation (for Schlumberger array) to probe it. Moreover the top layer is mostly dried saprolite having high resistivity values and bottom layer is

unfissured basement characterized by high resistivity values too. Thus current flow lines in the aquifer (i.e. fissured layer saturated with water) become channelized and flow horizontally. Thus, groundwater and current flows take place in equal media (i.e. aquifer) and also in identical direction.

This is the analogy between the two physical properties. Either in the cases of Darcy's law for groundwater flow or Ohm's law for current flow, the phenomena are governed by a common factor, i.e. aquifer porosity saturated with water (Chandra *et al.*, 2008).

2.4 Study Area Description

2.4.1 Location and Size

The study area is scantily populated with low level of infrastructure development and economic productivity. The Bawku West and Garu Tempane districts are two (2) of the thirteen (13) districts in Upper East region of Ghana. The Bawku West district is located between latitudes 10.7545° N and between longitudes 0.4880° W. It shares boundaries with Burkina Faso to the North, Bawku Municipality to the East, Talensi/Nabdam district to the West and East Mamprusi district to the South. The district covers a land area of approximately $1,070 \text{ km}^2$, which forms about 12% of the total area of Upper East region (Ministry of Food and Agriculture, Republic of Ghana, 2015). The Garu Tempane district shares boundaries with Republic of Togo to the East, Burkina Faso to the North, Bawku Municipality to the West and East Mamprusi district to the South. It covers an area of $1,230 \text{ km}^2$. It lies between latitude 10.7548° N and Longitude 0.1870° W and a population density of 99 persons per km^2 (Ministry of Food and Agriculture, 2015).

2.4.2 Topography, Drainage and Vegetation

The study areas are flat to gently undulating generally with slopes ranging from 1-5%. These plains are interspersed either with hills or ranges developed from either outcrops of Birimian rocks or granite intrusions in some areas. Areas bordering the White Volta are low and slightly undulating generally with gentle slopes between 120m – 150m above sea level (Ministry of Food and Agriculture, 2015). These

ranges lie along the border with Burkina-Faso, north of Zebilla, and turn south-west from the Red Volta, north of Nangodi in the Talensi/Nabdam district. The granitic areas are low to gently rolling generally (120 m-255 m). The Garu district marks the highest point of Upper East Region. It comprises a series of plateau surfaces of average height of 400m with isolated peaks of 430m above sea level. The general climatic conditions of the area can be summarized by the long-term records at Manga-Bawku Agricultural station, which are very representative of the Bawku West District (Ministry of Food and Agriculture, 2015). The district experiences a unimodal rainfall period lasting 4 to 6 months (May /June to September/October) and a longer dry period of 6 to 8 months annually. It is drained by both the White and Red Voltas and their tributaries. The rivers most often over flow their banks during the rainy season (April-October). The average amount of rainfall during the period is between 800 - 860mm per annum. The lowest mean temperature is 18⁰C occurring in December - January and the highest mean monthly temperature is 40⁰C occurring in March - April (Ghana Meteorological Agency, 2016). The dry season always allows an inflow of water from the Bagre dam (Burkina Faso), which makes it possible for farmers to pump for irrigation from the White Volta.

2.4.3 Geology and Soil

The Garu Tempane and Bawku West districts are geologically underlain by igneous plutonic rocks of the ‘Tamnean’ Plutonic Suite which are mostly granitoids (tonalite, minor granodiorite and minor quartz diorite) (Geological Survey of Ghana, 2009). Drilled logs within the study area indicate a three (3) layered profile (World Vision, GI-WASH drilled logs): topsoil, weathered zone/regolith and bedrock. The area is generally overlain by silty sandy clay top soil with few places of lateritic sandy gravels in strongly cemented clay matrix (hardpan), followed by sand with silt and quartz gravels, micaceous weathered zone/regolith and underlain with competent Granitoid bedrock. The area has a shallow groundwater table averaging about 12 – 25m generally beneath the ground surface with some very few exceptions.

The districts soils and water supply conditions are directly associated with the underlying rocks. Most of the soils are consequently of low intrinsic crop fertility. The two most frequently deficient nutrients are nitrogen and phosphorus (Ministry of

Food and Agriculture, 2015). The build-up of any amount of organic matter is constrained by regular burning of crop residues and/or competitive use of these residues for fuel, animal feed or building purpose. The low vegetative cover during the dry season also renders most of the soils susceptible to erosion during the rainy season. This, in turn, exacerbates the low fertility problem.

2.4.4 Groundwater Availability and Potential

The study area has been established as a serious water deficit area due its water supply coverage (Unihydro Ltd, 2000). Water supply availability is a serious challenge and the area relies mostly on dugouts, dams, hand-dug wells and some boreholes. Groundwater is the water supply alternative in the area because it is commonly present even in drought conditions and it has comparatively good quality. The occurrence of groundwater in the UER is most often controlled by structural features (i.e. the availability of faults, fractures, etc.), thickness of the overburden, the geology, the nature of the topography in the region and the degree of interconnectivity.

Movement of groundwater is usually limited to joints and fractures within the crystalline rock formations. In certain areas, a thick covering of weathered friable material ('regolith') overlies the crystalline basement and this provides ability for increased groundwater storage (Gumma and Pavelic, 2012). Geology plays a critical part in the determination of groundwater quality and potential water-quality challenges. As the country is dominated by crystalline silicate rocks and weathered derivatives (regolith), groundwater is predominantly of low salinity and usually acidic in composition ($\text{pH} < 6.5$), with low values of total hardness (British Geological Survey, 2000).

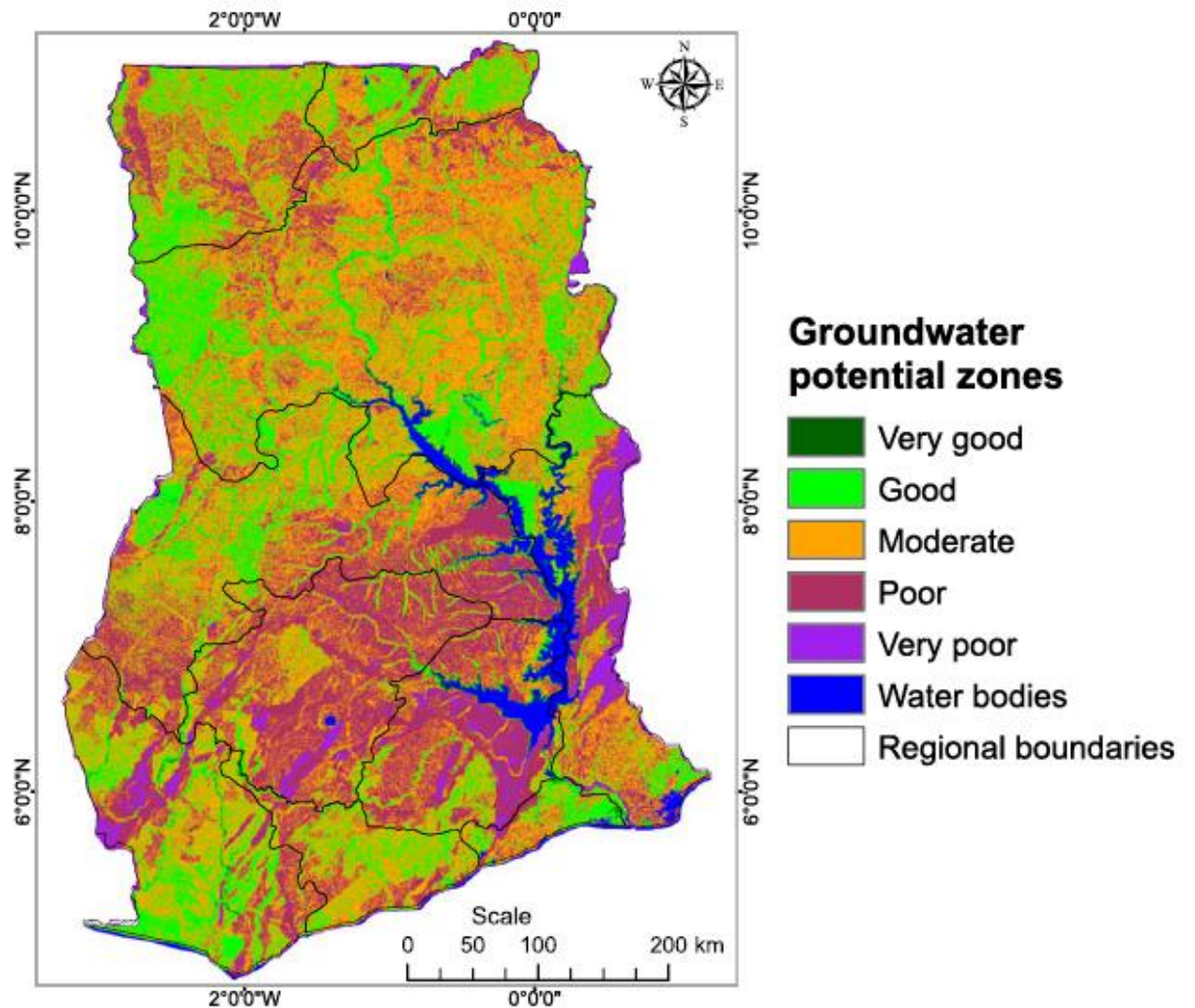


Figure 2: Groundwater potential zones within Ghana (Gumma and Pavelic, 2012)

Gumma and Pavelic (2012) mapped groundwater potential regions in Ghana with the use of remote sensing and geographic information system tools and verified with data on boreholes yields. Groundwater potential was mapped as a function of geomorphology, geology, slope, drainage density, rainfall, land use, and soil. The study revealed that, majority of areas in the UER have good groundwater potential (average well yield $5.5 \text{ m}^3/\text{h}$) especially in the eastern (Bawku East and Bawku West, and Garu-Tempane districts and Bawku municipality) and central (Bongo and Kassena – Nankana East districts, and Bolgatanga Municipality) portions of the UER as shown in Figure 2.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study Area

There are thirteen (13) districts in Upper East region of Ghana. But only two districts, Garu Tempane and Bawku West, were chosen because of availability of data necessary for the study as shown in Figure 3.

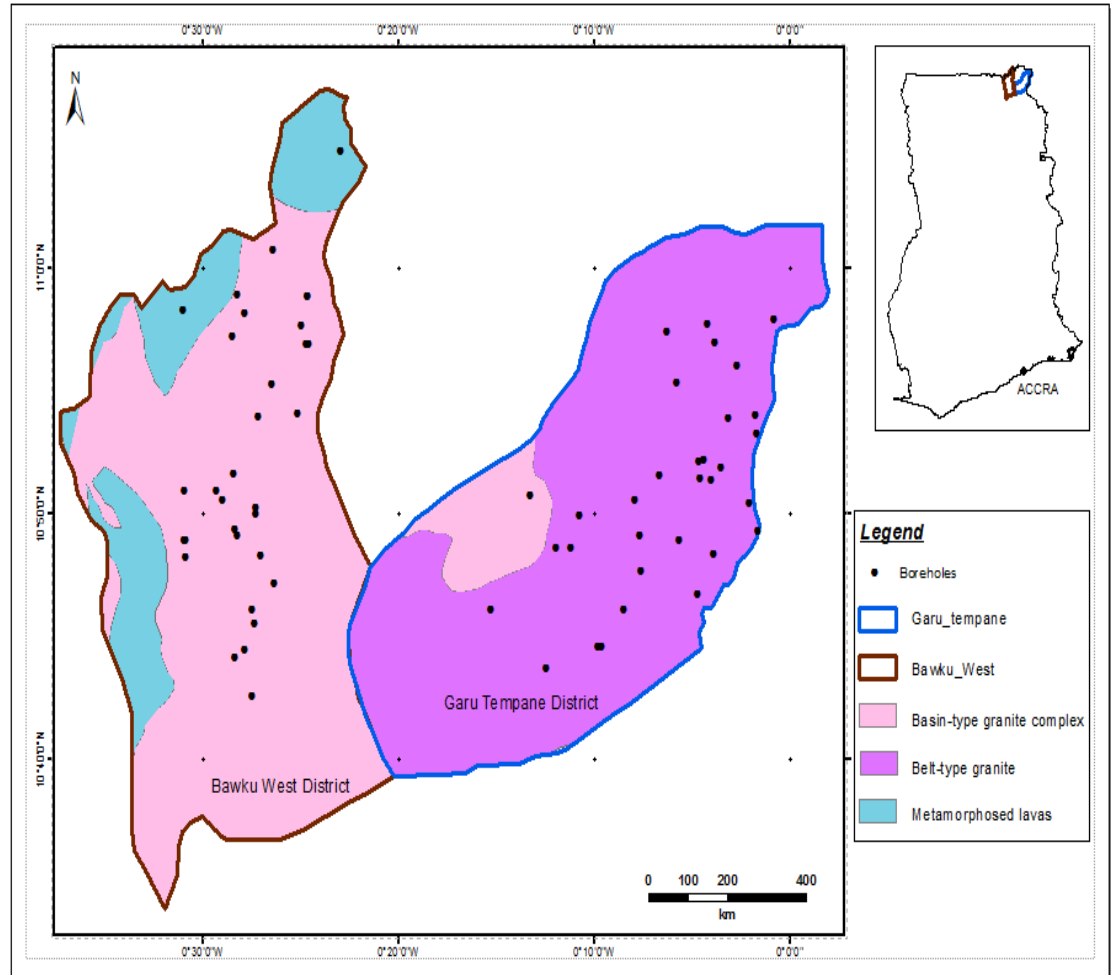


Figure 3: Map showing study area with drilled boreholes

3.2 Data Collection

Data for the study were mainly obtained from secondary sources. These comprise Dipole-Dipole electrical resistivity data and borehole drill logs for the study area collected from World Vision Ghana [Ghana Integrated Water, Sanitation and Hygiene (GI-WASH) project] at Savelugu-Tamale. This project (formerly Ghana Rural Water Project) launched in 1985 was the first major WASH intervention of

World Vision in West Africa to increase access to sustainable, safe water and environmental sanitation.

3.3 Vertical Electrical Sounding

Resistivity measurements from field work conducted in 33 communities in Garu Tempane district and 16 communities in Bawku West, Upper East region of Ghana were used. The data used was Vertical Electrical Sounding (VES) survey obtained using the Dipole-Dipole array type with investigation depth ranging between 50-90m. All the VES measurements were conducted such that the depth of investigation started from 8m beneath the ground surface. The VES field data sheet as shown in Figure 4 contained information such as:

- Community name, district and region
- Borehole ID or VES peg number
- VES survey date
- Depth of investigation
- Resistance and apparent resistivity
- Plot of Apparent resistivity against depth, etc.

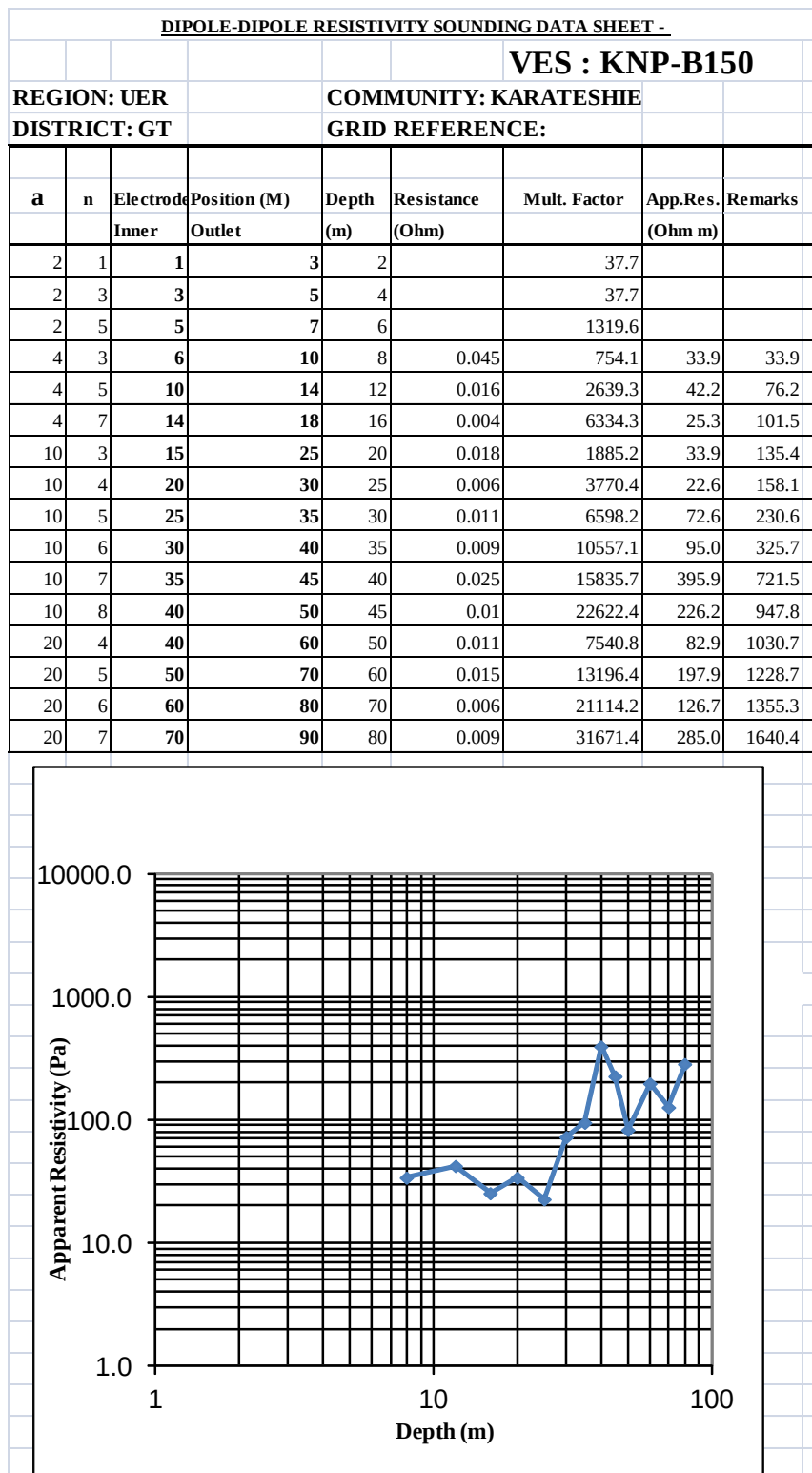


Figure 4: Dipole-Dipole field data sheet

3.4 Borehole Drill logs

Drill logs of all the 49 drilled boreholes in the study area were also collected. These were logged by a hydro-geologist during drilling. Commonly available information in the logs as shown in Figure 5 includes:

- Final borehole depth
- Estimated yield or air lift yield
- Water strike
- Geology description and thickness of the sub surface layers
- Borehole design and construction
- Borehole name/identity, GPS Coordinates, date drilled, rate of penetration, etc.

From the individual drill logs, the borehole depths, air lift yields, geology descriptions and subsurface layer thicknesses were extracted. The areas drilled were underlain by Granitoids. Appendices A and B provides the summary borehole data sheets and appendix G the borehole drill logs.

layer was taken to be the top most lateritic soil or overburden and was represented by black colour. The second layer being the entire weathered zone was depicted with blue colour while the last layer being the bedrock was represented with green colour as shown in Table 1. The thicknesses of the identified subsurface layers were estimated using two methods. The first estimation was from the drill logs and the other from the VES data. The estimation of the subsurface layers from the drill logs for each borehole was based on the information of layer thicknesses and details of subsurface geology provided in the drill logs.

Since drill logs can only be available after drilling, the subsurface layer was estimated from the VES data by plotting the cumulative resistivity against depth. The individual subsurface layers were then identified as the different slopes obtained in the plots.

3.6 Assigning Apparent Resistivity Values to Layer Thicknesses

Apparent resistivity values were assigned to the various thicknesses derived from the drill logs and cumulative resistivity plots. For each layer, the least measured resistivity value within the layer thickness was assigned for that layer. This is because, for a crystalline geological terrain a lower resistivity value is an indication of potential high water content and vice versa (Olayinka, 1992). Moreover, high densities of water-filled fracture zones usually produce low resistivity anomaly response within such geologic terrains.

3.7 Computation of Longitudinal Conductance and Transverse Resistance

Longitudinal conductance and transverse resistance were computed from the layer thicknesses and assigned apparent resistivities. Longitudinal conductance (LC) is defined as the sum of the ratio of various layer thicknesses to their corresponding resistivities ($\sum D_i / \rho_i$). Related to longitudinal conductance is transverse resistance (TR), which is the sum of the product of the different layer thicknesses and their respective resistivities ($\sum D_i \times \rho_i$) (Chandra et al, 2008). In this study, only the third layer was used for computing the LC and TR.

$$LC = D_3 / \rho_3 \quad (6)$$

$$TR = D_3 \times \rho_3 \quad (7)$$

Within the study area, borehole yield is greatly enhanced and controlled by the water-filled fractures within the bedrock since it has a very shallow overburden thickness. A study of the drill logs in the area of study indicated that the third layer is the possible aquifer zone and that it was of particular interest in this study. The longitudinal conductance and transverse resistance values were therefore computed using equations (6) and (7) respectively.

3.8 Developing Regression Models and Testing its Reliability

Different regression models (equations) were developed to relate borehole yield to the apparent resistivity, longitudinal conductance and transverse resistance of the third layer for Garu Tempane and Bawku West districts.

First, developed models using all 33 VES points from Garu Tempane were used to estimate yields for Bawku West. The estimated yields were then plotted against the actual borehole yields obtained from drilling to test the reliability of the models.

Secondly, twenty-five out of the thirty-three VES points from Garu Tempane was used to develop regression models and then the remaining eight (8) points were used for validation. The estimated yields were then plotted against the real borehole yields obtained from drilling to assess the reliability of the models. Thirdly, regression models were developed using all VES points (33) from Bawku West.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Layer Thicknesses

Drilled logs within the study area indicate a three (3) layered profile: overburden, weathered zone/regolith and bedrock. The area has a shallow groundwater table with most water strikes ranging between 12m-20m beneath the ground surface. Though the water strikes are within the 2nd layer (weathered zone), the yield increases significantly and controlled by water filled fractures in the bedrock (3rd layer). Drilled depths of between 40m-60m from the ground surface was observed from the drill logs.

Table 1: Subsurface layers thicknesses (Black-Overburden, Blue-Weathered zone, Green-Fractured Bedrock and Red-Fresh Bedrock)

Depth (m)	Karateshie Natinga			Konkomadaa			Tempelugo		
	App. Res. (Ohm m)	Thickness, m (Drill log)	Thickness, m (VES)	App. Res.(Ohm	Thickness, m (Drill log)	Thickness, m (VES)	App. Res. (Ohm m)	Thickness, m (Drill	Thickness , m (VES)
2									
4									
6									
8	33.9			70.1			36.20		
12	42.2			10.6			42.23		
16	25.3			44.3			50.67		
20	33.9			24.5			24.51		
25	22.6			79.2			26.39		
30	72.6			99.0			59.38		
35	95			126.7			10.56		
40	395.9			95.0			47.51		
45	226.2			678.7			113.11		
50	82.9			82.9			135.73		
60	197.9			145.2			39.59		
70	126.7			105.6			21.11		
80	285			285.0			63.34		

Three (3) subsurface layers were determined using the drill logs of the thirty-three (33) points as shown in Table 1. The layer 1 (overburden) in these areas were very shallow ranging from 2 m to 12 m beneath ground surface.

All the VES measurements were conducted such that the depth of investigation started from 8m as in Table 1; hence the overburden was not captured in the survey and on the cumulative VES plots. Particular interest and attention was given to the second layer in the VES, this is actually the third layer in the field because the 1st layer was not captured in the VES. Beyond this layer represents the fresh competent

bedrock represented by red colour in Table 1 (3rd layer in cumulative VES plots) which of course is of no interest to this study of estimating borehole yield, hence no attention was given but rather served as the limiting depth for the cumulative VES plots as shown in Figure 6.

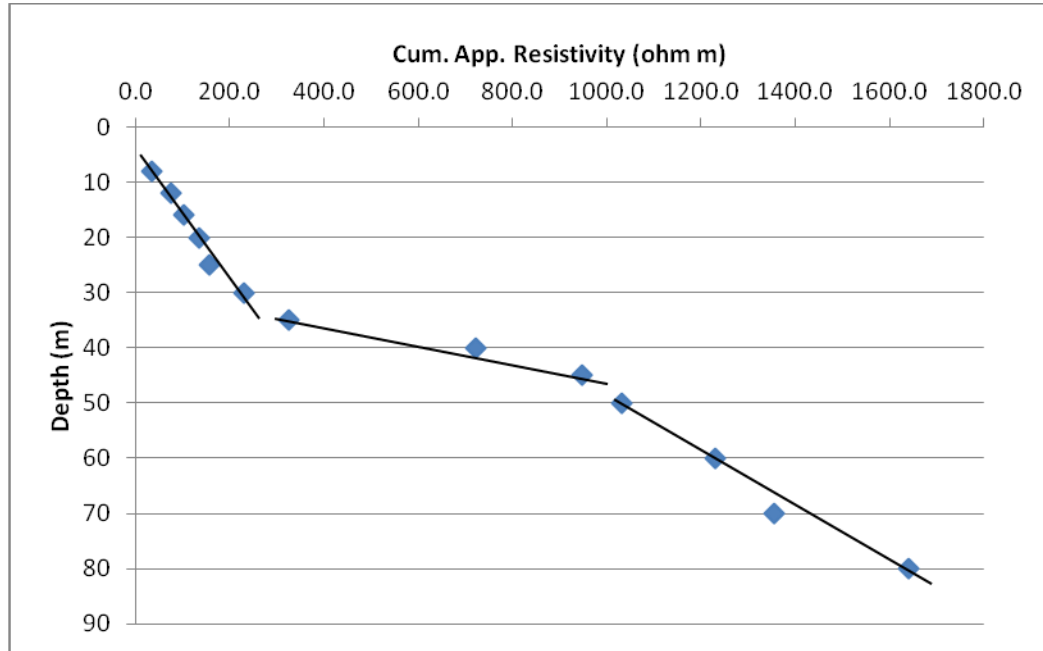


Figure 6: VES plot for Karateshie

From Figure 6, four (3) layers were determined. Since the depth of investigation started from 8 m beneath ground surface, the 1st layer was not captured. 8 m to 30 m (22 m thickness) represents the 2nd layer, 35 m to 45 m (10 m thickness) represents the 3rd layer and 50 m to 80 m (30 m thickness) is the 4th layer.

4.2 Assigning Resistivity Values to Layer Thicknesses

The least apparent resistivity value for each layer as determined from the drill logs and cumulative VES plots was assigned to the third layer. Three (3) subsurface layers were established in all the cumulative VES plots because depth of investigation in all the survey conducted was from 8 m down beneath the earth surface. The change in slopes identifies and differentiates the subsurface layers. From Figures 6 and 7, 8 m to 30 m signifies the 2nd layer with the lowest apparent resistivity value within thickness being 23 Ohm-m and used to represent the layer. The third layer which is 35 m to 45 m is represented with lowest apparent resistivity

value of 95 Ohm-m. 50 m to 80 m represents the 4th layer with lowest apparent resistivity value of 285.0 Ohm-m.

Karateshie Natinga				
Depth (m)	App. Res. (Ohm m)	Thickness, m (Drill log)	Thickness, m (VES)	Assigned Layer App. Res. (Ohm m)
2				
4				
6				
8	33.9			
12	42.2			
16	25.3			
20	33.9			
25	22.6			
30	72.6			
35	95			
40	395.9			
45	226.2			
50	82.9			
60	197.9			
70	126.7			
80	285			

Figure 7: Assigned Apparent Resistivity Values to Layers for Karateshie

4.3 Computation of Longitudinal Conductance and Transverse Resistance

Results presented in Table 2 from all 33 of drill logs for Garu Tempene shows subsurface layer 1 to have thicknesses ranging from 3 m to 12 m, with an average thickness of 6 m. Layer 2 has thicknesses from 8 m to 42 m, with an average thickness of 21 m. Layer 3 showed thicknesses ranging from 10 m to 40 m and an average thickness of 22 m.

Apparent resistivity values range from 5 Ohm-m to 170 Ohm-m with an average of 47 Ohm-m for layer 2 whereas layer 3 has values ranging from 7 Ohm-m to 352 Ohm-m with an average of 66 Ohm-m. Layer 2 (weathered layer) comparatively had the lowest apparent resistivity value because of the added influence of clay minerals from weathering in addition to its water content as against only the water content influence of layer 3.

Longitudinal conductance had values ranging from 0.06 Ohm^{-1} and 4.0 Ohm^{-1} with an average of 1.0 Ohm^{-1} whereas transverse resistance values range from 132.0 Ohm m^2 to 8105.0 Ohm m^2 with an average of 1351.0 Ohm m^2 .

Table 2: Subsurface layers with computed longitudinal conductance and transverse resistance using drill logs

Community	Yield (l/m)	Resistivities, R (ohm m)			Thicknesses, D (m)			LC	TR
		Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3		
Karateshie	40		22.6	95	6	24	10	0.11	950
Tempelugo	125		24.5	10.6		23	17	1.60	180.2
Gbanterago	60		33.2	90.5	4	27	20	0.22	1810
Kpalsako	230		9.4	6.6		17	20	3.03	132
Worikambo	85		41.5	38.5	4	27	26	0.68	1001
Old Natenga	180		11.3	11.31	6	12	23	2.03	260.13
BimpellaNo.3	40		21.9	26.4	6	32	20	0.76	528
Poazia	120		31.7	46.2	6	8	20	0.43	924
Tuduriga Top	28		108.68	95.01	4	16	13	0.14	1235.13
SumaduriJHS	170		18.9	18.85	6	22	23	1.22	433.55
Nyosbara	100	49.77	20.7	11.3	8	12	20	1.77	226
Kplug	24		11.3	95	4	22	20	0.21	1900.00
Tirutiga	55	98.79	67	39.6	8	17	25	0.63	990.00
Tambona	60		6.6	47.51	6	17	25	0.53	1187.75
Bariboki	58	18.85	18.5	30.2	8	17	25	0.83	755.00
Yabrago	62		37	31.7	6	22	25	0.79	792.50
Benguri	100	19.61	11.3	11.31	8	12	15	1.33	169.65
Korinzia	60		64.1	26.4	5	12	20	0.76	528.00
Abaripusiga	65		13.2	42.2	4	22	25	0.59	1055.00
Banginong	28		60.3	316.7	3	42	20	0.06	6334.00
Akara Tim.	37		12.7	63.3	8	22	35	0.55	2215.50
Sambona Far.	18		5.3	352.4	8	22	23	0.07	8105.20
Lokoam	18		35.8	211.1	6	17	20	0.09	4222.00
Benatinga	36		85.8	84.5	4	22	20	0.24	1690.00
Farfar	170		55.4	13.2	6	17	30	2.27	396.00
Gbelingivuus	75		50.8	22.6	6	24	35	1.55	791.00
Nag. Palace	13		70.9	72.6	8	20	20	0.28	1452.00
Menatenga	110		120.2	10.6	6	18	40	3.77	424.00
Siguri Prim.	71		94.5	31.7	4	15	20	0.63	634.00
Tinsugu Bisa	50		70.2	15.8	3	12	20	1.27	316.00
Wabugkpesir	40		80.3	31.7	5	25	20	0.63	634.00
Bangoli	40		71.80	67.87	7	30	20	0.29	1357.40
Konkomadaa	12		24.50	95	12	18	10	0.11	950.00

Table 3 from all 33 VES of Garu Tempane showed subsurface layer 2 to have thicknesses ranging from 10 to 45 m, with an average thickness of 24 m. Layer 3 has thicknesses from 10 to 35 m, with an average thickness of 19 m.

Apparent resistivity values range from 7 to 150 Ohm-m with an average of 45 Ohm-m for layer 2 whereas layer 3 has values ranging from 7 to 352 Ohm-m with an average of 66 Ohm-m. Again predictably, layer 2 recorded the lowest apparent resistivities comparative to layer 3 because of the added influence of clay minerals as a result of weathering.

Longitudinal conductance had values ranging from 0.03 Ohm^{-1} and 3.0 Ohm^{-1} with an average of 1.0 Ohm^{-1} whereas transverse resistance values range from 113.0 Ohm m^2 to 5286.0 Ohm m^2 with an average of 1078.0 Ohm m^2 .

Table 3: Subsurface layers with computed longitudinal conductance and transverse resistance using VES data

Community	Yield (l/m)	App. Resistivity (Ohm m)		Thicknesses, D (m)		LC	TR
		Layer 2	Layer 3	Layer 2	Layer 3		
Karateshie	40	22.6	95	22	10	0.11	950
Tempelugo	125	24.5	10.6	30	15	1.42	159
Gbanterago	60	33.2	90.5	25	10	0.11	905
Kpalsako	230	9.4	6.6	25	20	3.03	132
Worikambo JHS	85	41.5	38.5	30	30	0.78	1155
Old Natenga	180	11.3	11.31	15	20	1.77	226.2
Bimpella No.3	40	21.9	26.4	35	15	0.57	396
Poazia	120	31.7	46.2	10	20	0.43	924
Tuduriga - Top	28	108.68	95.01	20	13	0.14	1235.13
Sumaduri JHS	170	18.9	18.85	25	15	0.80	282.75
Nyosbara No. 1	100	20.7	11.3	15	10	0.88	113
Kplug	24	11.3	95	25	10	0.11	950.00
Tirutiga	55	67	39.6	20	30	0.76	1188.00
Tambona	60	6.6	47.51	25	20	0.42	950.20
Bariboki	58	18.5	30.2	25	20	0.66	604.00
Yabrago	62	37	31.7	15	15	0.47	475.50
Benguri	100	11.3	11.31	30	20	1.77	226.20
Korinzia	60	64.1	26.4	12	15	0.57	396.00
Abaripusiga	65	13.2	42.2	25	25	0.59	1055.00
Banginong	28	60.3	316.7	30	10	0.03	3167.00
Akara Tim.	37	12.7	63.3	25	25	0.39	1582.50
Sambona Farfar	18	5.3	352.4	20	15	0.04	5286.00
Lokoam	18	35.8	211.1	20	20	0.09	4222.00
Benatinga	36	85.8	84.5	17	15	0.18	1267.50
Farfar	170	55.4	13.2	20	20	1.52	264.00
Gbelingivuu	75	40	22.6	30	35	1.55	791.00
Nagani Palace	13	60	72.6	25	20	0.28	1452.00
Menatenga	110	110	10.6	25	35	3.30	371.00
Siguri Primary	71	90.5	31.7	20	30	0.95	951.00
Tinsugu Bisa	50	65.5	15.8	30	20	1.27	316.00
Wabugkpesir	40	70.8	31.7	20	25	0.79	792.50
Bangoli	40	66.70	67.87	17	20	0.29	1357.40
Konkomadaa	12	24.50	95	17	10	0.11	950.00

4.4 Developing Regression Models

4.4.1 Using Subsurface Layers from 33 Drill Logs for Garu Tempene

Regression models were developed for Garu Tempene using the subsurface layers obtained from the drill logs in Table 2 for all thirty three (33) boreholes. Figures 8 to

10 show the relationships developed between aquifer yield and apparent resistivity, longitudinal conductance and transverse resistance from the regression models.

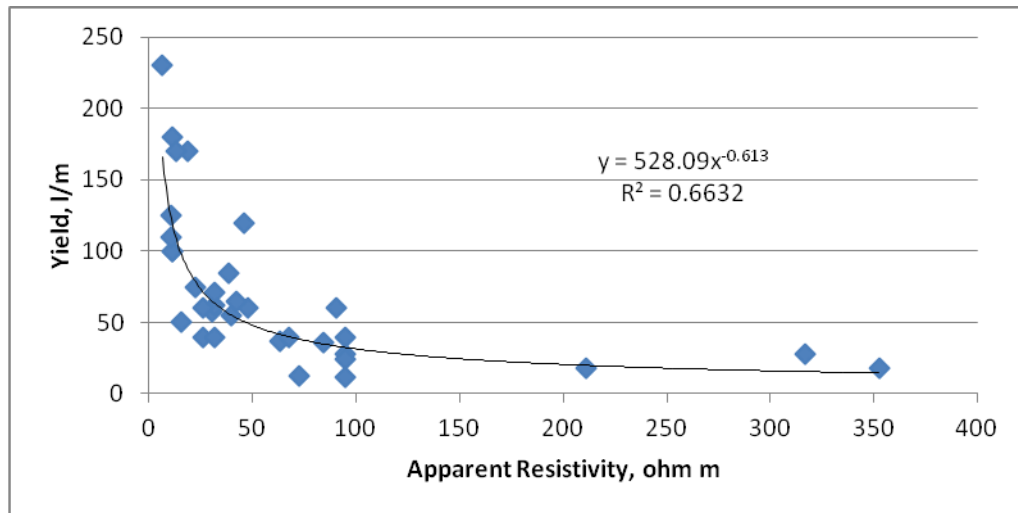


Figure 8: Yield vrs Apparent Resistivity from 33 Drill logs

Figure 8 shows that the borehole yield has an exponential relationship with apparent resistivity. As apparent resistivity increases, yield decreases. This shows a good relationship between the two variables with R^2 of 0.66.

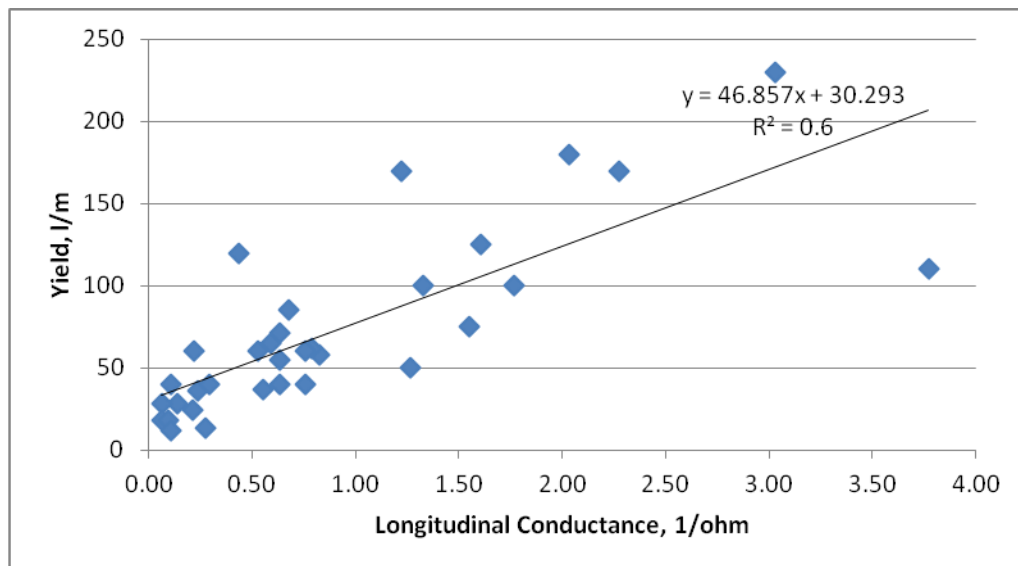


Figure 9: Yield vrs Longitudinal Conductance from 33 Drill logs

Longitudinal conductance in Figure 9 exhibited positive linear relationship with borehole yield; as longitudinal conductance increases yield increases as well. R^2 of 0.6 was obtained, which shows a good relationship between the two variables.

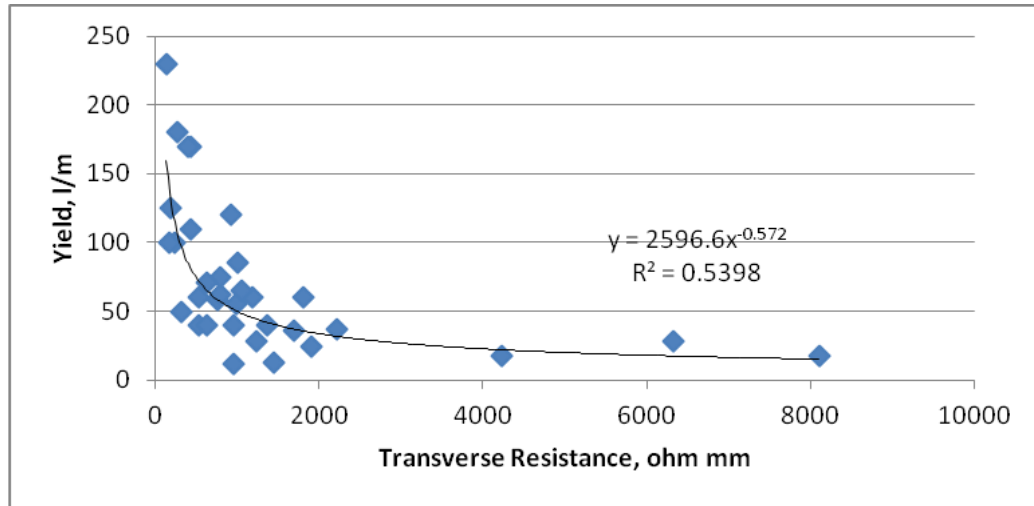


Figure 10: Yield vrs Transverse resistance from 33 Drill logs

Transverse resistance and borehole yield had an exponential relationship as shown in Figure 10. Hence an increase in transverse resistance causes a decrease in yield with R^2 of 0.54 which shows a promising relationship between the two variables. This indicates that one is a power function of the other.

In all the relationships, the predictor variables (apparent resistivity, longitudinal conductance and transverse resistance) all showed and agreed with the proven observation/theory that areas with high water content have lower resistivities and vice versa. This is so because as water content reduces as a result of decrease in porosity and water filled fractures, resistivity increases.

4.4.2 Using Subsurface Layers from 33 VES for Garu Tempane

The subsurface layers obtained using only the cumulative VES plots for all 33 VES data in Table 3 were used to develop regression models for Garu Tempane as well. Figures 11 to 13 show the relationships between borehole yield and the three electrical parameters.

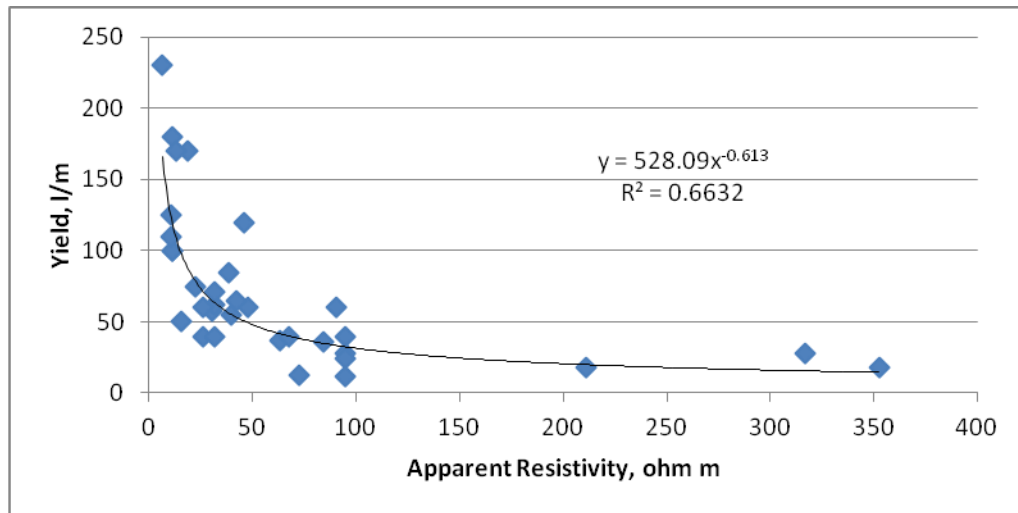


Figure 11: Yield vrs Apparent Resistivity from 33 VES data

Figure 11 shows an exponential relationship between yield and apparent resistivity. As apparent resistivity increases yield decreases with R^2 of 0.66, showing a good relationship between the two variables.

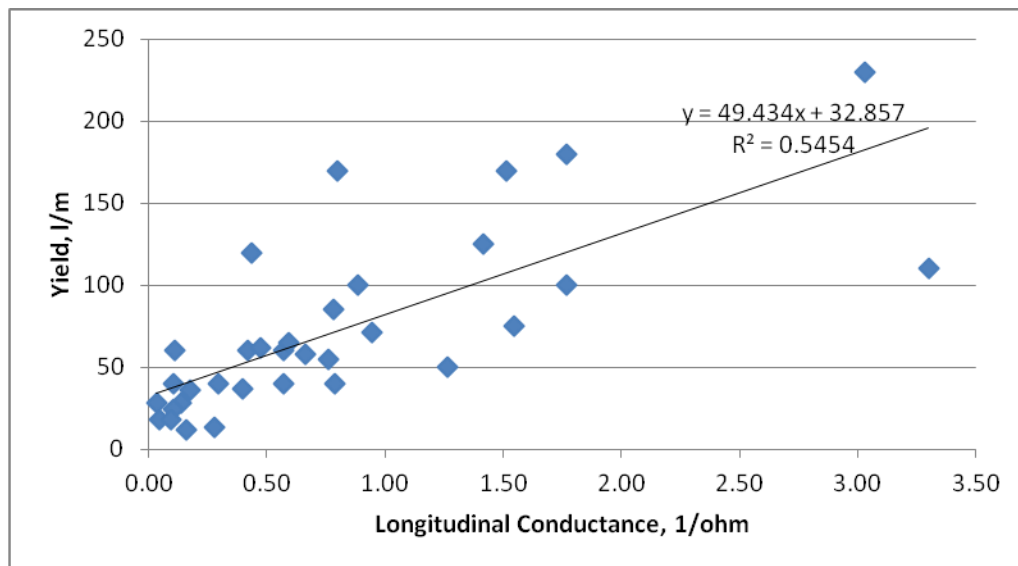


Figure 12: Yield vrs Longitudinal Conductance 33 VES data

A positive linear relationship was determined between yield and longitudinal conductance as shown in Figure 12. An increase in longitudinal conductance results in an increase in yield with R^2 of 0.55, which looks good.

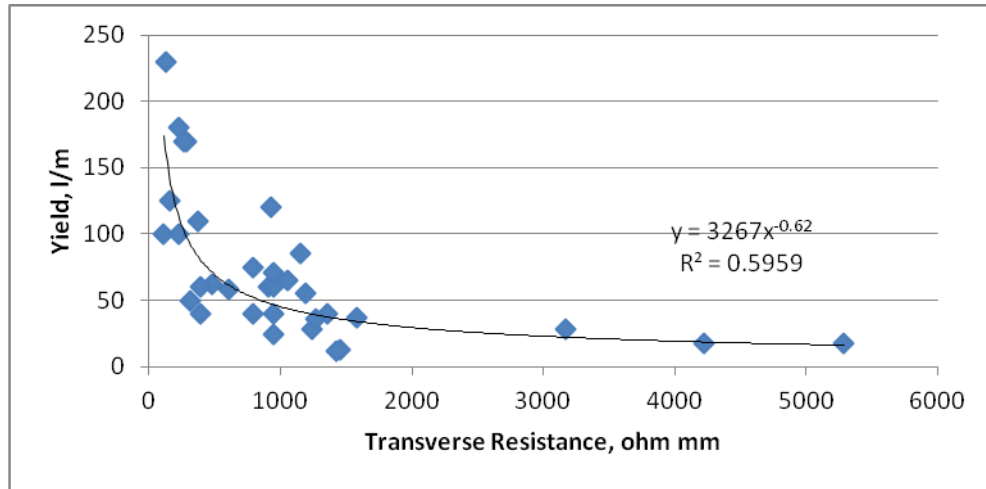


Figure 13: Yield vrs Transverse Resistance from 33 VES data

An exponential relationship was determined between yield and transverse resistance as shown in Figure 13. This indicates that one is an exponential function of the other; hence an increase in transverse resistance causes a decrease in yield with R^2 of 0.60, which shows a good relationship between the two variables. Both techniques showed similar good relationships between borehole yield and apparent resistivity, longitudinal conductance and transverse resistance with not too different R^2 values.

4.4.3 Using Subsurface Layers from 25 VES for Garu Tempane

Part (25 of 33) of the Garu Tempane VES data in Table 3 was used to develop regression models from the third subsurface layers obtained from only the cumulative VES plots. Figures 14 to 16 illustrate the relationships between borehole yield and the three variables.

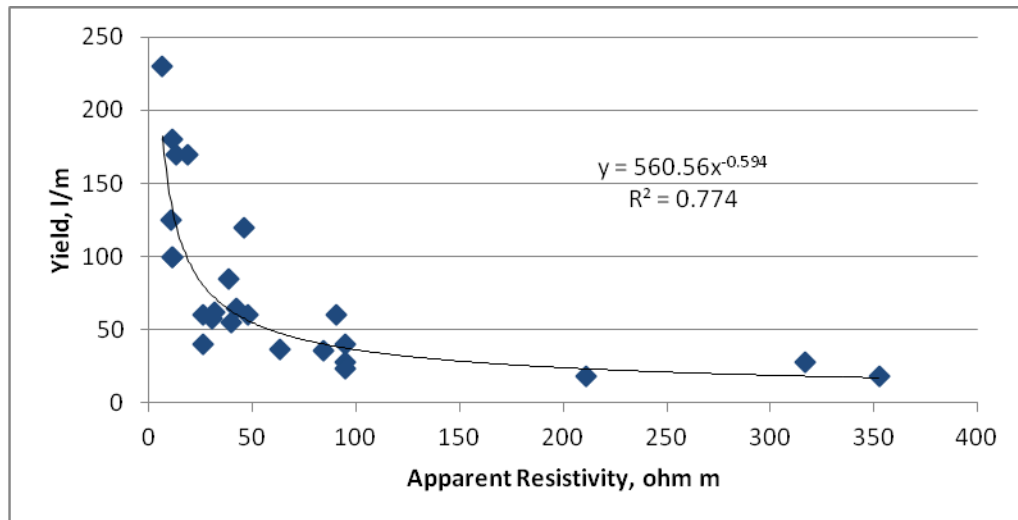


Figure 14: Yield vrs Apparent Resistivity from 25 VES data

Figure 14 shows there is a very good relationship between borehole yield and apparent resistivity values with R^2 of 0.77. An exponential relationship was established between the two variables; as apparent resistivity increases yield decreases and vice versa.

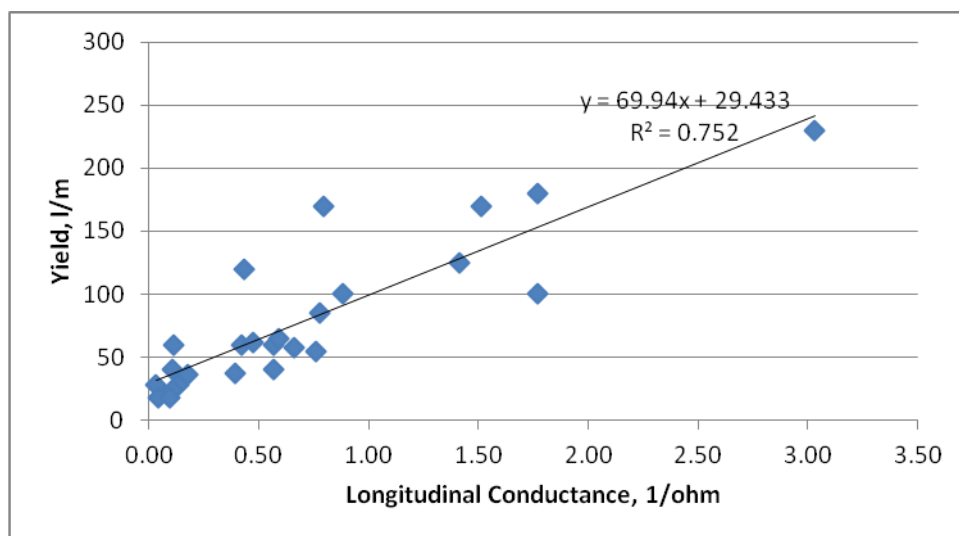


Figure 15: Yield vrs Longitudinal Conductance from 25 VES data

A very good positive linear relationship between yield and longitudinal conductance was also determined with R^2 of 0.75 as shown in Figure 15. So as longitudinal conductance increases yield also increases linearly.

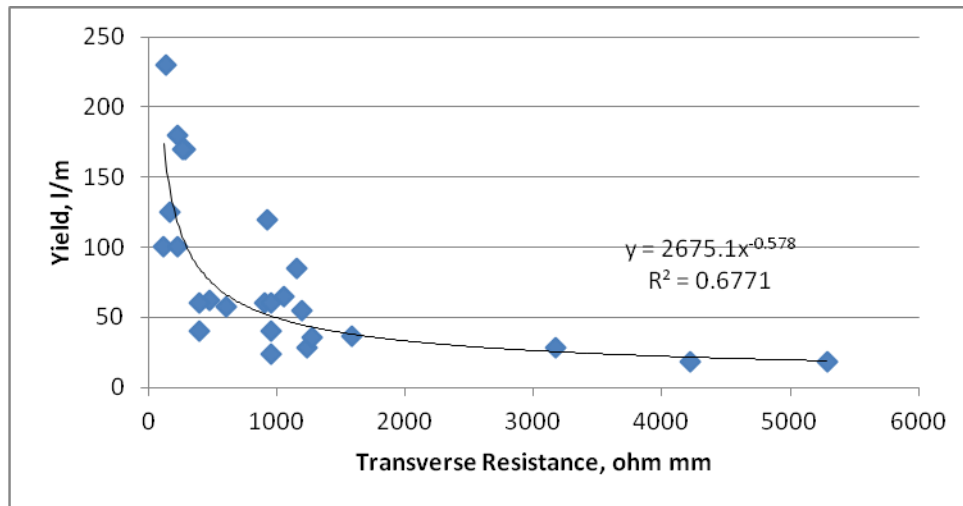


Figure 16: Yield vrs Transverse Resistance from 25 VES data

Transverse resistance shows a good exponential relationship with yield with R^2 of 0.68 as shown in Figure 16. Hence an increase in yield results in a decrease in transverse resistance.

Part (25 of 33) of Garu Tempene in Table 2 was used to develop regression models from the subsurface layers obtained using the drill logs. Figures 17 to 19 illustrate the relationships between borehole yield and the three variables.

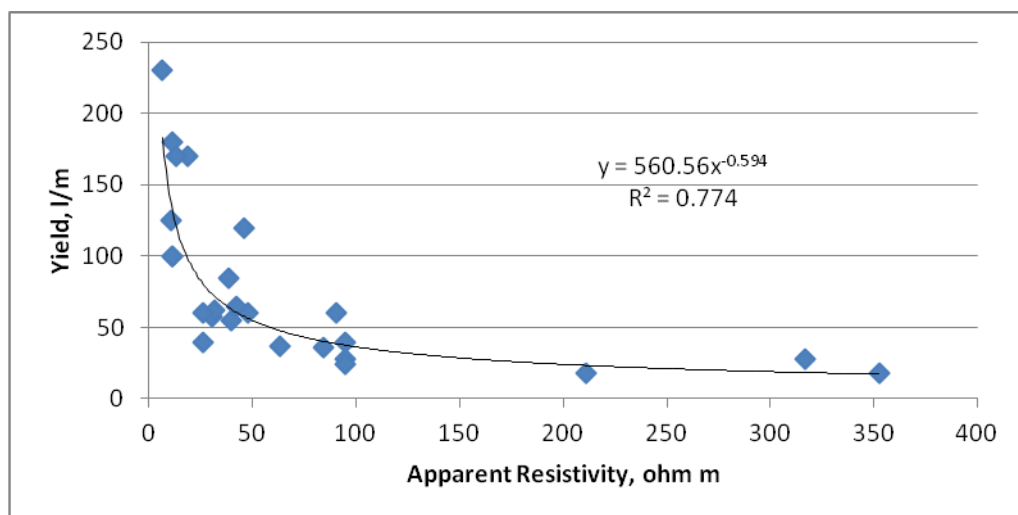


Figure 17: Yield vrs Apparent Resistivity from 25 Drill logs

Figure 17 shows there is a good relationship between borehole yield and apparent resistivity with R^2 of 0.77. An exponential relationship was established between the two variables; as apparent resistivity increases yield decreases and vice versa.

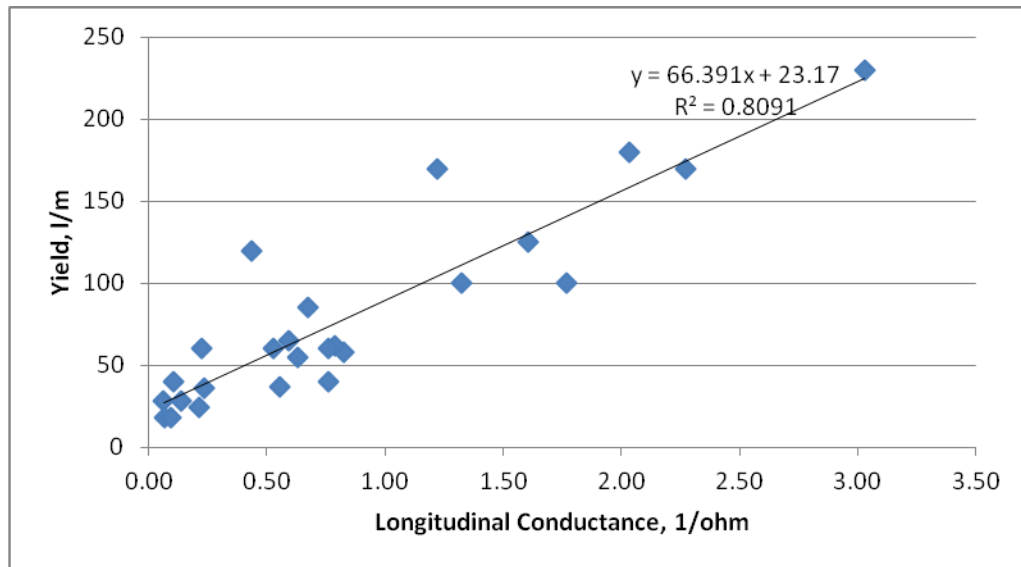


Figure 18: Yield vrs Longitudinal Conductance from 25 Drill logs

A positive linear relationship between yield and longitudinal conductance was also determined with R^2 of 0.81 as shown in Figure 18. So as longitudinal conductance increases yield also increases linearly.

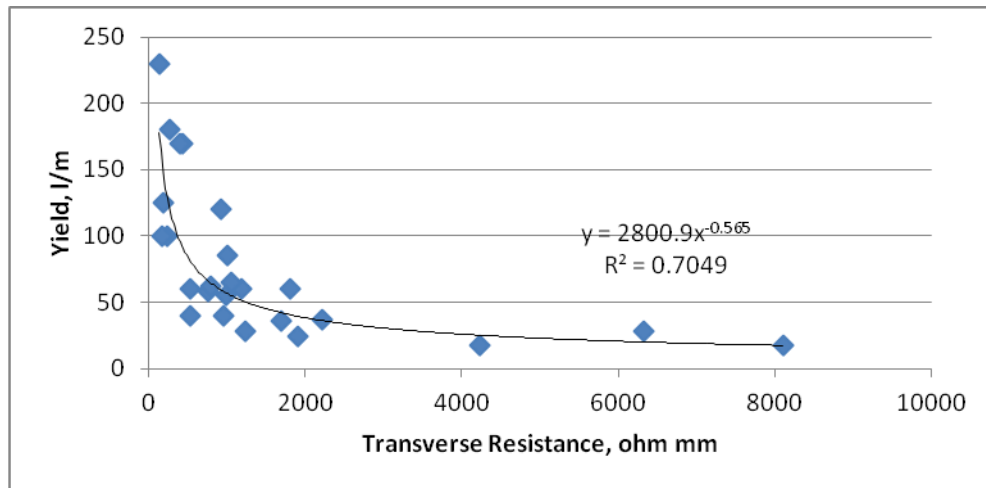


Figure 19: Yield vrs Transverse Resistance from 25 Drill logs

Transverse resistance shows an exponential relationship with yield with R^2 of 0.70 as shown in Figure 19. Hence an increase in the yield results in a decrease in transverse resistance.

4.4.4 Using Subsurface Layers from VES for Bawku West

Regression models were developed for Bawku West district using the subsurface layers obtained from only cumulative VES plots in Table 4. Table 4 showed subsurface layer 2 to have thicknesses ranging from 8 to 37 m, with an average thickness of 24 m. Layer 3 has thicknesses from 10 to 45 m, with an average thickness of 23 m.

Apparent resistivity values range from 12.0 to 69.0 Ohm-m with an average of 32.0 Ohm-m for layer 2 whereas layer 3 has values ranging from 13.0 to 206.0 Ohm-m with an average of 61.0 Ohm-m.

Table 4: Subsurface layers with computed longitudinal conductance and transverse resistance for Bawku West (VES data)

Community	Yield (l/m)	App. Resistivity (Ohm m)		Thicknesses, D (m)		LC	TR
		Layer 2	Layer 3	Layer 2	Layer 3		
Biringu Boki	13	44.9	73.9	22	25	0.34	1847.5
Aboadabogo	55	31.7	47.51	17	20	0.42	950.20
Zoayan. Azure	35	44.3	105.6	37	40	0.38	4224.00
Gabuliga	200	37.7	15.1	17	20	1.32	302.00
Gore Kpalsako	30	24.1	205.9	27	10	0.05	2059.00
Abulanga-Apot.	45	12.7	47.51	22	15	0.32	712.65
GabulugaCHPS	140	18.9	13.2	27	30	2.27	396.00
Galaka CHPS	85	12.4	52.8	32	35	0.66	1848.00
Bugnaba Kuga	80	37.7	45.2	22	10	0.22	452.00
NagbereNatinga	179	18.9	13.2	27	30	2.27	396.00
GoreBulpeliga	90	15.1	42.2	22	15	0.36	633.00
Ankpa. Prim	25	32	67.9	32	15	0.221	1018.5
Adonsi Prim.	86	68.6	37.7	8	20	0.53	754.00
Tandabote	20	60.3	126.7	27	10	0.08	1267.00
Peri Yapala	158	35.8	21.10	12	45	2.13	949.5
Peri	85	24.5	67.90	32	35	0.52	2376.5

Figures 20 to 22 illustrate the relationships established between borehole yield and apparent resistivity, longitudinal conductance and transverse resistance.

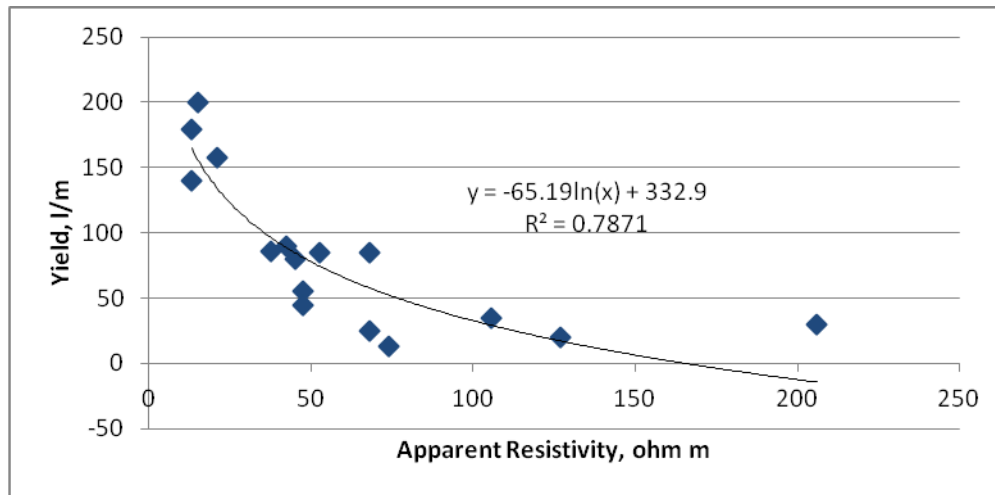


Figure 20: Yield vrs Apparent Resistivity from 16 VES data

Borehole yield and apparent resistivity showed a very good correlation with R^2 of 0.79 in Figure 20. A negative logarithmic relationship was established between the two. So as yield increases, apparent resistivity decreases and vice versa.

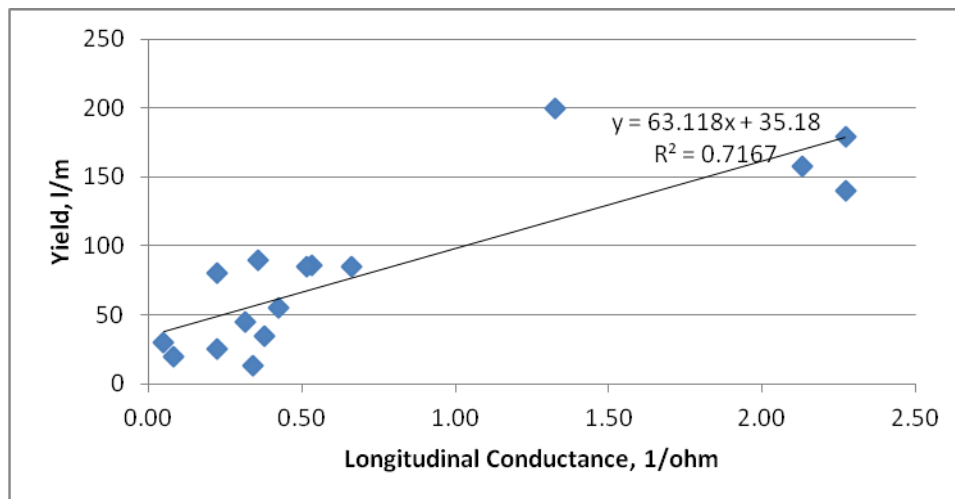


Figure 21: Yield vrs Longitudinal Conductance from 16 VES data

Very good positive linear correlation was established between yield and longitudinal conductance with R^2 of 0.72 as illustrated in Figure 21. Hence an increase in longitudinal conductance results in an increase in yield and vice versa.

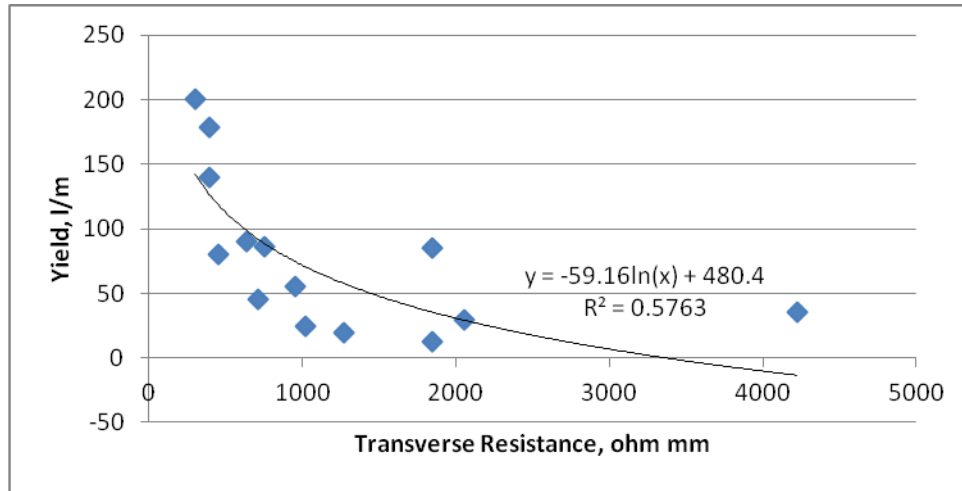


Figure 22: Yield vrs Transverse Resistance from 16 VES data

Transverse resistance showed a good negative logarithmic relationship with yield with R^2 of 0.58 as shown in Figure 22. Hence an increase yield results in a decrease in transverse resistance and vice versa.

4.4.5 Testing Reliability of Regression Models

Figures 23 to 25 illustrate plots of actual yields versus estimated yields computed from the regression models or equations developed from section 4.4.1 (using drill logs of all 33 in Garu Tempane). The results are as presented in appendix G. The lines in Figures 23 to 25 signify the 45 degrees line.

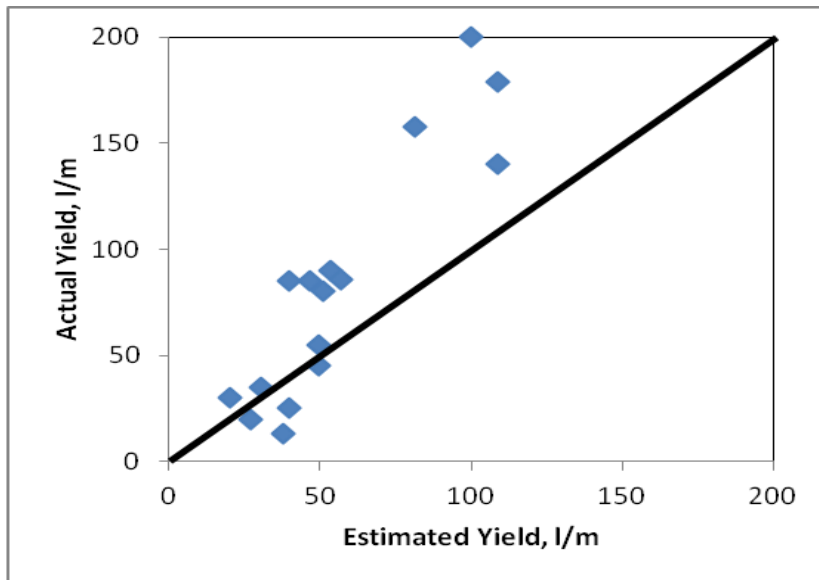


Figure 23: Actual Yield vrs Estimated Yield from Apparent resistivity from 33 Drill logs

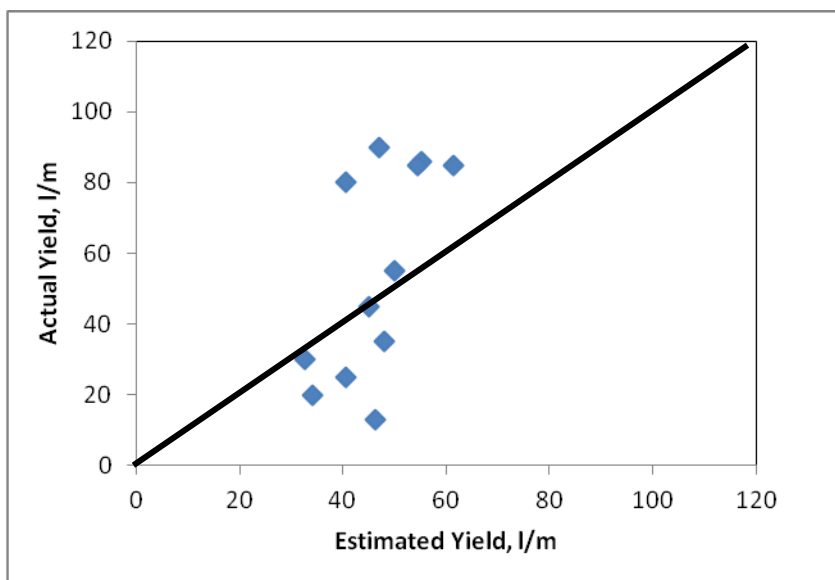


Figure 24: Actual Yield vrs Estimated Yield from Longitudinal conductance from 33 Drill logs

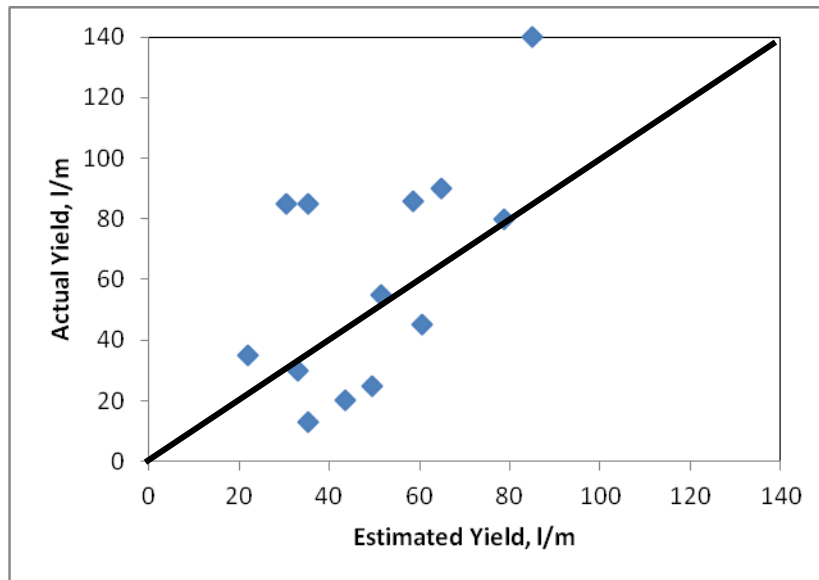


Figure 25: Actual Yield vrs Estimated Yield from Transverse resistance from 33 Drill logs

All three showed good correlation between the actual yields and estimated yields from the apparent resistivity, longitudinal conductance and transverse resistance.

Figures 26 to 28 illustrate plots of actual yields versus estimated yields computed from the regression models or equations developed in section 4.4.3 (using part of Garu Tempane from VES plots). The results are as presented in appendix H. The 45 degrees lines in Figures 26 to 28 represent lines of equality.

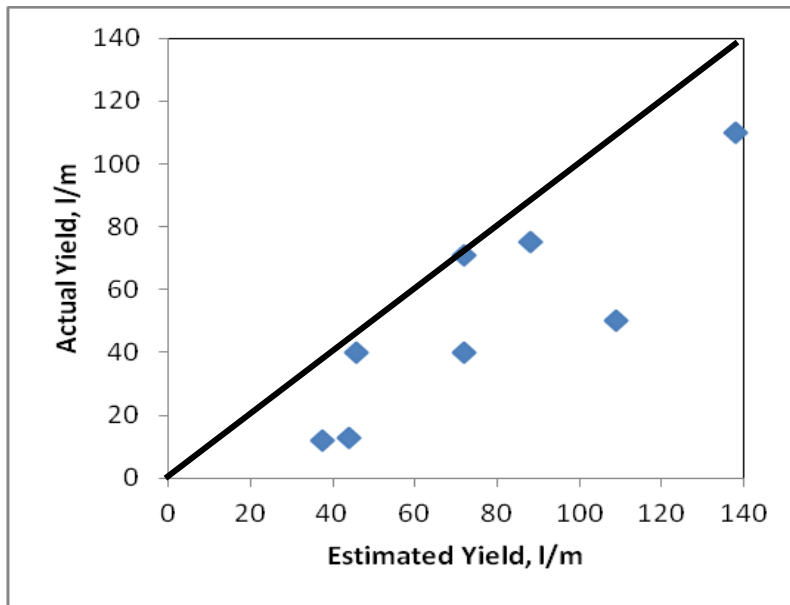


Figure 26: Actual Yield vrs Estimated Yield from Apparent resistivity from 25 VES data

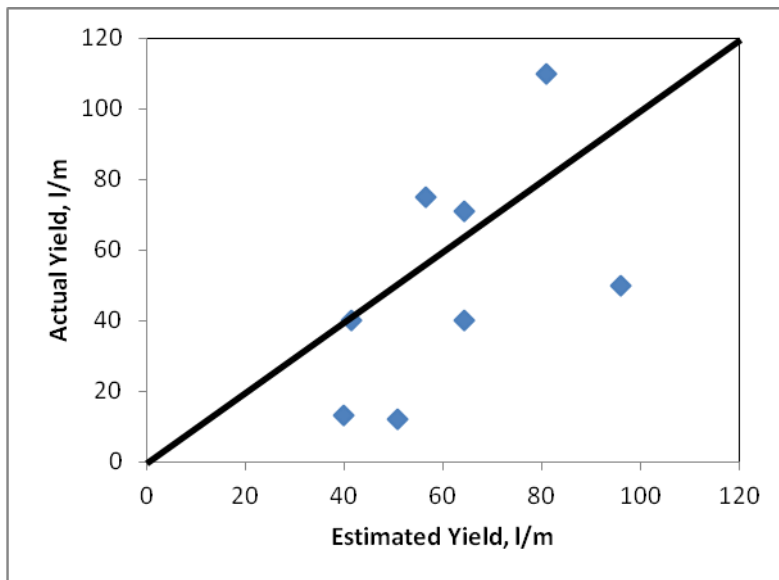


Figure 27: Actual Yield vrs Estimated Yield from Longitudinal Conductance from 25 VES data

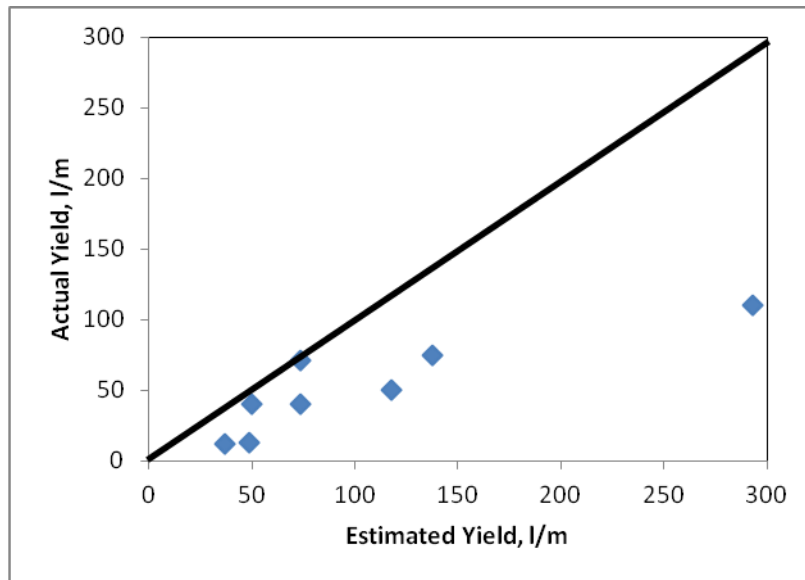


Figure 28: Actual Yield vrs Estimated Yield from Transverse Resistance from 25 VES data

Weak correlations were established between the actual yields and estimated yields from apparent resistivity, longitudinal conductance and transverse resistance. This could be possibly as a result of the lesser data points used in developing the regression models in the borehole yield estimations.

Figures 29 to 31 illustrate plots of actual yields versus estimated yields computed from the regression models or equations developed in section 4.4.3 (using all 33 VES data of Garu Tempane). The results are as presented in appendix I. The 45 degrees lines in Figures 29 to 31 represent lines of equality.

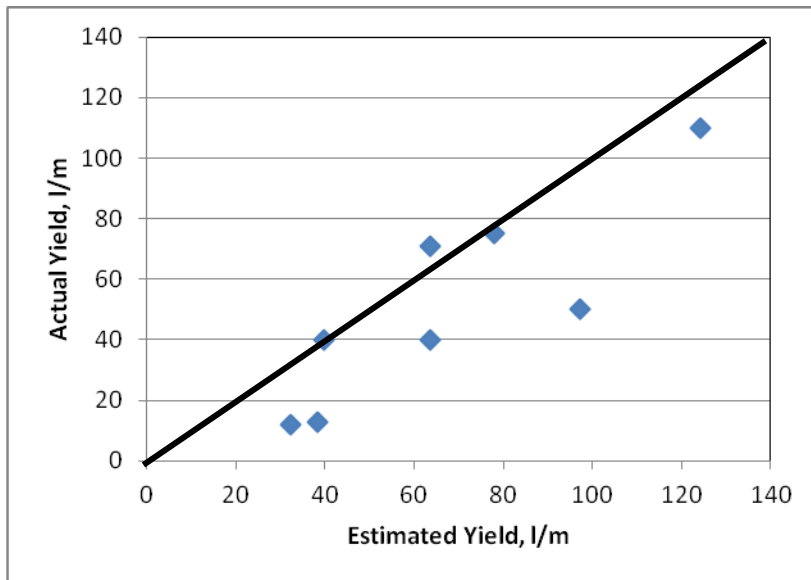


Figure 29: Actual Yield vrs Estimated Yield from Apparent resistivity from 33 VES data

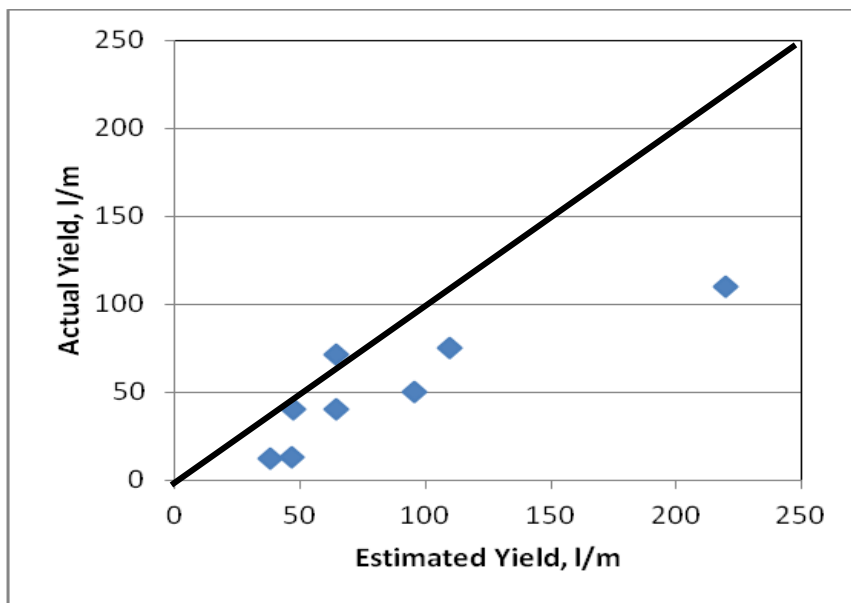


Figure 30: Actual Yield vrs Estimated Yield from Longitudinal Conductance from 33 VES data

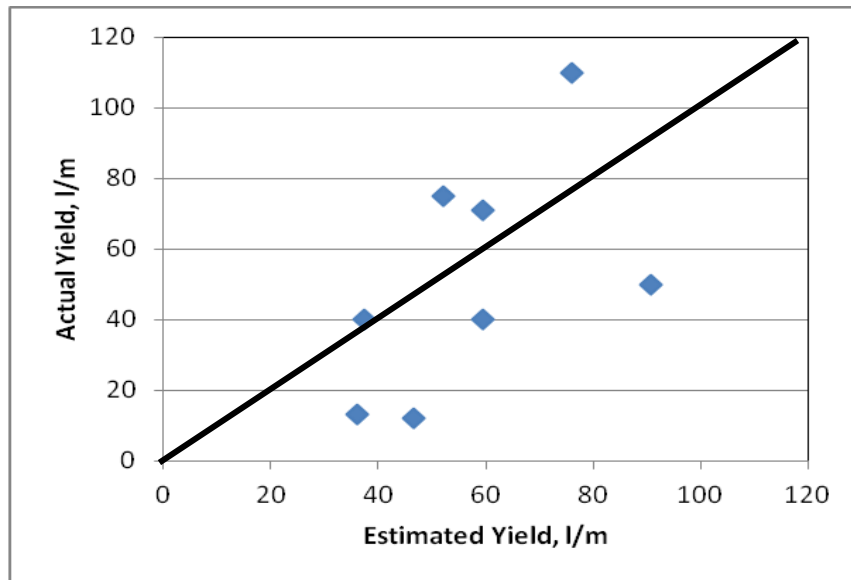


Figure 31: Actual Yield vrs Estimated Yield from Transverse Resistance from 33 VES data

Good correlations were established between the actual yields and estimated yields from apparent resistivity, longitudinal conductance and transverse resistance. This could be possibly attributed to the increased number of data used in developing the regression models in the borehole yield estimations.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Subsurface layers have been generated using drill logs and VES data. Longitudinal conductance and transverse resistance were computed using only the third layer subsurface layers obtained. Relationships were determined between borehole yield and the third subsurface layer apparent resistivity, longitudinal conductance and transverse resistance. Regression models from the relationships were used to estimate borehole yields for Garu Tempane and Bawku West districts in Upper East region. The models reliability was tested with known borehole yields within the study area.

There was not a significant difference in the models developed using the different subsurface layers generated from the drill logs and VES data. Hence the VES results can be potentially used in place of the drill logs in generating subsurface layers.

All predictor variables (apparent resistivity, longitudinal conductance and transverse resistance) agree with the proven observation/theory that areas with high water content have lower resistivities. All individual third layer apparent resistivity values were determined to have an exponential relationship with yield. Longitudinal conductance was found to have a positive linear relationship with yield while the transverse resistance was established to have a power law relationship with yield.

The results also showed that the third layer contributes significantly to borehole yields in the area; hence the subsurface layer is of primary interest for consideration in groundwater exploration and estimating potential borehole yield from VES data. The good correlations between borehole yield and apparent resistivity with R^2 values ranging from 0.66 to 0.79 and longitudinal conductance with R^2 values from 0.60 to 0.75 emphasized the possibility of using geoelectrical (VES) methods as a contributing factor for borehole yield estimation in the same geologic setting (unit).

The study has proven the potential and importance of the method to potentially help reduce dry and marginal boreholes, which increase the cost of groundwater supplies particularly for developing countries with limited financial resources.

5.2 Recommendations

This method can be used to map out potential drilling points for groundwater supplies and to aid reduce dry and marginal wells.

However, before adopting this approach, factors controlling the groundwater occurrence, groundwater potential, its movement and geology must be taken into consideration.

The results presented in this study show promising methods that provide a framework for further studies on the subject. Further studies should be undertaken with increased number of VES measurements; taken at more varied geographical locations to see if there could be an improvement in the developed models and testing its reliability.

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APPENDICES

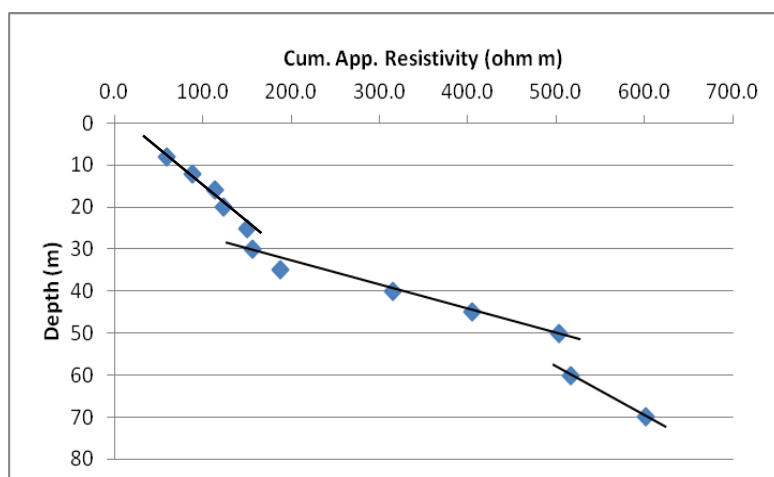
Appendix A: Summary Borehole/VES Data Sheet (Garu Tempene)

Community	VES PEG No.	Depth	Water				Air Lift Test
			Strike				
		(m)	(m)	GPS Coordinates			Yield
				Y	X	Elev (m)	(lpm)
Kpalsako	KPS-B50	43	15	10°48.615'	0°11.199'	247	230
Nyosbara No 1	NYB-C30	40	21	10°50.532'	0°07.919'	223	100
Tempelugo	TMP-B20	37	15	10°55.994'	0°02.714'	249	125
Sumaduri JHS	SJ-C30	43	12	10°49.914'	0°10.735'	235	170
Menatenga	MNT-D100	43	15	10°46.077'	0°15.284'	216	110
Nagani Chief Palace	NN-C90	55	16	10°57.918'	0°0.850'	235	13
Gbelinginvuus	GV-A70	40	9	10°53.907'	0°03.158'	241	75
Kugasheigu	KG-E20	40	9	10°55.357'	0°05.775'	229	100
Farfar	FF-D170	40	12	10°44.578'	0°09.837'	235	170
Gbanterago	GG-D40	40	18	10°50.755'	0°13.246'	214	60
Wabugkpersir	WBP-F45	40	18	10°49.277'	0°1.587'	210	40
Bangoli	BG-A20/D20	45	18	10°43.736'	0°12.422'	222	40
Tambona	TMB-A30	43	15	10°48.380'	0°03.900'	227	60
Benguri	BN-A30	37	18	10°48.596'	0°11.946'	224.4	100
Tirutiga	TD-C170	43	21	10°52.178'	0°04.395'	245	55
Benatinga	BG-C130	46	24	10°52.150'	0°04.685'	240	36
Karateshie Nan. Prim	KNP-B150	37	9	10°57.706'	0°04.230'	263	40
Konkomadaa	KZ-C50	40	18	10°51.428'	0°04.626'	147	12
Sambona-Farfar	SMB-A80	73	45	10°44.600'	0°09.595'	229	18
Bimpilla No. 3	BMP-A70	40	12	10°53.226'	0°01.732'	232	40
Banginong	BNG-BB30	45	19	10°41.295'	0°4.380'	259	28
Lokoam	LOK-C30	36	17	10°51.391'	0°04.014'	252	18
Tuduriga-Top	TDT-A30	33	15	10°51.855'	0°03.507'	264	28
Old Natenga	NYB-C30	43	12	10°53.994'	0°01.746'	237	180
Posia	POA-D60	40	12	10°50.447'	0°02.077'	226	120
Akara Timbilgbeog	AKT-D40	43	24	10°56.955'	0°03.814'	249	37
Yabrago	YAG-A40	46	18	10°51.569'	0°6.656'	220	62
Worikambo Cath. JHS	WCJ-AA40	46	18	10°46.113'	0°08.505'	254	85
Korinzia	KOR-B40	40	18	10°47.683'	0°07.614'	261	60
Kpalug	KPG-CC30	40	12	10°49.108'	0°07.702'	233	24
Siguri Primary Sch.	SGP-C80	40	21	10°46.711'	0°04.734'	224	71
Bariboki	BAB-A60	43	12	10°09.567'	0°03.936'	257.7	58
Tinsugu Bisa	TIG-C30	49	12	10°44.716'	0°49.722'	233	0

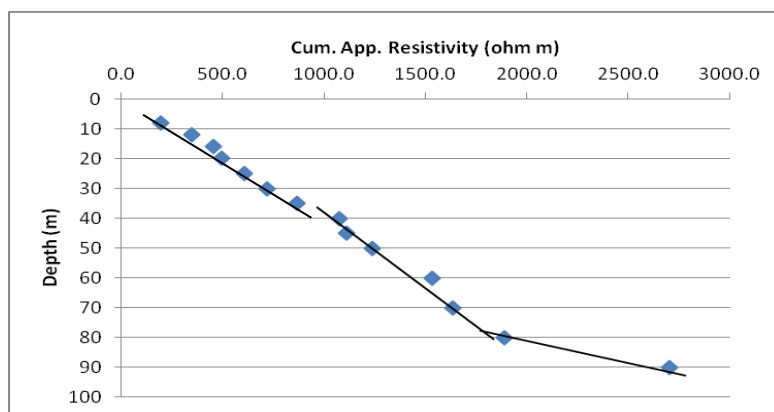
Appendix B: Summary Borehole/VES Data Sheet (Bawku West)

Community	VES PEG No.	Depth	Water				Air Lift Test
			Strike				
		(m)	(m)	GPS Coordinates			Yield
				Y	X	Elev(m)	(lpm)
Gore Bulpeliga	GB-B20	43	24	10°45.548'	0°27.350'	208	90
Bugnaba Kuga	K-20	43	27	10°53.933'	0°27.122'	225	80
Tangdabote	TG-A110	67	48	10°55.233'	0°26.472'	215	20
Gabuluga CHPS	G10	43	18	10°57.223'	0°28.470'	208	140
Galaka CHPS	D15	43	18	11°04.754'	0°22.926'	200	85
Aboadabago	C50	52	27	10°48.950'	0°30.828'	232	55
Abulanga-Apotadogo	A40	52	18	10°48.935'	0°30.905'	232	45
Biringu Boki	BB-E110	52	27	10°56.876'	00°24.558'	193	13
Ankpaliga Prim Sch.	B30	58	48	10°58.152'	0°27.824'	245	25
Peri	P-F150	46	11	10°44.476'	0°27.855'	201	85
Gabuliga	GG-B120	43	12	10°48.307'	0°26.981'	208	200
Gore Kpalsako	GK-B100	43	18	10°46.073'	0°27.461'	225	30
Peri Yapala	PY-C20	43	9	10°44.178'	0°28.335'	219	158
Adonsi Prim. Sch.	APS-B30	46	21	10°49.116'	0°28.237'	208	86
Zoayanga Azure.	ZA-B50	40	18	10°50.224'	0°27.249'	202	35
Nagbere Natinga	NN-A70	46	27	10°50.954'	0°30.875'	221	179

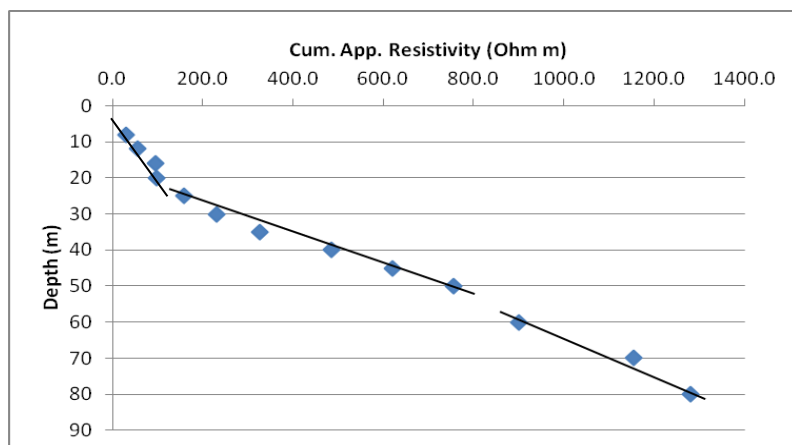
Appendix C: VES Cumulative Plots



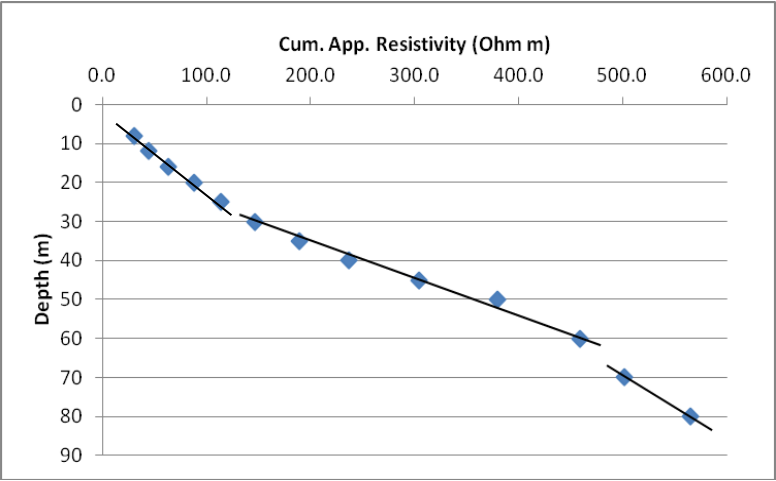
Kpalsako



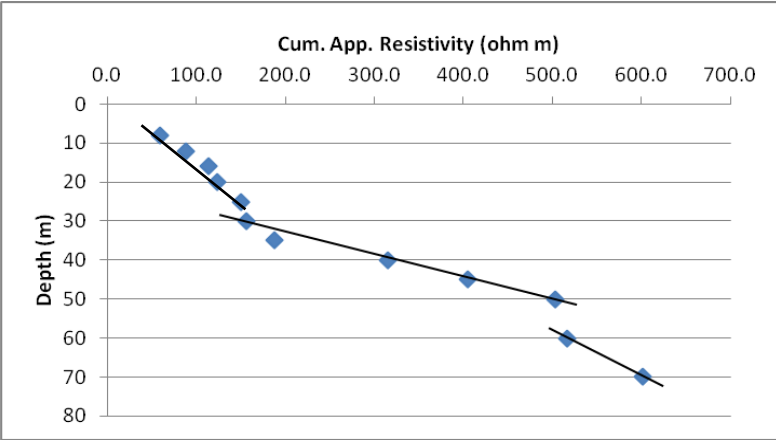
Worikambo Catholic JHS



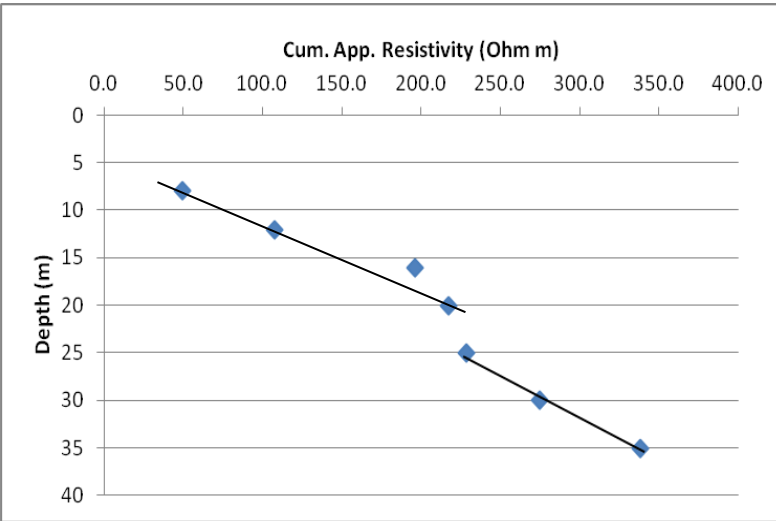
Nagani Chief Palace



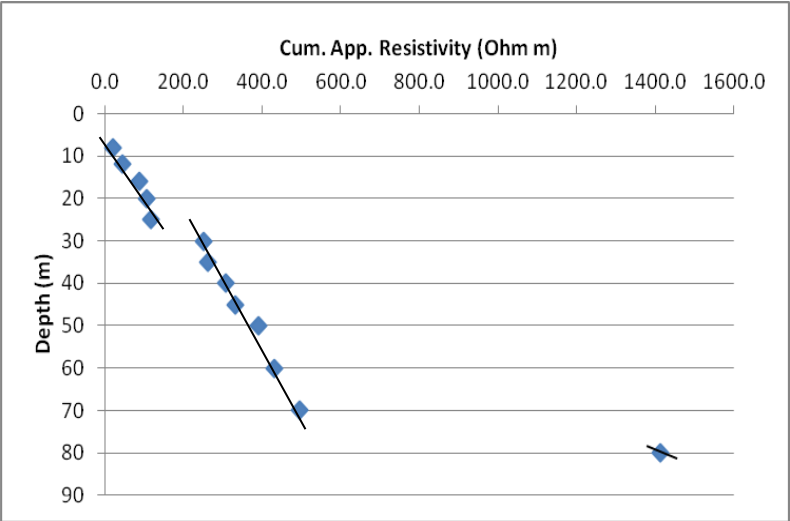
Abaripusiga



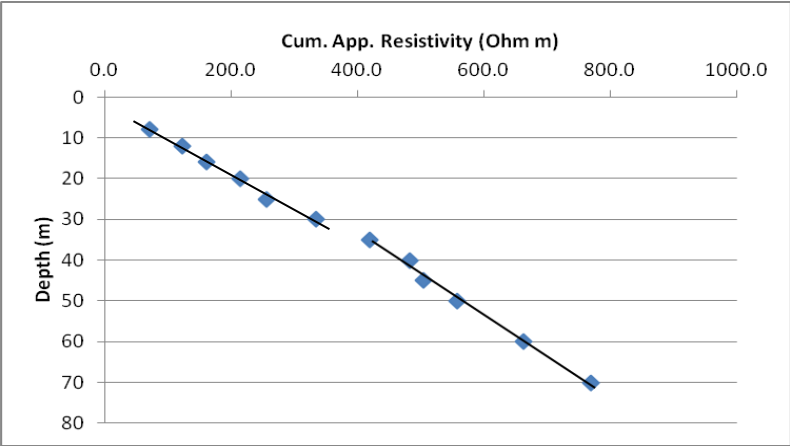
Kpalsako



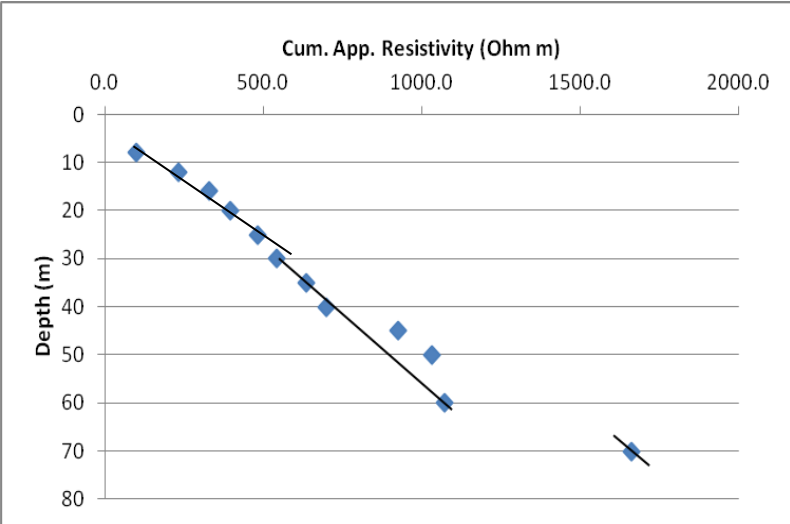
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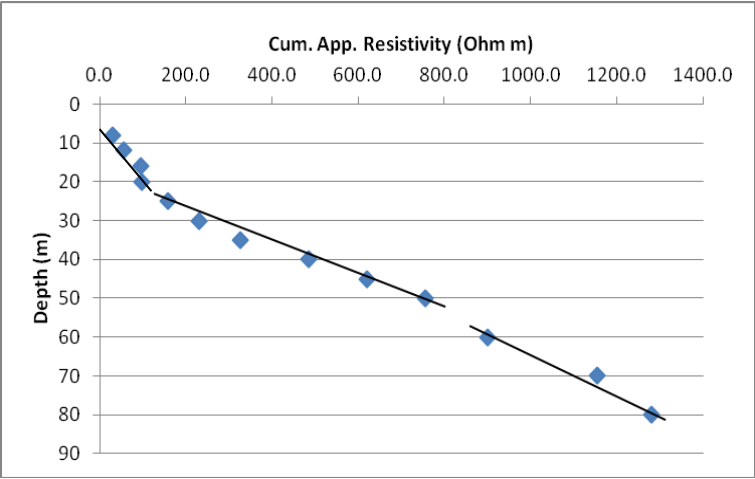
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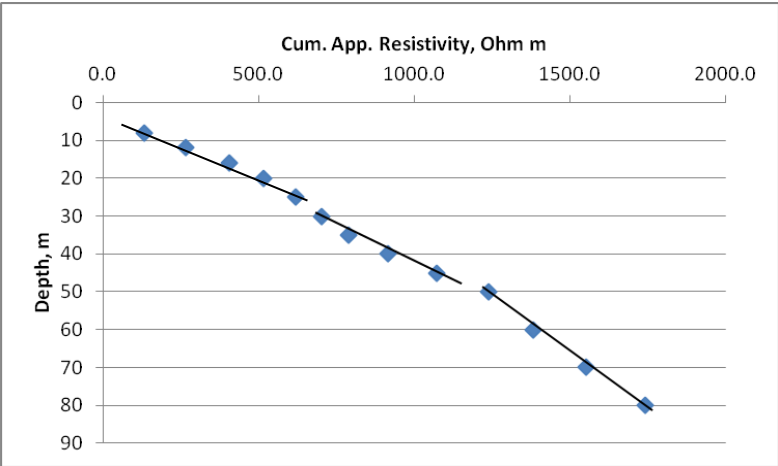
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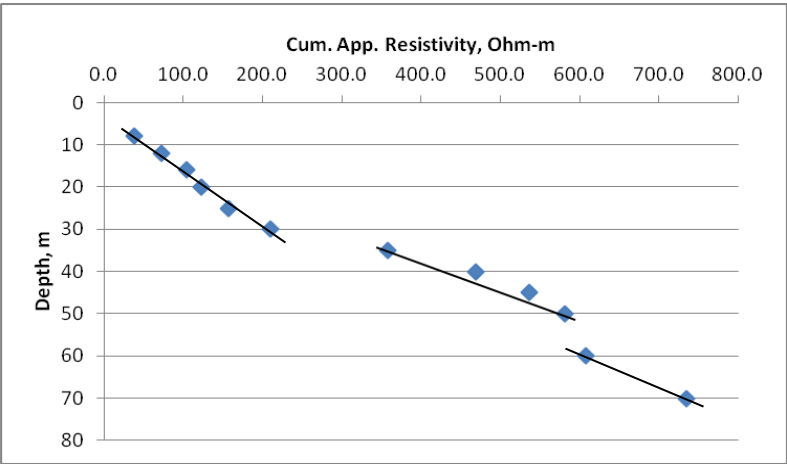
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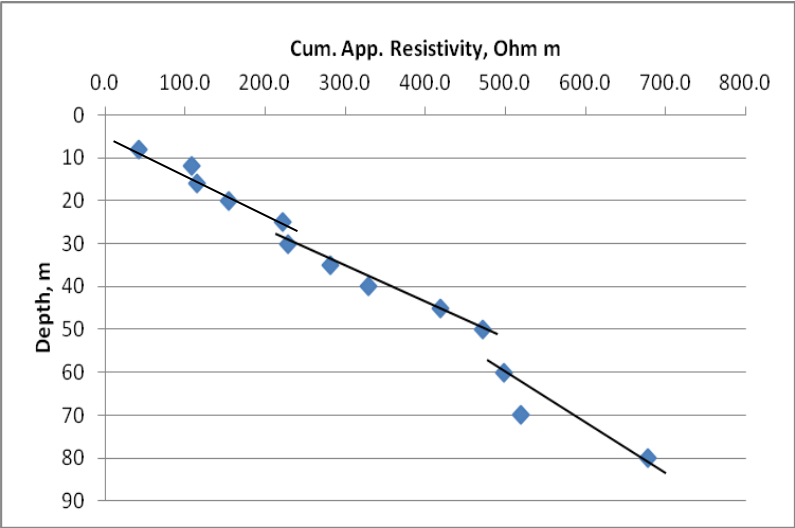
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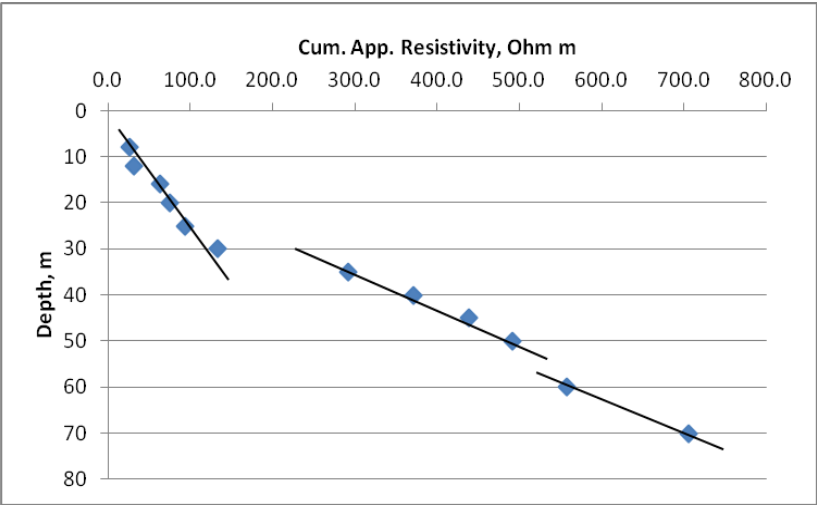
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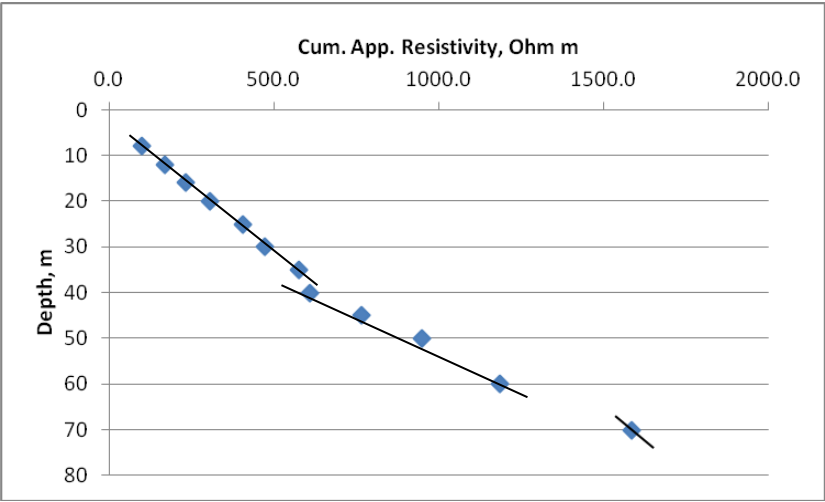
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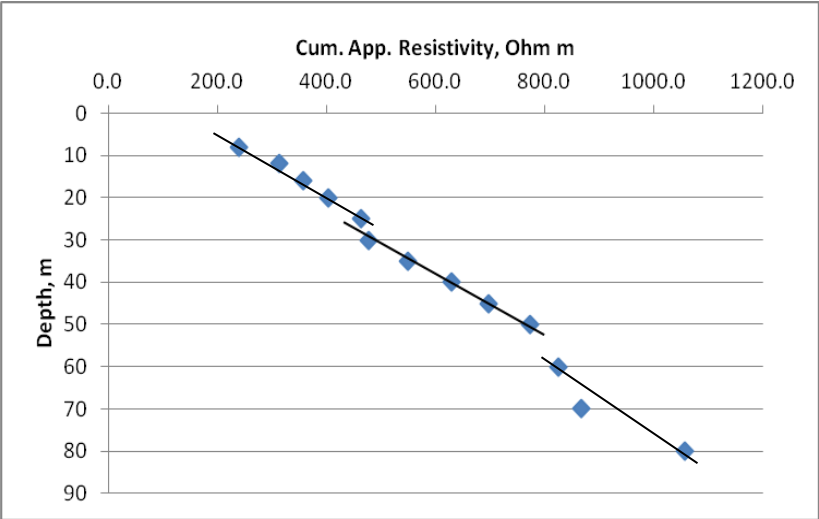
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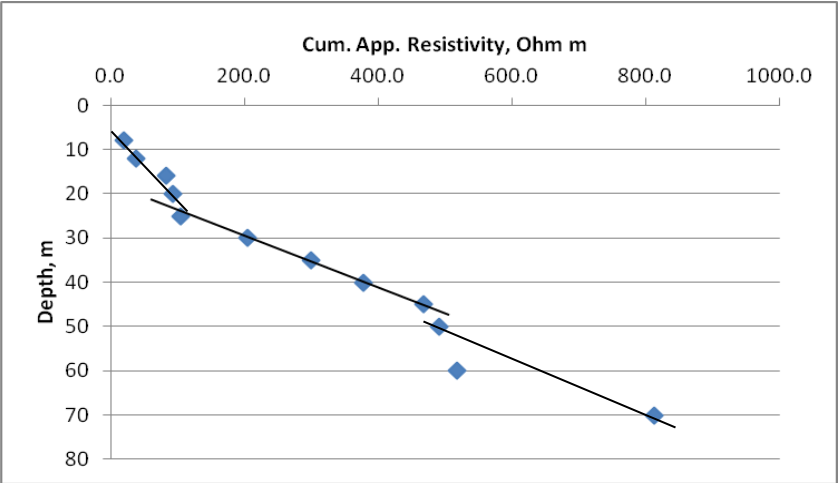
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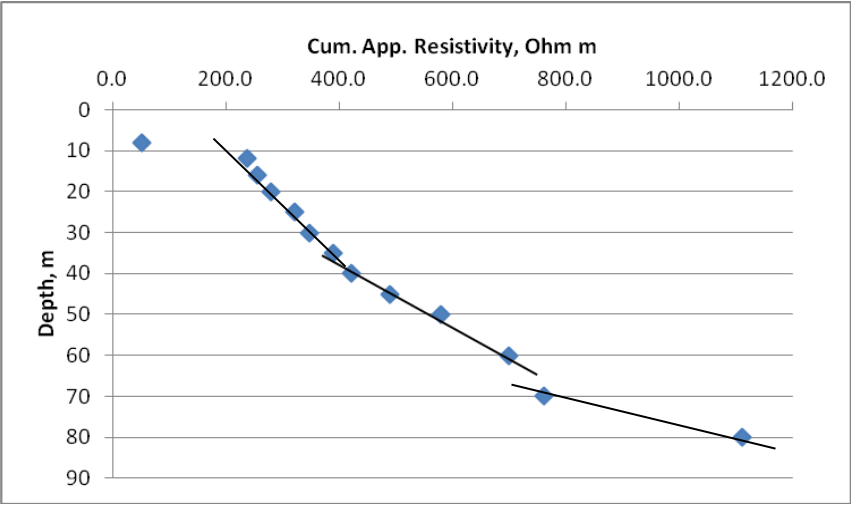
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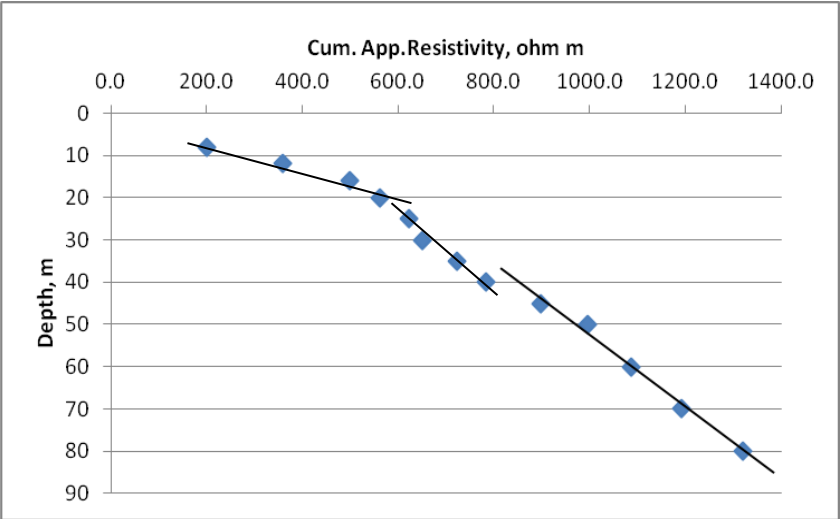
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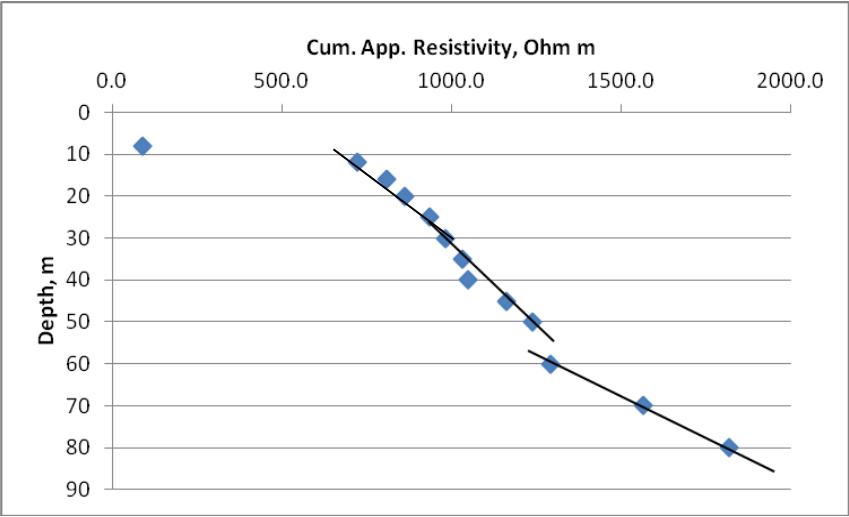
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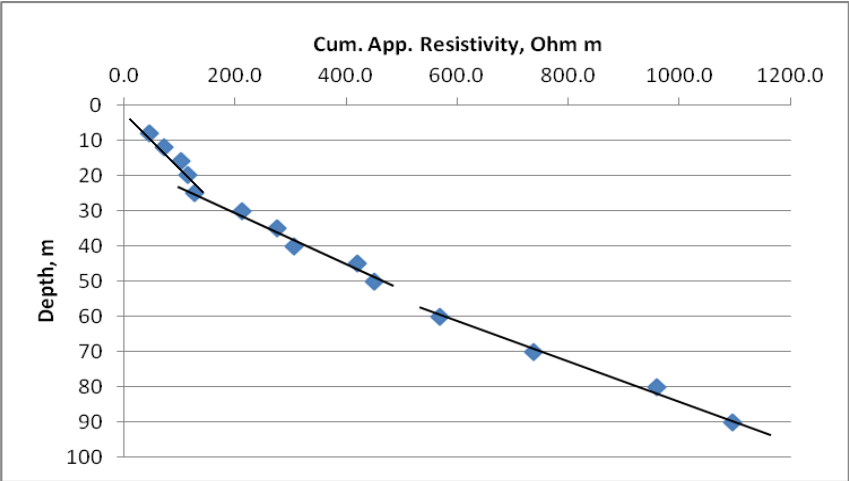
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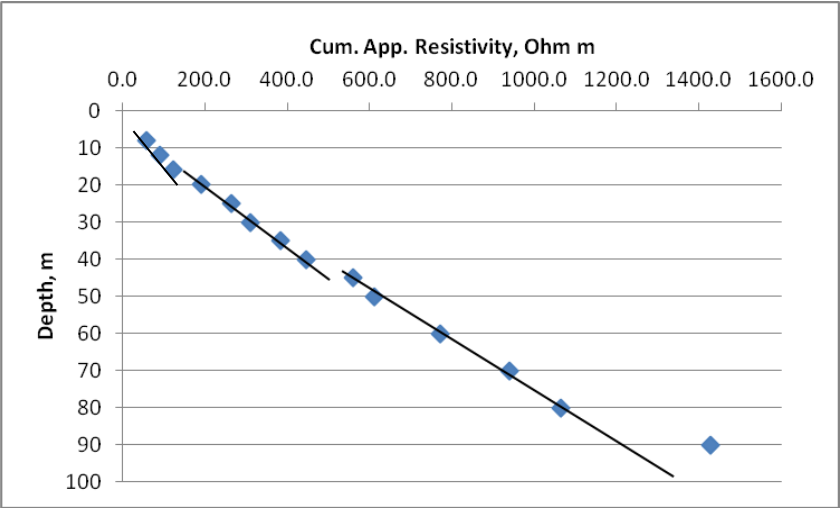
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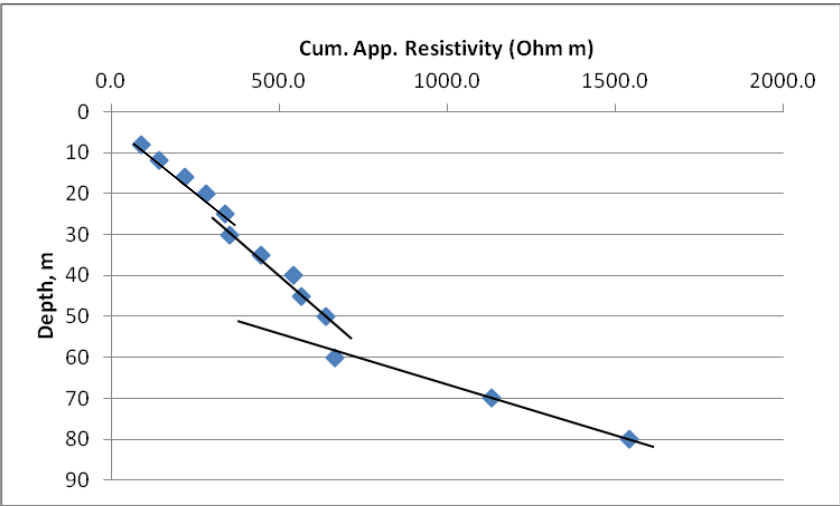
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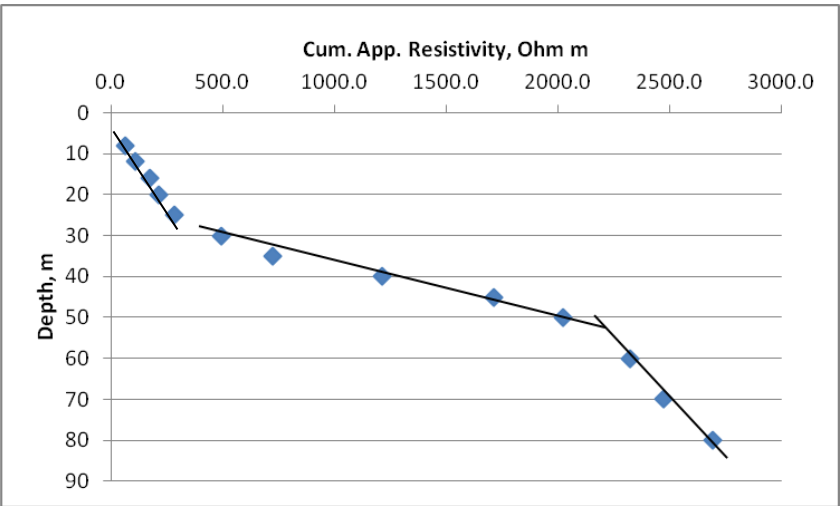
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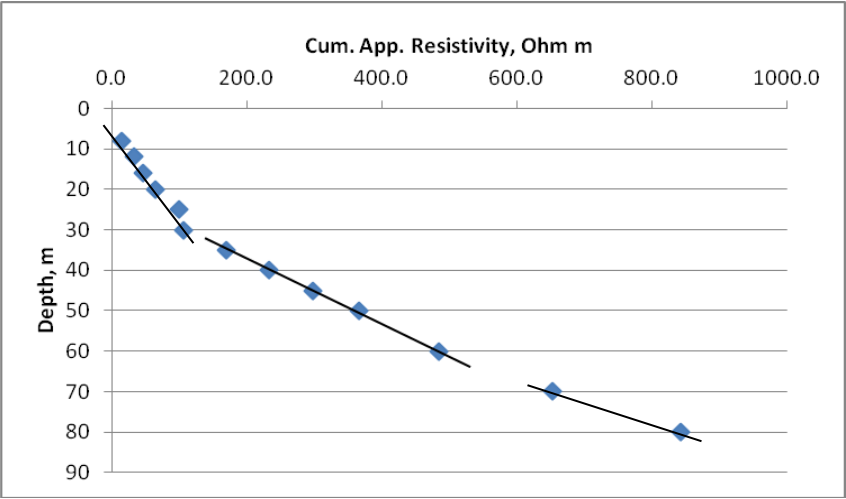
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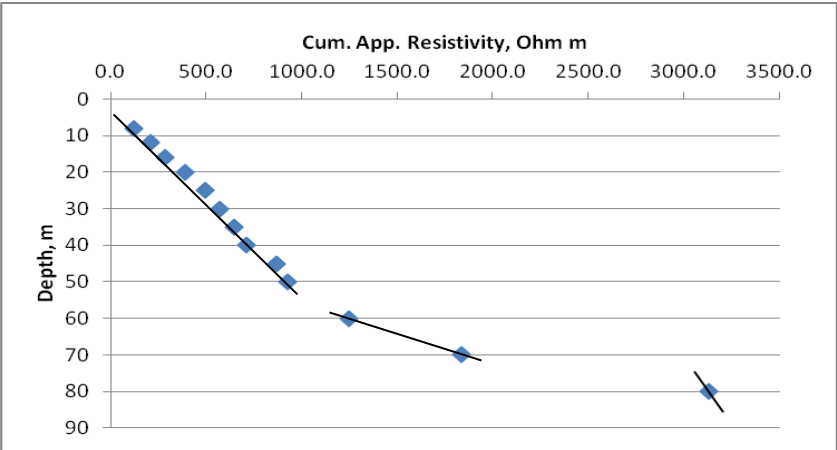
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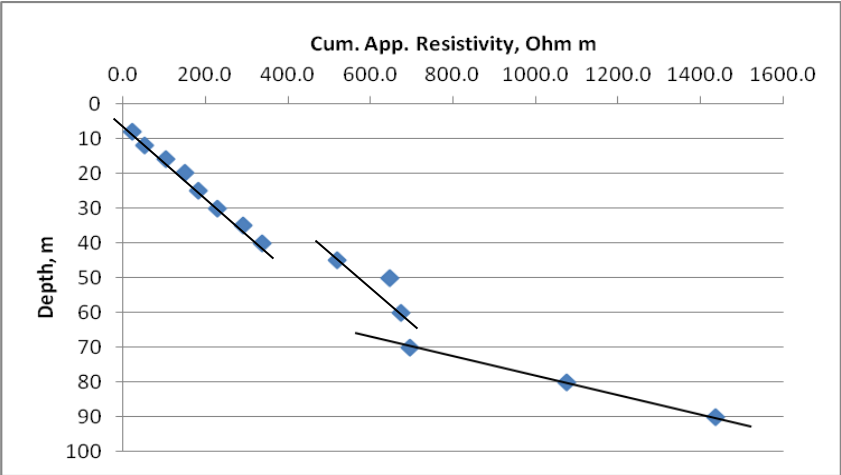
Lokoam



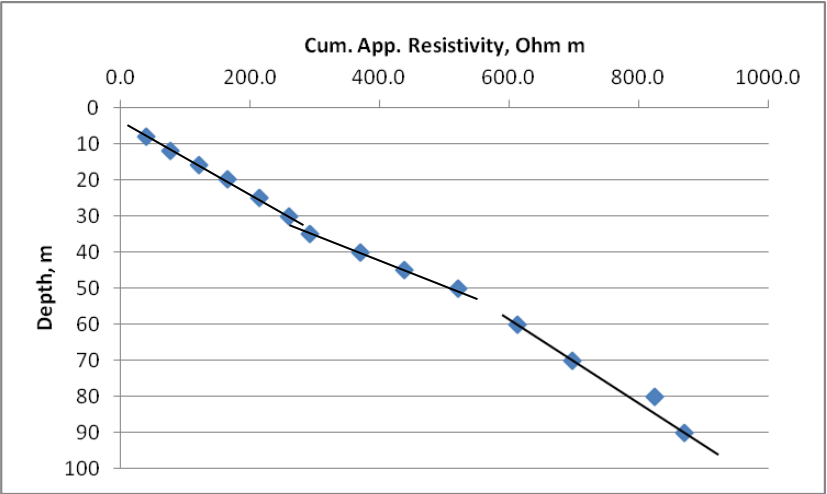
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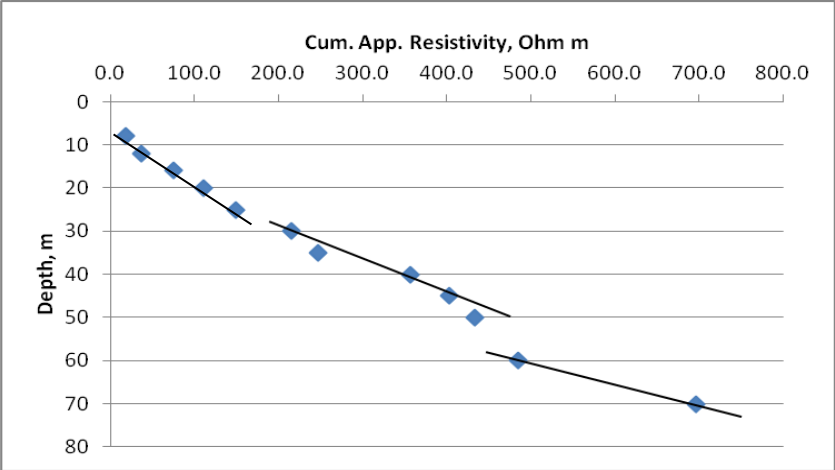
Banginong



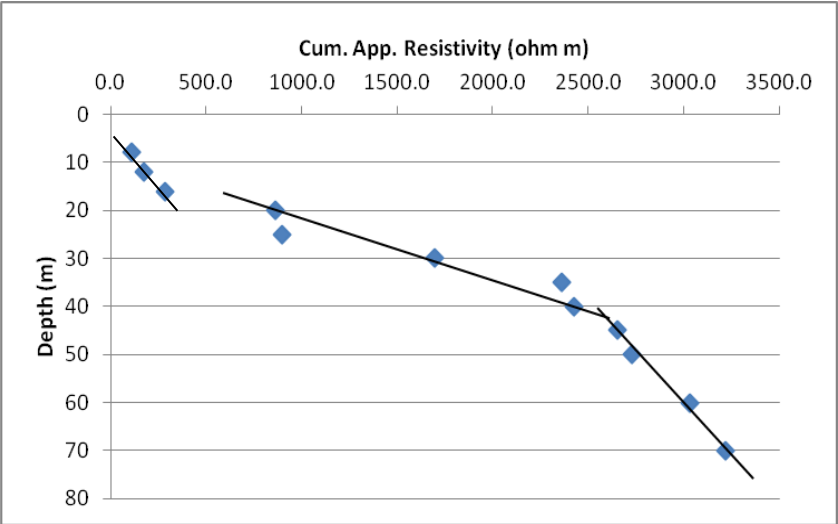
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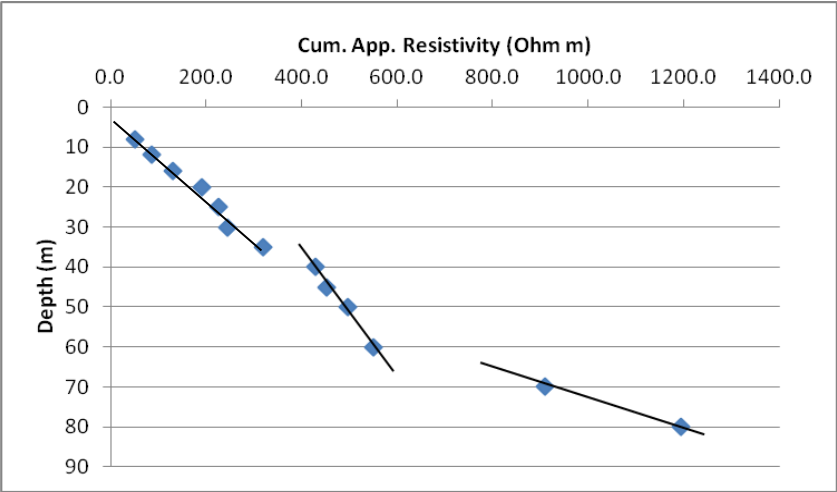
Yabrago



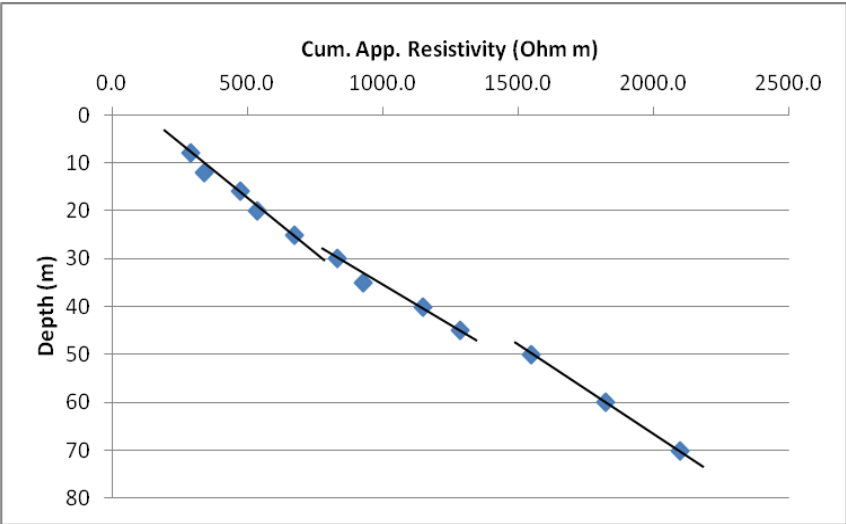
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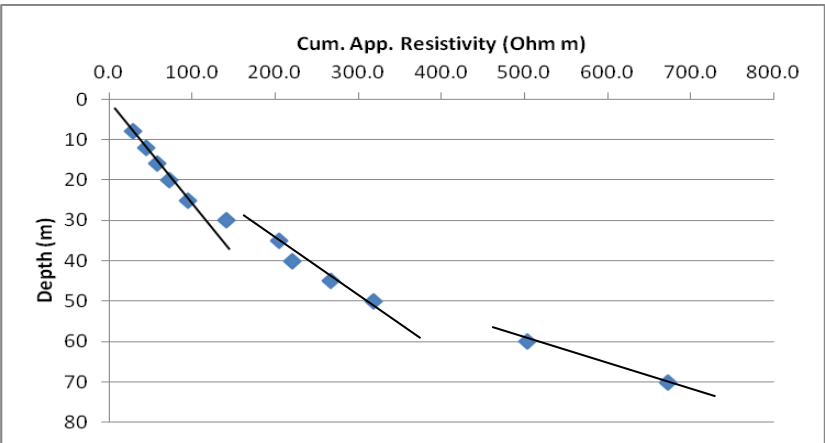
Adonsi Primary School



Zoayanga Primary School



Saka Aniego



Aboadabogo

Appendix D: Subsurface layers with computed longitudinal conductance and transverse resistance from Drill logs for Garu Tempene

Community	Yield (l/m)	Resistivities, R (ohm m)			Thicknesses, D (m)			LC	TR
		Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3		
Karateshie	40		22.6	95	6	24	10	0.11	950
Tempelugo	125		24.5	10.6		23	17	1.60	180.2
Gbanterago	60		33.2	90.5	4	27	20	0.22	1810
Kpalsako	230		9.4	6.6		17	20	3.03	132
Worikambo JHS	85		41.5	38.5	4	27	26	0.68	1001
Old Natenga	180		11.3	11.31	6	12	23	2.03	260.13
Bimpella No.3	40		21.9	26.4	6	32	20	0.76	528
Poazia	120		31.7	46.2	6	8	20	0.43	924
Tuduriga - Top	28		108.68	95.01	4	16	13	0.14	1235.13
Sumaduri JHS	170		18.9	18.85	6	22	23	1.22	433.55
Nyosbara No. 1	100	49.77	20.7	11.3	8	12	20	1.77	226
Kplug	24		11.3	95	4	22	20	0.21	1900.00
Tirutiga	55	98.79	67	39.6	8	17	25	0.63	990.00
Tambona	60		6.6	47.51	6	17	25	0.53	1187.75
Bariboki	58	18.85	18.5	30.2	8	17	25	0.83	755.00
Yabrago	62		37	31.7	6	22	25	0.79	792.50
Benguri	100	19.61	11.3	11.31	8	12	15	1.33	169.65
Korinzia	60		64.1	26.4	5	12	20	0.76	528.00
Abaripusiga	65		13.2	42.2	4	22	25	0.59	1055.00
Banginong	28		60.3	316.7	3	42	20	0.06	6334.00
Akara Tim.	37		12.7	63.3	8	22	35	0.55	2215.50
Sambona Farfar	18		5.3	352.4	8	22	23	0.07	8105.20
Lokoam	18		35.8	211.1	6	17	20	0.09	4222.00
Benatinga	36		85.8	84.5	4	22	20	0.24	1690.00
Farfar	170		55.4	13.2	6	17	30	2.27	396.00
Gbelingivuus	75		50.8	22.6	6	24	35	1.55	791.00
Nagani C. Palace	13		70.9	72.6	8	20	20	0.28	1452.00
Menatenga	110		120.2	10.6	6	18	40	3.77	424.00
Siguri Primary	71		94.5	31.7	4	15	20	0.63	634.00
Tinsugu Bisa	50		70.2	15.8	3	12	20	1.27	316.00
Wabugkpesir	40		80.3	31.7	5	25	20	0.63	634.00
Bangoli	40		71.80	67.87	7	30	20	0.29	1357.40
Konkomadaa	12		24.50	95	12	18	10	0.11	950.00

Appendix E: Subsurface layers with computed longitudinal conductance and transverse resistance from VES data (Garu Tempene)

Community	Yield (l/m)	App. Resistivity (Ohm m)		Thicknesses, D (m)		LC	TR
		Layer 2	Layer 3	Layer 2	Layer 3		
Karateshie	40	22.6	95	22	10	0.11	950
Tempelugo	125	24.5	10.6	30	15	1.42	159
Gbanterago	60	33.2	90.5	25	10	0.11	905
Kpalsako	230	9.4	6.6	25	20	3.03	132
Worikambo JHS	85	41.5	38.5	30	30	0.78	1155
Old Natenga	180	11.3	11.31	15	20	1.77	226.2
Bimpella No.3	40	21.9	26.4	35	15	0.57	396
Poazia	120	31.7	46.2	10	20	0.43	924
Tuduriga - Top	28	108.68	95.01	20	13	0.14	1235.13
Sumaduri JHS	170	18.9	18.85	25	15	0.80	282.75
Nyosbara No. 1	100	20.7	11.3	15	10	0.88	113
Kplug	24	11.3	95	25	10	0.11	950.00
Tirutiga	55	67	39.6	20	30	0.76	1188.00
Tambona	60	6.6	47.51	25	20	0.42	950.20
Bariboki	58	18.5	30.2	25	20	0.66	604.00
Yabrago	62	37	31.7	15	15	0.47	475.50
Benguri	100	11.3	11.31	30	20	1.77	226.20
Korinzia	60	64.1	26.4	12	15	0.57	396.00
Abaripusiga	65	13.2	42.2	25	25	0.59	1055.00
Banginong	28	60.3	316.7	30	10	0.03	3167.00
Akara Tim.	37	12.7	63.3	25	25	0.39	1582.50
Sambona Farfar	18	5.3	352.4	20	15	0.04	5286.00
Lokoam	18	35.8	211.1	20	20	0.09	4222.00
Benatinga	36	85.8	84.5	17	15	0.18	1267.50
Farfar	170	55.4	13.2	20	20	1.52	264.00
Gbelingivuuus	75	40	22.6	30	35	1.55	791.00
Nagani Palace	13	60	72.6	25	20	0.28	1452.00
Menatenga	110	110	10.6	25	35	3.30	371.00
Siguri Primary	71	90.5	31.7	20	30	0.95	951.00
Tinsugu Bisa	50	65.5	15.8	30	20	1.27	316.00
Wabugkpesir	40	70.8	31.7	20	25	0.79	792.50
Bangoli	40	66.70	67.87	17	20	0.29	1357.40
Konkomadaa	12	24.50	95	17	10	0.11	950.00

Appendix F: Subsurface layers with computed longitudinal conductance and transverse resistance from VES plots only (Bawku West)

Community	Water Strike	Yield (l/m)	App. Resistivity (Ohm m)		Thicknesses, D (m)		LC	TR
			Layer 2	Layer 3	Layer 2	Layer 3		
Biringu Boki		13	44.9	73.9	22	25	0.34	1847.5
Aboadabogo		55	31.7	47.51	17	20	0.42	950.20
Zoayan.Azure		35	44.3	105.6	37	40	0.38	4224.00
Gabuliga		200	37.7	15.1	17	20	1.32	302.00
G. Kpalsako		30	24.1	205.9	27	10	0.05	2059.00
AbulangaApot.		45	12.7	47.51	22	15	0.32	712.65
GabulugaCHPS		140	18.9	13.2	27	30	2.27	396.00
Galaka CHPS		85	12.4	52.8	32	35	0.66	1848.00
Bugnaba Kuga		80	37.7	45.2	22	10	0.22	452.00
Nag. Natinga		179	18.9	13.2	27	30	2.27	396.00
Gore Bulpeliga		90	15.1	42.2	22	15	0.36	633.00
Ankpaliga Prim		25	32	67.9	32	15	0.221	1018.5
Adonsi Prim.		86	68.6	37.7	8	20	0.53	754.00
Tandabote		20	60.3	126.7	27	10	0.08	1267.00
Peri Yapala		158	35.8	21.10	12	45	2.13	949.5
Peri		85	24.5	67.90	32	35	0.52	2376.5

Appendix G: Estimated yields for Bawku West using developed yield models for Garu Tempene.

Community	Yield (l/m)	Layer 3 App. Resistivity	LC	TR	EST. Yield(resistivity), l/m	EST. Yield (LC), l/m	EST. Yield (TR), l/m
Biringu Boki	13	73.9	0.34	1847.50	38	46	35
Aboadabogo	55	47.51	0.42	950.20	50	50	51
Zoayanga Az.	35	105.6	0.38	4224.00	30	48	22
Gabuliga	200	15.1		302.00	100	30	99
Go. Kpalsako	30	205.9	0.05	2059.00	20	33	33
Abulan-Apot.	45	47.51	0.32	712.65	50	45	61
Tandabote	20	126.7	0.08	1267.00	27	34	44
Gabulu.CHPS	140	13.2	2.27	396.00	109	137	85
Galaka CHPS	85	52.8	0.66	1848.00	46	61	35
BugnabaKuga	80	45.2	0.22	452.00	51	41	79
NagbereNatinga	179	13.2	2.27	396.00	109	137	85
Gore Bulpeliga	90	42.2	0.36	633.00	53	47	65
Ankpaliga Prim	25	67.9	0.22	1018.50	40	41	49
Adonsi Pri. Sch	86	37.7	0.53	754.00	57	55	59
Peri Yapala	158	21.10	2.13	949.50	81	130	51
Peri	85	67.90	0.52	2376.50	40	54	30

Appendix H: Estimated yields for Garu Tempane from developed yield models

(part) for Garu Tempane

Community	Yield (l/m)	Layer 3 App. Resistivity	LC	TR	EST. Yield(resistivity), l/m	EST. Yield (LC), l/m	EST. Yield (TR), l/m
Gbelingivuus	75	22.6	1.55	791	88	138	57
Nagani C. Palace	13	72.6	0.28	1452	44	49	40
Menatenga	110	10.6	3.77	424	138	293	81
Siguri Primary	71	31.7	0.63	634	72	74	64
Tinsugu Bisa	50	15.8	1.27	316	109	118	96
Wabugkpesir	40	31.7	0.63	634	72	74	64
Bangoli	40	67.87	0.29	1357.4	46	50	41
Konkomadaa	12	95	0.11	950	37	37	51

Appendix I: Estimated yields for Garu Tempene from developed yield models

(all) for Garu Tempene

Community	Yield (l/m)	Layer 3 App. Resistivity	LC	TR	EST. Yield(resistivity) , l/m	EST Yield (LC) , l/m	EST Yield (TR) , l/m
Gbelingivuus	75	22.6	1.55	791	78	109	52
Nagani C. Palace	13	72.6	0.28	1452	38	47	36
Menatenga	110	10.6	3.77	424	124	219	76
Siguri Primary	71	31.7	0.63	634	63	64	59
Tinsugu Bisa	50	15.8	1.27	316	97	96	91
Wabugkpesir	40	31.7	0.63	634	63	64	59
Bangoli	40	67.87	0.29	1357.4	40	48	38
Konkomadaa	12	95	0.11	950	32	38	47