CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Public health and food security are jeopardized due to climate change caused by the emission of green-house gases from fossil fuel, which alters the rainfall pattern and consequently have serious implications on freshwater in aquifers (Okoro *et al*., 2010). The excessive demand for potable water by the increasing population of most developing countries has resulted in the drying up of surface water and depletion of groundwater (Okoro *et al.*, 2010). WHO/UNICEF (2017) revealed that as at 2015, 58% of the estimated 159million people that are still collecting drinking water directly from the surface water sources lived in sub-Saharan Africa. Notably, surface water sources are open water bodies that may be polluted and contaminated. Orakwe (2010) stated that potable water supply should be affordable, available and easily accessible at all time with special emphasis on meeting at least the local standard on potable water quality.

The World Health Organisation, after the expiration of the Millennium Development Goals (MDGs) in 2015 came up with another programme called Sustainable Development Goals (SDGs) which is aimed at improving and sustaining the various achievements of the MDGs. The SDG progamme is expected to last till 2030 and has the following among its mandates (WHO/UNICEF, 2017);

- Call for a total and unbiased access for all, which promotes equity in service levels.
- Hygiene. (This was not addressed in the MDGs)
- Safe and affordable drinking water with adequate sanitation.

The World Health Organization (WHO/UNICEF, 2017) also noted that as at 2015, 844 million people still do not have access to basic drinking water service. Out of the 900 million human populations in Africa, 80% rely on groundwater for their different water needs (JMP, 2008).

Many communities in Africa rely on groundwater supplies for domestic, industrial and agricultural purposes. Osei-Asare (2004) concluded that water scarcity is high in Sub-Saharan Africa, thus making it gradually more difficult for most developing countries to meet up with the WHO minimum standard for per capita water consumption of 20 litres per day (Ezenwaji *et al.*, 2014).

Surface water is a major source of clean drinking water all over the world. However, increased demands for water have stimulated development of underground water resources. Open water bodies are usually polluted and contaminated and often times shared with grazing livestock. Groundwater has become immensely important for human water supply in urban and rural areas in developed and developing nations alike (Omosuyi,2010). 60% of people in developing countries have access to average water supply; while about 35% had access to good sanitation facilities, hence, about 80% of ill health in developing countries is related to inadequate quality and quantity of water as well as sanitation (Orakwe, 2010). Groundwater is well suited to rural water supply in sub- Saharan Africa (MacDonald and Davies, 2000). Groundwater has numerous advantages and has been exploited increasingly in recent years: groundwater responds slowly to changes in rainfall, the impacts of droughts are often buffered; in areas with long dry season, groundwater is still available when sources such as rivers and streams have run dry. This resource is relatively cheap to develop, since large surface reservoirs are not required and water sources can usually be constructed close to areas of demand. Groundwater remains a reliable source of clean water to a large population of developing countries.

However, in many areas throughout Nigeria, a staggering proportion of wells and boreholes fail. Failure can occur for a number of reasons; inadequate maintenance and community involvement, poor engineering or over exploitation. Often, it can be difficult to work out the exact reason after the event. However, in many geological environments the impacts of poorly sited and designed boreholes and wells are of major concern to funding agencies, implementing institutions and local communities. Boreholes and wells must be sited and designed carefully to make use of the available groundwater. In order to appropriately site and design groundwater sources, the groundwater resources of the area must firstly be investigated to understand how water occurs in the ground (MacDonald *et al.*, 2001). As a result, techniques for investigating the occurrence and movement of groundwater have been improved, better equipment for extraction has been developed, concepts for resource management have been established, and research has contributed to a better understanding of the subject. Geophysical exploration is the scientific measurement of physical properties of the earth crust for investigation of mineral deposits or geologic structure, there is need to apply geophysical exploration research to provide sufficient data for groundwater exploration. This study is geared towards application of geophysical exploration techniques using electrical resistivity method in groundwater exploration and characterization of the groundwater quality. This method in particular will enhance estimation of the groundwater reserve within various geological formations.

1.2 Statement of Problem

Adequate and regular water supply is a basic requirement for every resident of Anambra State but due to the ever growing population and the inability of the government to provide potable water schemes in the State, coupled with the lack of developed potable surface water sources, private individuals have resorted to exploitation of groundwater supplies in order to meet their daily water needs. However, many problems exist as a result of insufficient knowledge of the subsurface geophysical conditions coupled with the questionable water quality and its sustainability in many parts of the state.

The development of groundwater involves the sinking of boreholes at sites, which most times are chosen arbitrarily. In several cases, this has resulted in abortive boreholes, extreme low yield and total failure of some supply wells within the State. This has therefore undermined the importance of taking proper precautions in groundwater development. It is also very important to note that indiscriminate siting of boreholes without proper understanding of the groundwater characteristics usually present serious problems towards actualizing the objectives of exploiting underground water resources for domestic, agricultural and commercial purposes. Consequently, proper understanding of groundwater characteristics like the geological formations of the water bearing aquifers, depth of occurrence, recharge ability, flow dynamics, aquifer thickness etc. is very important.

1.3 Aim and Objectives of the Study

The aim of this research work is to carry out a baseline study of groundwater potentials in Anambra State. Thus, the following are specifically the primary objectives of the study:

i. To characterize different aquifer parameters by applying the electrical resistivity method in the assessment of groundwater reserve in the study area

ii. To evaluate data generated from detailed interpretation of vertical electrical sounding curves and groundwater qualities within the study area.

iii. To determine the groundwater flow direction, assess the groundwater potentials (quantity and quality) and determine soil erodibility of the overburden layers within the study area.

iv. To develop a risk model chat for groundwater resources, propose a model for siting of potential boreholes within the study area

v. To develop generalized geological and statistical models that will assist both the government and individuals in groundwater assessment, development and management.

1.4 Significance of Study

Public water supply schemes in Anambra State are incapacitated to the extent of near total collapse. However, limited service coverage and poor service delivery have forced most individuals to opt for alternative source of water supply, which in most cases is the groundwater reservoir. Therefore, it has become imperative that most research on groundwater should be tailored towards filling in the gaps associated with lack of well-organized and integrated water resources database both at the National and Regional levels. Thus, this study will provide such data/information for effective groundwater development and management in Anambra State.

1.5 Scope of the Study

In this study, data on aquifer resistivity, thickness and depth at the study area were investigated and documented. Also, data on other groundwater characteristics such as the water quality, erodibility, transmissivity, hydraulic conductivity, apparent resistivity, reflection coefficient, fractured contrast and the contributions of the different types of geological formations to the water bearing aquifer, soil characteristics and structures of aquifer were also investigated. This study developed relationships between the various geological formations and aquifer characteristics.

CHAPTER TWO

LITERATURE REVIEW

2.1 Geology of Anambra State

Anambra State lies within the Benue Trough and it is underlain by Cretaceous to recent sedimentary formations of the Anambra Basin that have varying aquifer potentials (Nfor *et al.*, 2007; Chinwuko and Anakwuba, 2016). Most of the geological formations found within the Anambra Basin did not outcrop from the state but are found in the subsurface (Figure 2.1).

Chinwuko and Anakwuba (2016) in the research done for the Anambra State Government, produced the most recent detailed geological mapping of the State, revealing the five predominant lithostratigraphic formations (Figure 2.2; Table 2.1)

These formations include; Nsukka Formation (Maastrichtian – Danian), Imo Formation (Imo shale and Ebenebe sandstone) (Paleocene), Ameki Formation (Nanka sandstone and Nsugbe sandstone) (Eocene), Ogwashi-Asaba Formation (Oligocene – Miocene) and Benin Formation (Pliocene-Recent). The report indicated that every other formation found in the state is referred to as Niger Delta formation apart from Nsukka formation that occupies a very minute portion of the south-eastern end of the State.

The varying aquifer potentials of these different geological formations are enormous and worthy of development.

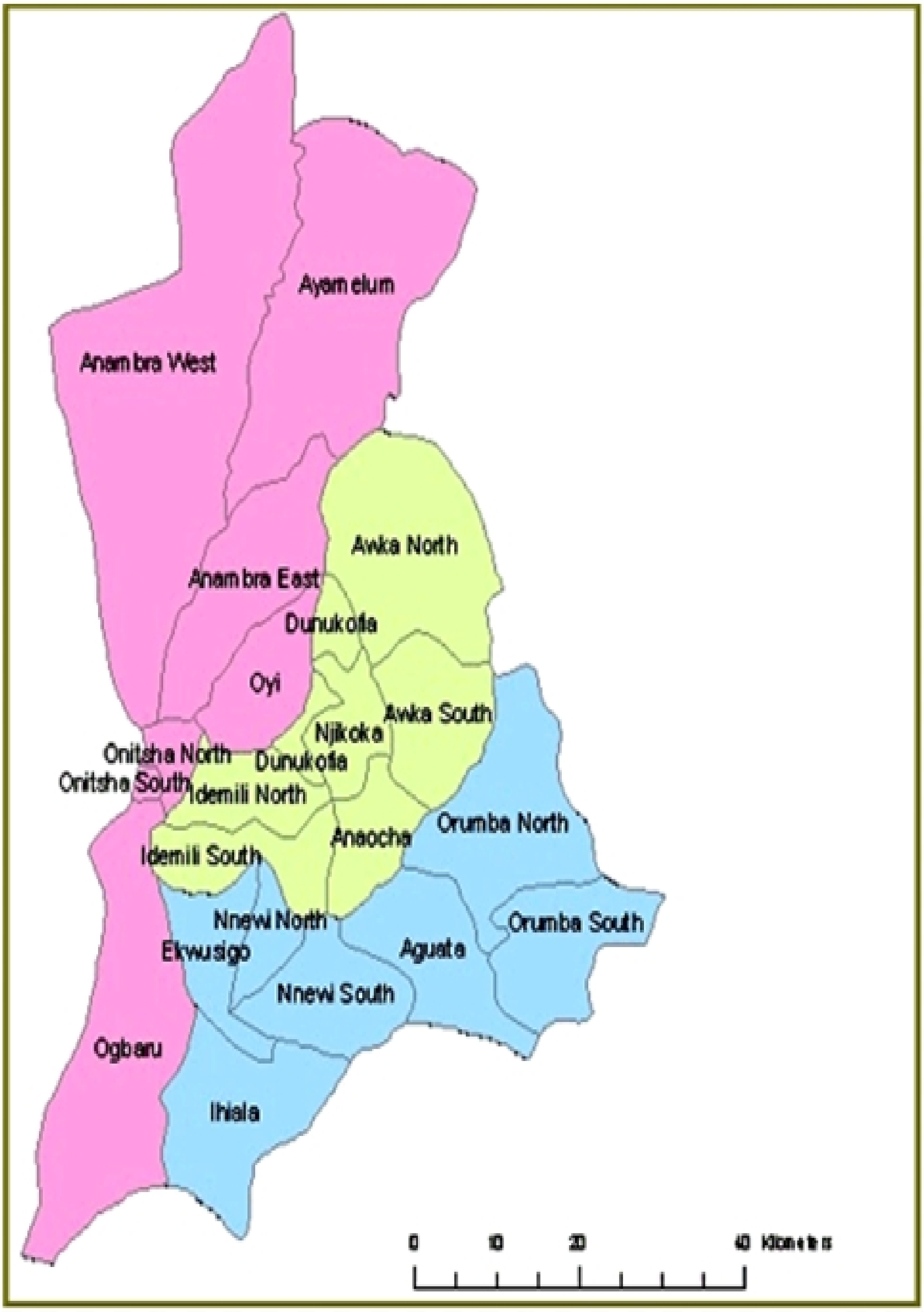


Figure 2.1: Anambra State Map showing the 21 Local Government Areas (NGSA, 2010)

GEOLOGIC MAP OF ANAMBRA STATE

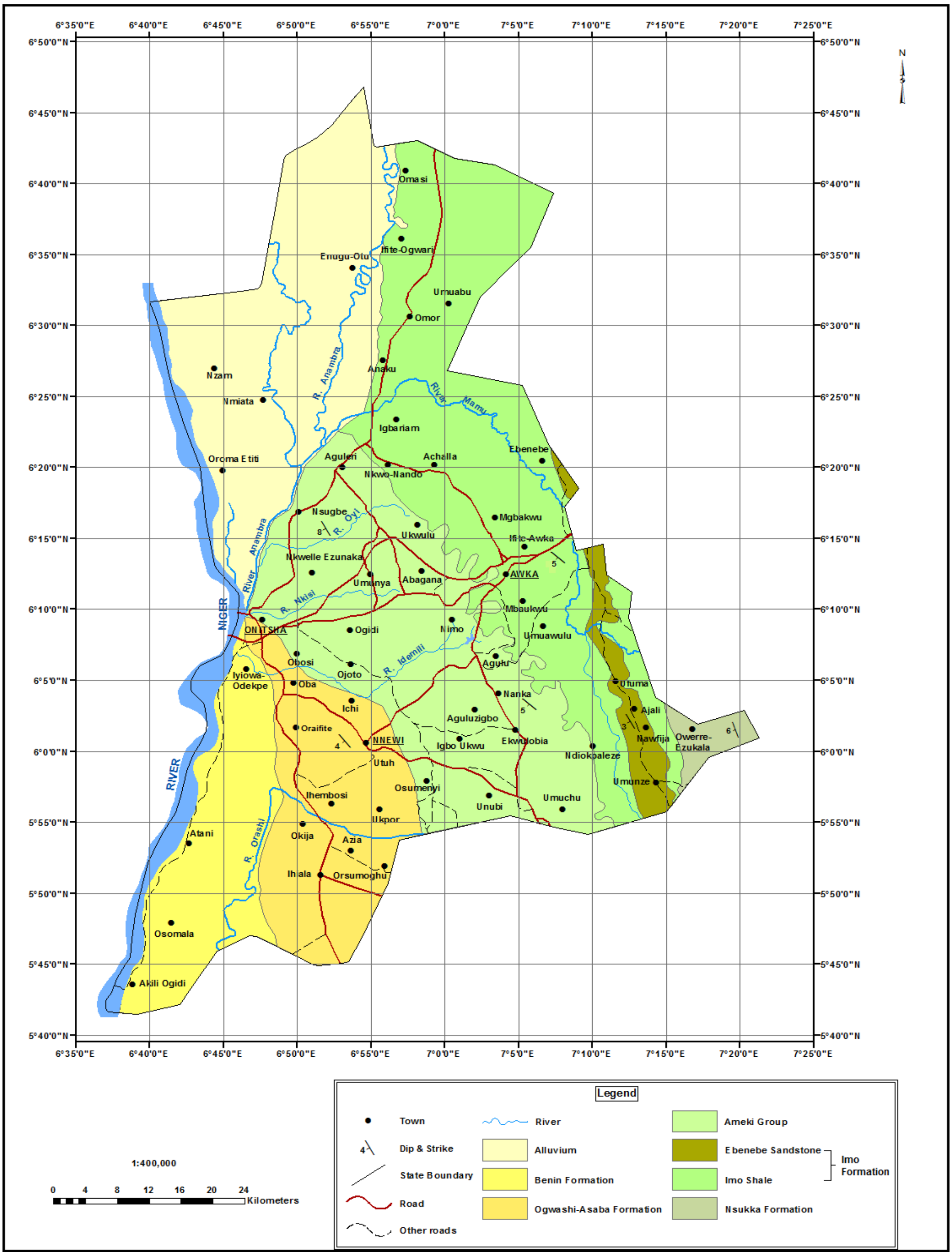


Figure 2.2: Geological Map of Anambra State (Chinwuko and Anakwuba, 2016)

Table 2.1: Correlation Chart for Early Cretaceous Tertiary strata in the Southeastern Nigeria

PICK (m.y)	AGE	ABAKALIKI-ANAMBRA BASIN	AFIKPO BASIN
30	Oligocene	Ogwashi-Asaba Formation	Ogwashi-Asaba Formation
54.9	Eocene	Ameki/Nanka Formation/Nsugbe Sandstone	Ameki Formation
65	Paleocene	Imo Formation Nsukka Formation	Imo Formation Nsukka Formation
73	Maastrichtian	Ajalli Sandstone Mamu Formation	Ajalli Sandstone Mamu Formation
83	Campanian	Nkporo/Owelli Formation/Enugu Shale	Nkporo Shale/Afikpo Shale
87.5	Santonian	Non-deposition	
88.5	Coniacian	Awgu Group (Agbani Sandstone/Awgu Shale)	
93	Turonian	Ezeaku Group	Ezeaku Group (Including Amaseri Sandstone)
100	Cenomanian-Albian	Asu River Group	Asu River Group
119	Aptian Barremian Hauterivian	Unnamed Units	
Precambrian		Basement Complex	

Source: Chinwuko and Anakwuba, 2016

2.2 Geologic Formation of Groundwater

Groundwater abstraction is from Geologic units, however, the strata that yields and transmits groundwater is referred to as aquifers. Other terms, such as aquitard, are used to describe geologic units that do not allow water to flow through them as easily as an aquifer.

2.3 Groundwater and Geologic Units

Groundwater is the water that is found in cracks and spaces within the soil, sand and rocks. The area where water fills the space is called the saturated zone. The top of this zone is the water table. Assuming the top of water to be a table, the water may be only a meter below the earth's surface or it may be hundreds of meters down. Groundwater can be found almost everywhere. The water table may be deep or shallow and may rise or fall depending on many factors. Heavy rains or melting snow may cause the water table to rise, while an extended period of dry weather may cause the water table to fall. Groundwater is stored in, and moves slowly through layers of soil, sand and rocks called aquifers. The size of the spaces in the soil or rock and how well the spaces are connected determine the speed at which groundwater flows.

The geologic units associated with groundwater hydrology are classified into four categories namely; Aquifer, Aquitard, Aquiclude and Aquifuge

a. Aquifers

Aquifers are saturated bodies consisting of geologic materials that can yield exploitable quantities of ground water. Characteristically, they consist of gravel, sand, sandstone, or fractured rock, like limestone. These materials are permeable because they have large connected spaces that allow water to flow through. Aquifers are also known as underground reservoirs otherwise called underground flood and the water that reached this chamber is usually much cleaner than the water or reservoirs at the earth surface. Aquifer could be confined or unconfined or perched.

Unconfined aquifers lie very near the water table, with little or no overlying rock or sediment and their water is usually at atmospheric pressure. Shallow water-table wells are known to respond quickly to precipitation and the water-level changes in response to wet seasons or dry season rapidly. Most local groundwater comes from unconfined aquifers made of loose slope materials, sands, gravels, and floodplain deposits left by stream(s) and rivers.

Confined aquifers are sandwiched between rock layers that are either effectively impermeable or have very low permeability. However, a combination of the two can occur and that aquifer is called leaky or a semi-confined aquifer (see Fig. 2.3). The very low permeability towards the bedrock is because of increase in overburden pressures caused by the weight of the rocks. Hence, permeability decreases with depth in the bedrock, since the density of open fractures diminishes also with depth (Buckwalter *et al.*, 1996). Water levels of semi-confined or confined aquifers respond to precipitation slowly, and water-level changes, in response to wet seasons or dry season are usually delayed.

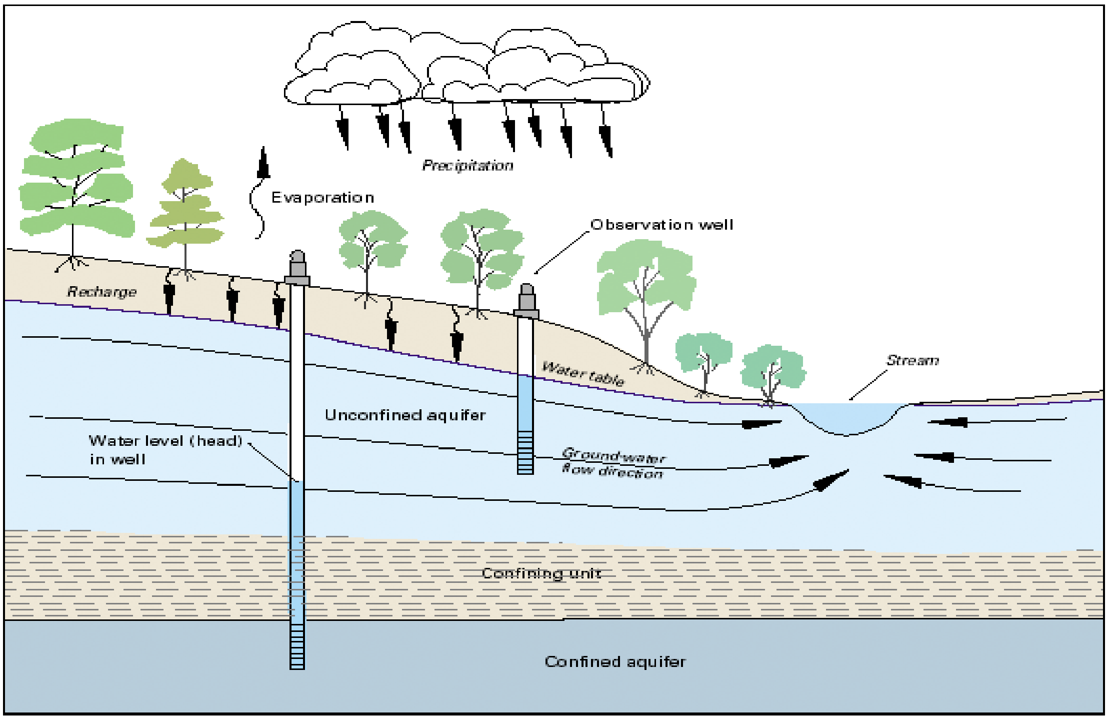


Figure 2.3: Schematic cross sectional diagram showing layered system with an upper unconfined aquifer above a confining unit, and underlain by a confined aquifer (https://www.e-education.psu.edu/earth111/node/911)

In figure 2.3, the water level in the confined aquifer well is higher than the top of the aquifer, signifying that the aquifer is fully saturated with the water under intense pressure. Whereas, in the unconfined aquifer the water level in the well and that of the water table are equal in height.

A special case of an unconfined aquifer which occurs when a local zone of saturation exist at some level above the main water table is the perched water table (Figure 2.4 and Figure 2.5). This situation occurs when an impervious stratum within the zone of aeration interrupts percolation and causes groundwater to accumulate in a limited area above that stratum. In this case, the upper surface of the groundwater is called a perched water table. These aquifers can often provide very reliable supplies where there is a reasonable thickness of saturated sediment present. In some places, the aquifer may be perched above a clay layer which is not extensive enough to provide enough storage for a good water supply.

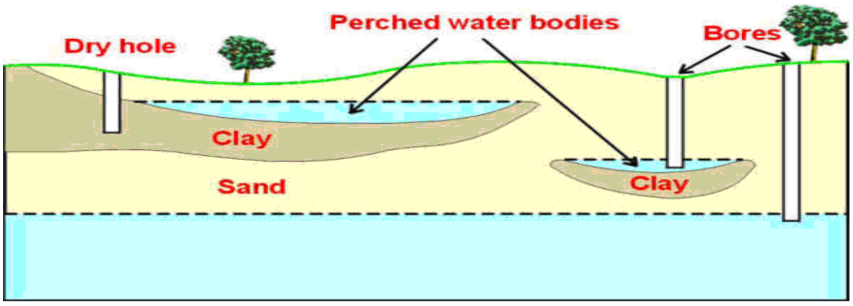


Figure 2.4: Perched Aquifer (Fleming, 1994)

The local occurrence of groundwater is the consequences of a finite combination of climatic, hydrologic, geologic, topographic, ecological and soil forming factors.

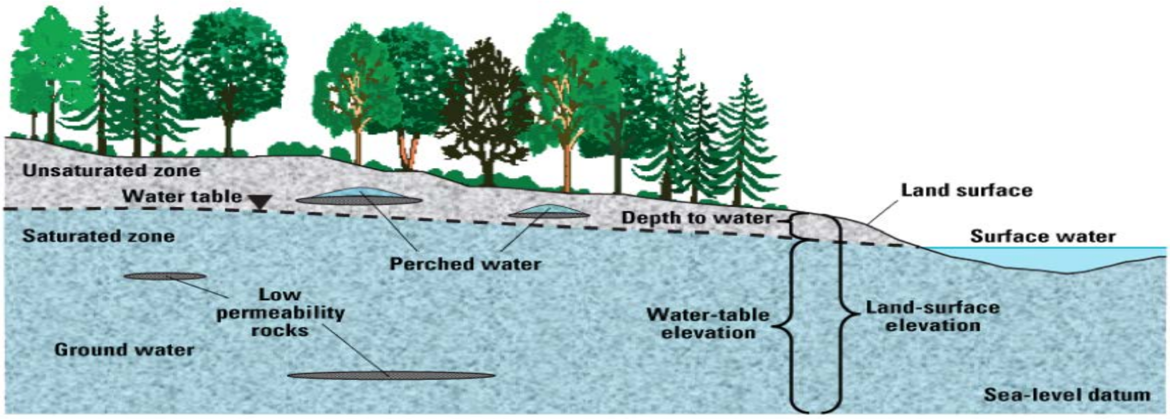


Figure 2.5: Schematic cross section showing occurrence of perched aquifers above an unconfined aquifer. (Snyder, 2008)

Leaky aquifer is a semi-confined aquifer that has its upper and lower boundaries as aquitards, or one boundary is an aquitard and the other is an aquiclude.

b. Aquitard

An aquitard is a geologic unit that transmits water, but at a lower rate than aquifers because of its low porosity and permeability. The aquitard transmits water at such a slow rate that the yield is insufficient and makes pumping by wells practically impossible. Although Lough and Williams (2009) argued that by only assessing the thickness of an aquitard based on the absence of well screens over certain depth interval may not be appropriate because some aquidards in the zone within the same depth interval may be prolific but yet to be exploited.

c. Aquiclude

An aquiclude is a geologic unit that has good water storage capacity and very low transmitting capacity. It is composed of rock or sediment that has low porosity and permeability and precludes the flow of groundwater. Probably there might not be a true aquiclude.

d. Aquifuge

An aquifuge is a geologic unit that does not have interconnected pores and can neither store nor transmit water. It is also neither porous nor permeable.

2.4 Groundwater Occurrence

The subsurface within which groundwater occurs is either porous or fractured or both, in other words, occurrence of groundwater largely depends on the nature of the underlying rocks within the area. Thus, porosity and permeability are the major properties of rocks that determine their ability to store and transmit water. The subsurface occurrence of groundwater can be divided into two zones (Figure 2.6): (i) the vadose zone or unsaturated zone or zone of aeration, and (ii) the phreatic zone or zone of saturation (Asawa, 2009)

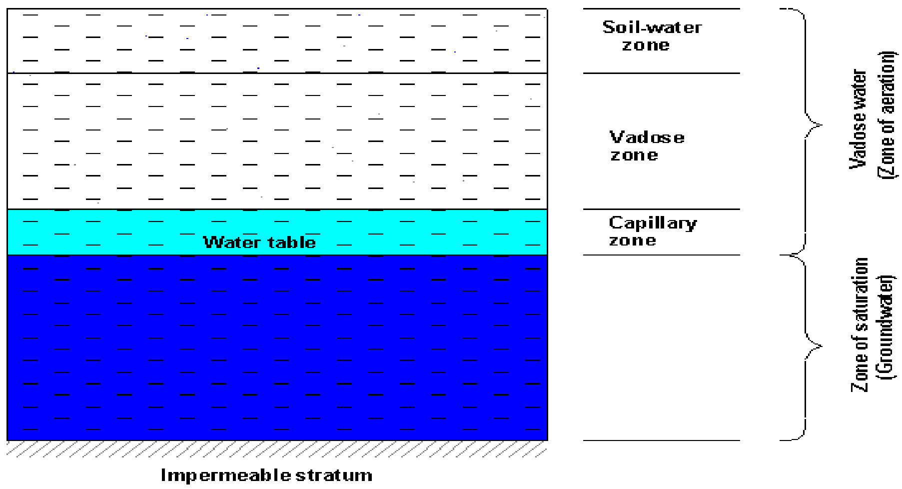


Figure 2.6: Vertical Distribution Zones of Subsurface Water

In the saturated zone, all pores or voids are filled with water whereas in the unsaturated zone, pores contain gases (mainly air and water vapours) in addition to water. The water table is the upper limit of the saturated zone. The number of pores filled with water decreases in the upward direction of the capillary water zone.

2.4.1 Porosity, Permeability and Water Table

a. Porosity

The porosity of a soil is expressed as a percentage of the total volume of the soil material and it is the amount of pore or open space between soil/rock particles. The major factors that control porosity are grain size and shape, amount of fracturing and the degree of sorting. Well-sorted sediment has a narrow range of grain size and if the grains are rounded and of uniform size, the sediment is said to be perfectly sorted and most porous, whereas poorly sorted sediment lowers porosity. This is because smaller grains may occupy the spaces between larger grains. Nevertheless, porosity can also be described as a measure of how much water can be stored in a rock. Geological formations that have larger or greater number of pore spaces, the porosity will be higher, thus, the larger the water-holding capacity.

Porosity is connoted as **"n'** and defined mathematically by the equation;

$$\mathbf{n} = \frac{\mathrm{V_v}}{\mathrm{V}} \times \mathbf{100\%} \qquad (2.1)$$

Where, $\mathbf{V}$ = total volume of earth materials ($\mathrm{l^3, cm^3, m^3}$)

$\mathbf{V_v}$= volume of void space in a unit volume of earth materials ($\mathrm{l^3, cm^3, m^3}$)

The porosity "$\mathbf{n}$" is always expressed as a percentage. It is important to note that the rate of groundwater flow is controlled by porosity and permeability, the two very important properties of the rock. Table 2.2 shows the porosity range for various geologic materials.

Table.2.2: Porosity Range for Various Geologic Materials

Unconsolidated deposits	**Porosity (n %)**
Gravel	25 - 40
Sand	25 - 50
Silt	35 - 50
Clay	40 - 70
Rocks	
Fractured basalt	05 - 50
Karst limestone	05 - 50
Sandstone	05 - 30
Limestone, dolomite	00 - 20
Shale	00 - 10
Fractured crystalline rock	00 - 10
Dense crystalline rock	00 - 05

Source: Freeze & Cherry, 1979

b. Permeability

Permeability is the measure of the properties of the rock, which determines how easily water can flow through it. Permeability depends largely on the interconnection of the pores. Consequently, rocks are permeable, if fluids pass through and impermeable, if the fluids flow through the rock is negligible (Orakwe, 2010). It is important to note that hydraulic conductivity is dependent on permeability. Permeability also decreases generally with depth in the bedrock because of the weight of the rocks, which increases overburden pressures, therefore, causes the density of open fractures to diminish with depth (Buckwalter *et al.*, 1996).

c. Water Table

In most areas with sufficient rainfall, water infiltrates through the pore spaces and cracks in the soil, passing through the unsaturated zone. Water fills in more pores/cracks as the depth increases, until a zone of saturation (or phreatic zone) is reached. However, the upper surface of the saturated zone where the water pressure head is equal to the atmospheric pressure is referred to as the water table (Freeze and Cherry, 1979). It can also be said to be the depth where the soil becomes completely saturated. Water Table or Groundwater Table is deeper in areas with hill but superficial in valleys. It is mostly affected by climatic variations; amount of rainfall used by vegetation in the area, excessive discharge of water from borehole/wells and by artificial recharge.

2.4.2 Categories of Earth Materials

Earth materials consist of two types of rock materials namely, the unconsolidated loose material such as the sand, gravel, silt and clay and the consolidated rocks which is also known as the bedrock or crystalline rock.

Unconsolidated deposits are made up of well - poorly delineated layers of clay, silt, sand, gravel, and some boulders. They are basically deposits from flowing water in channels / plains and are better classified according to their various formations.

Consolidated Sediments/Rocks are solid rocks made from materials that have been metamorphosed or cemented together over a long period of time. They consist of the sedimentary (e.g., limestones, shales and sandstones) the metamorphic (e.g., gnesis, slates and mables) and the igneous rocks (e.g., basalt and granite). Ground water flows freely through fractures and pore spaces in these consolidated sediments.

2.5 Groundwater Replenishment

The main source through which groundwater is replenished is by precipitation. The rate by which groundwater is replenished is related to precipitation pattern, surface runoff and stream flow. Groundwater replenishment rate also varies with the intrinsic permeability of the soil and other earth materials through which the water must percolate to reach the zone of saturation (Michael, 1978). In some areas where the water level in surface water bodies are higher than the water table and the intervening layer is permeable, groundwater reservoir is replenished through these sources. Table 2.3 shows the summary of the range of recharge values for different regions in Nigeria.

Table 2.3: Summary of the Range of Recharge Values for Different Regions in Nigeria

Region	Mean annual rainfall (mm)	Recharge estimates (mm yr^{-1})	Method	Reference
North West	600	4-28	Empirical, streamflow, CMB	Adelana *et al.*, 2006a
North East	500	14–49	Unsaturated zone Cl profile, Stable Isotopes	Edmunds *et al.*, 2002
Hadejia/Nguru	200-600	73–197	Water budget	Goes *et al.*, 1999, Acharya & Barbier 2002
Kano-Maiduguri	530	169	Soil moisture deficit	Ndubuisi 2007
South East	1,800	281-1,047	Simplified recharge, equations, baseflow recession analysis and water balance method	Uma 1988
SE (Owerri urban)	2,152	446-667	Simplified calculations	Ibe *et al.*, 2003
SW (Ile-Ife/Middle Osun valley)	1,480	191-225	Empirical equations	Omorinbola 1986
SW (Kwara)	1,200-1,400	158-605	Empirical, Stable Isotopes profile	Adelana *et al.*, 2006b

Source: Adelana *et al.*, (2006)

2.5.1 Artificial Groundwater Recharge

This becomes necessary in places that have the rate of groundwater withdrawal equals or exceeds the average recharge. When the rate of groundwater withdrawal is higher than recharge in coastal regions, seawater intrusion into coastal aquifers occurs. The situation stated above has underscored the importance of artificially recharging groundwater. Groundwater can also be increased by soil conservation measures. The amount of rainfall or ponded surface water infiltrated into the soil varies greatly with the soil surface conditions and the moisture content of the soil at the time of rainfall.

Artificial sources of replenishment include the following (Michael, 1978)

Leakage from reservoirs, conduits, septic tanks, and similar water related structures;

irrigation or other water application including deliberate flooding on a naturally porous area.

Injection through wells or other similar structures.

2.6 Groundwater Exploration

Several techniques are employed for a detailed study of groundwater and its occurrence. In most cases, water quality, quantity and even depth to the water bearing aquifers are identified for proper planning and management of the resources. These techniques are discussed below.

2.6.1 Dowsing (Water Witching)

Dowsing which is often referred to as water witching or divining was mostly used in Europe and America in the 16th century. This technique employs the use of a rod, pendulum and forked stick to locate groundwater. The Dowser will be walking back and forth around the area under probe with one arm of the folk held in each of his/her hands with the palms upwards. While the “Y” shaped bottom of the forked stick will be pointing upwards at about an angle of 45 degrees with the pendulum hung on it. The bottom of the stick usually points downwards or the pendulum rotates once the Dowser passes over an underground water source. This technique has been a subject of controversy since the advancement of scientific knowledge in hydrology.

However, the National Ground Water Association, USA, strongly recommended the use of proven geophysical and hydrogeological techniques for groundwater reconnaissance since controlled experimental evidence clearly justifies dowsing as a technique that is totally without scientific merit (NGWA, 2017).

2.6.2 Geological and Hydrological Survey

The occurrence of groundwater below the earth surface is simply as a result of some hydrogeological factors. Over the years, in the cause of groundwater development and management, Geologists, Hydrologists and water Engineers have not only identified the different geological formations, where water can be found but also gave information on the conditions favourable to the occurrence of groundwater. Orakwe (2010) in his study provided some of the useful clues on the availability of groundwater.

- The presence of water loving plants in arid regions suggests the obvious presence of shallow depth ground water
- The availability of springs, streams, seeps, lakes or swamps suggests the presence of groundwater, though may not be in substantial quantity.
- Groundwater occurs in valleys more than hills
- The rock types and orientation of joints or other fractures in any geological formation determine how prolific the water bearing aquifer will be. Gravel, limestone and sandstone are better water bearers than clay, crystalline rocks and shale.
- The information (like the location of the wells, amount of water pumped, depth to water and types of rocks penetrated by the wells) obtained from the existing wells provides useful clues on groundwater in the area.
- In sedimentary rocks, cavernous limestone and clean sandstone offer the best prolific aquifers

- The suitability of volcanic rocks differs widely in aquifer productivity. Tuffs and rhyolites are porous yet have very low permeability while recent basalts are extremely permeable and make highly productive aquifer
- When Metamorphic and igneous rocks (gneisses, granites and others) are fractured by faulting or weathering, they yield moderate amount of groundwater.
- One of the most common sources of groundwater is aquifers of unconsolidated materials (e.g. glacial, alluvial or aeolian deposits).

Further assessment on geology, geomorphology, drainage density, slope, soil thickness, rainfall pattern and electrical resistivity should be carried out for a well-integrated and sustainable groundwater exploration, development and management.

2.6.3 Pilot Hole Drilling

A pilot test hole is usually drilled before the actual well drilling, once the well location is determined. This perhaps is the most reliable method in groundwater investigation because more detailed information pertaining to the production capabilities of the geological formation, the water levels, and the groundwater quality is obtained. The final design is subject to site-specific observations made in the test hole. During the pilot hole drilling, soil samples are collected from returned cuttings for geologic logging purposes. These soil samples collected at every meter drilled (or once there is a change in soil type) are put on a plastic sheet for easy visual display and comparison. The soil descriptions/ formations are then recorded against their corresponding depths in a drilling log. The drilling log (Figure 2.7), which is a written record of the soil layers drilled according to depth, will help to determine the right aquifer for installation of the well-screen, depth and length of the well-screen, depth and thickness of the gravel pack and location of the sanitary seal (Van der Wal, 2010).

2.6.4 Geophysical Methods for Groundwater Exploration

The purpose of groundwater exploration is to delineate the water bearing formation, estimate their hydrological characteristics and determine the quality of water present in these formations. Geophysical methods are used to provide an indirect evidence of the subsurface formation that indicate whether the formations may possibly be aquifers (Michael, 1978). A number of geophysical exploration techniques are available, which enables an insight to be obtained rapidly in the nature of water bearing layers and they include; geoelectric, electromagnetic, seismic and geophysical borehole logging (Alile *et al.*, 2008). These methods measure properties of formation materials, which determine whether such formation may be sufficiently porous and permeable to serve as an aquifer. The electrical resistivity method and seismic refraction method are the surface geophysical methods commonly used for groundwater exploration (Asawa, 2009).

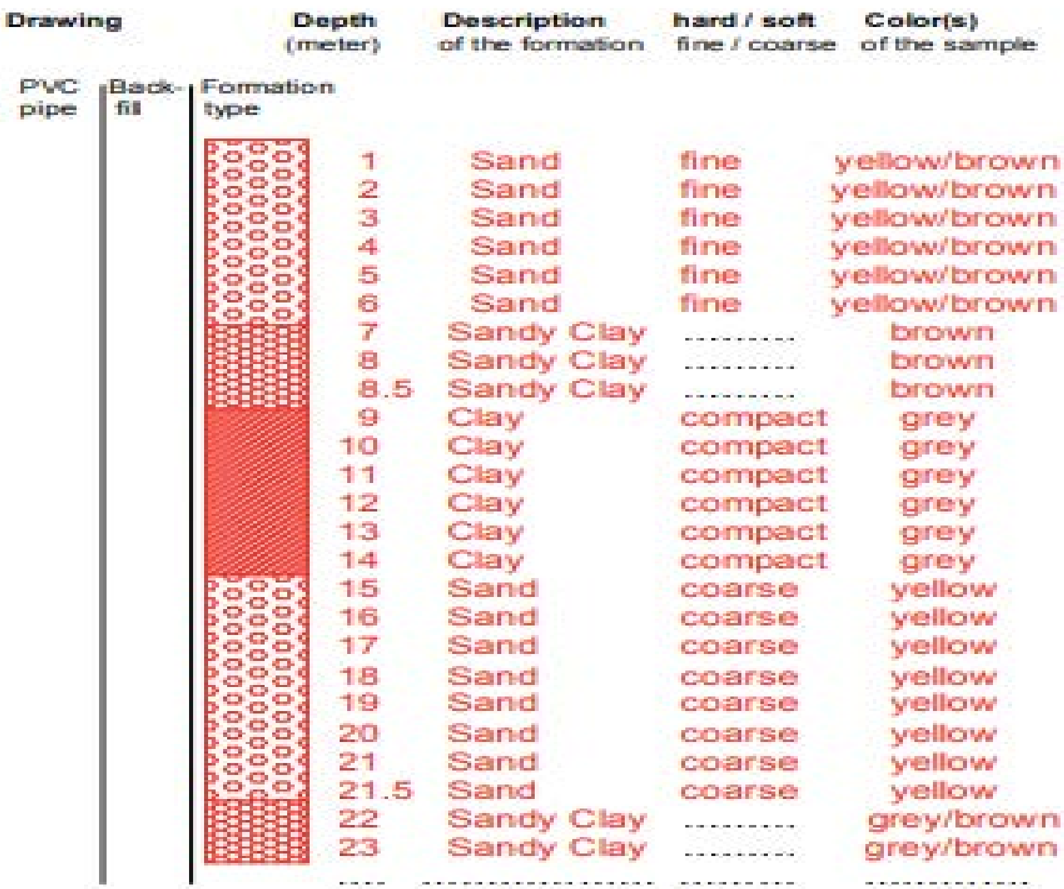


Figure 2.7: Drilling Log (Van der Wal, 2010)

2.6.5 Electrical Resistivity Method

The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity can be estimated. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity, nature and degree of water saturation in the rock. Electrical resistivity surveying is a geophysical operation in which measurements of earth resistivity are made from the ground surface (Michael, 1978). Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigations. More recently, it has been used for environmental surveys.

The resistivity measurements are normally made by injecting current into the ground through two current electrodes; C1 and C2 (Figure 2.8 and Figure 2.9)), and measuring the resulting voltage differential at two potential electrodes; P1 and P2.

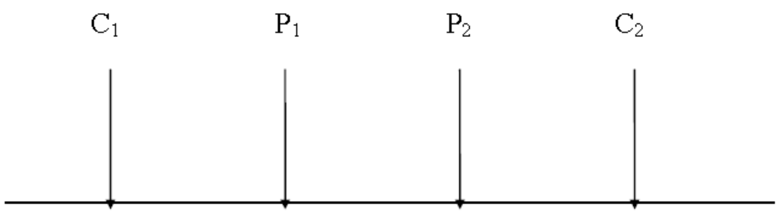


Figure 2.8: Conventional Four-electrode Array to Measure Subsurface Resistivity.

Figure 2.8, provides a schematic view of the basic components involved in making resistivity measurements. A battery is used to generate a measured current (I) between two current electrodes (C1 and C2). The resulting voltage difference (V) between two potential electrodes (P1 and P2) is then measured to provide a measure of resistance, which can be converted into an apparent resistivity depending on the electrode configuration.

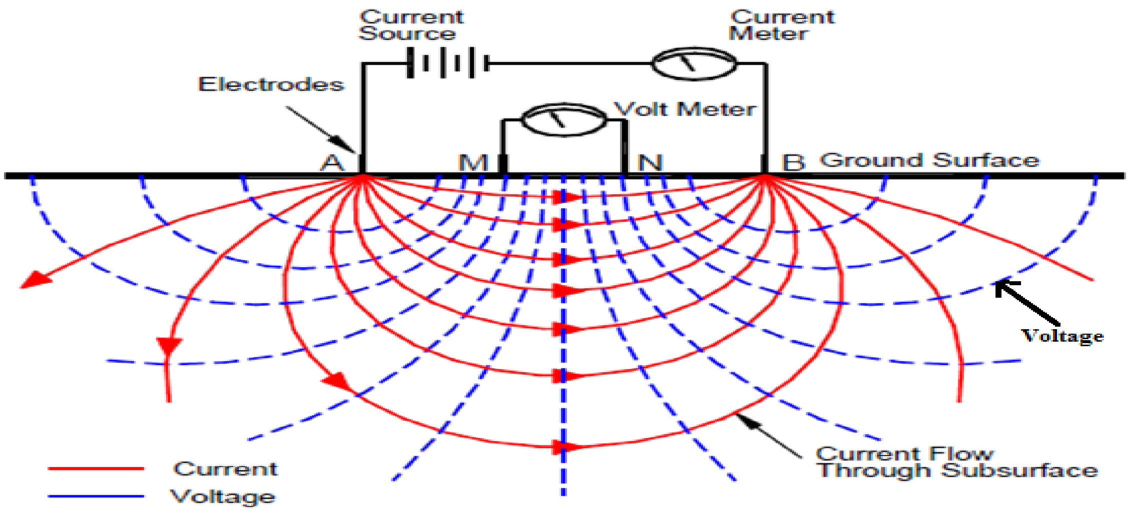


Figure 2.9: Schematic diagram Illustrating basic arrangement for Electrical Resistivity Measurement (NGA, 2013).

From the current (I) and voltage (V) values, an apparent resistivity (ρa) values is calculated using an equation:

$$\rho_a = \frac{kV}{I} \tag{2.2}$$

Where, k is geometric factor, which depends on the arrangement of the four electrodes.

The apparent resistivity is computed from the potential drop, the applied current, and the electrode spacing. Resistivity meters normally give a resistance value, R = V/I so in practice the apparent resistivity value is calculated by

$$\rho_a = kR \tag{2.3}$$

The resistivity value calculated is not the true resistivity of the subsurface, but an "apparent" value, which is the resistivity of a homogeneous ground, which will give the same voltage, and current values for the same electrode arrangement. The relationship between the "apparent" resistivity and the "true" resistivity is a complex relationship. To determine the true subsurface resistivity, an inversion of the measured apparent resistivity values using a computer program must be carried out. Apparent resistivity is considered as being a weighted average of the real resistivities of the individual strata within the depth of penetration of the resistance equipment (Micheal, 1978).

The depth of measurement is decided by the distance and the arrangement pattern of the four electrodes and the standard calibration curves (Asawa, 2009). Table 2.4, lists typical order of values of resistivity for some common soils. Using this table and plot of electrical resistivity versus depth, one can determine the type of subsurface layers at different depth.

Table 2.4: Typical Values of Electrical Resistivity for Some Soils

Earth Material	**Electrical Resistivity (Ohm-Metres)**
Clay	1 – 400
Loam	4 – 40
Clayey soil	100 – 380
Sandy soil	400 – 4000
Loose sand	1000 – 180,000
River sand and gravel	100 – 4000
Chalk	4 – 100
Limestone	40 – 3000
Sandstone	20 – 20,000
Basalt	200 – 1000
Crystalline rocks	1000 – 1000,000

Source: Asawa, 2009.

- **Electrode Configurations**

The “Schlumberger” and “Wenner” array configurations are two electrode layouts that are widely employed in the resistivity surveys. The Schlumberger array (Figure 2.10) is an electrode configuration in which the spacing of the two potential electrodes is less than one-fifth of the distance between the centre of the array and one current electrode.

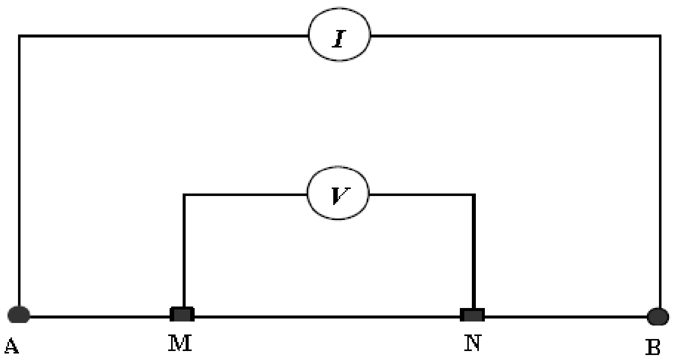


Figure 2.10: Schlumberger Arrangement (Arshad, *et al*. 2007)

A direct current is introduced into the ground through two current electrodes A and B. The potential electrodes M and N are inserted in the ground between the outer current electrodes A and B, where the potential difference is measured across two potential electrodes. By measuring the current (I) between the two current electrodes A and B and the associated potential difference (V) between the potential electrodes M and N, the apparent resistivity (ρa) is computed by the equation

$$\rho_a = K\frac{V}{I} \tag{2.4}$$

Where

K is the geometric factor of the electrode arrangement in case of Schlumberger electrode configuration, which is given by Equation:

$$K = \frac{\pi\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \tag{2.5}$$

By repeating the Schlumberger measurements with the entire setup moved one step to the side, vertical electrical soundings (VES) are performed continuously and the resistivity along a profile could be measured.

- **Vertical Electrical Sounding**

In the vertical electrical sounding, the goal is to observe the variation of resistivity with depth (Lowrie, 2007). Vertical electrical sounding (VES) furnishes information concerning the vertical succession of different conducting zones and their individual thickness and resistivities (Ekwe *et al.*, 2010). In the electrical sounding with the Schlumberger array, the midpoint of the electrode array remains fixed but the spacing between the electrodes is generally increased to obtain more information about the deeper sections of the subsurface (Ekwe *et al.*, 2010). This causes the current lines to penetrate to ever greater depths, depending on the vertical distribution of conductivity (Lowrie, 2007). For Schlumberger configuration, apparent resistivity is given by (Keller and Frischknecht, 1966):

$$\rho_a = \tau\tau R\left(\frac{a^2}{b} - \frac{b}{4}\right) \tag{2.6}$$

Where

a = half current electrode separation

b = potential electrode spacing

When the thickness of an aquifer is known, its transverse unit Resistance (R) and longitudinal conductance (S) can be calculated from (Ezeh and Ugwu, 2010):

$$S = \frac{hi}{\ell i}$$

(2.7)

$$\boldsymbol{R = hi\ell i} \tag{2.8}$$

Where

hi = thickness

ℓi = resistivity

Niwas and Singhai (1981) show that an analytical relationship can be established to estimate transimissivity values for an aquifereous layer from the above equation as:

$$Tr = K\sigma R = K\frac{S}{\sigma} \tag{2.9}$$

Tr = transmissivity

σ = aquifer conductivity

K = hydraulic conductivity

The Schlumberger configuration is most commonly used for vertical electrical sounding investigation (Lowrie, 2007). For this study, the Vertical electrical sounding using schlumberger arrangement was used because the instrumentation is simple, filed logistics are easy and straightforward, analysis of data is less tedious and economical, less manpower is required (Ekwe, et al. 2010).

Wenner electrode array is an electrode configuration in which four electrodes are deployed in a line, with equal spacing between the two potential electrodes, and between each current electrode and its nearest potential electrode. Offset Wenner" method is an improvement on the standard Wenner array. In the Offset Wenner method, five electrode positions are used to measure two (offset) Wenner resistances and three additional resistances (Figure 2.11). The displacement (offset) of each of the Wenner arrays reduces undesirable spurious effects due to lateral underground resistivity variations. Three additional resistance measurements allow calculation of the observation error, which gives an indication of the reliability of the measurement for each electrode spacing.

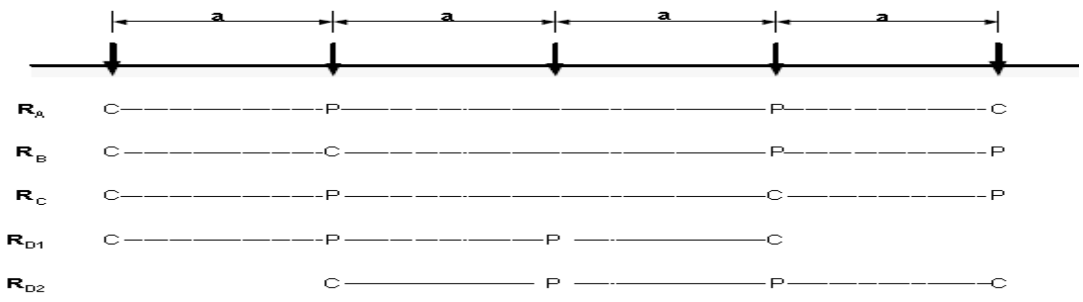


Figure 2.11: Electrode configurations used in the Offset Wenner Array (Scott *et al.*, 1999)

C indicates that the electrode is used as a current electrode

P indicates that the electrode is used as a potential electrode

The choice of the "best" array for a field survey depends on the type of structure to be mapped, the sensitivity of the resistivity meter and the background noise level (Scott, *et al.*, 1999). In practice, the most commonly used arrays are the Wenner and Schlumberger arrays. The most effective characteristics of array to be considered are: sensitivity of the array to vertical and horizontal changes in subsurface resistivity.

Figure 2.12, shows a plot of the sensitivity function for the Wenner and Schulumberger arrays for a homogeneous earth model. The sensitivity basically tells the degree in which the change in the resistivity of a section of the subsurface will influence the potential measured by the array. The higher the value of the sensitivity function, the greater is the influence of the section on the measurement.

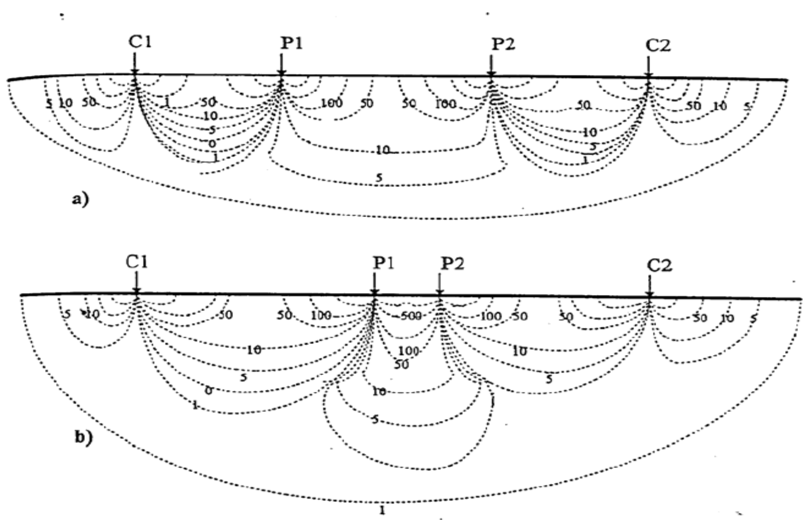


Figure 2.12: Sensitivity Pattern for the (a) Wenner and (b) Schlumberger (Loke, 1997)

2.6.6 Seismic Refraction Method

This geophysical method employs seismic waves to determine variations in the thickness of the unconfined aquifer and the zone where the most permeable strata are likely to exist (Asawa, 2009). The principle of seismic refraction surveying is based on the fact that shock waves travel through different strata of earth materials at different velocities and on velocity variation of artificially generated seismic waves in the ground. The denser the material, the faster the waves travel through it. Thus, from field measurements of differences in velocity, the existence of differing layers of subsurface materials are identified (Michael, 1978).

Seismic waves are generated either by hammering on a metal plate or by dropping a heavy ball, or by using explosives (Asawa, 2009). The time between the initiation of a seismic wave on the ground and its first arrival at a detector (seismometer) placed on the ground is then measured. For this method of groundwater exploration, interest lies on the arrival of the critically refracted ray, i.e. the ray which encounters the boundary at such an angle that when it refracts in the lower medium, it travels parallel to the boundary at a higher velocity. This critically refracted ray travelling along the boundary radiates waterfronts in all directions and some of which return to the surface. This groundwater exploration method is more precise than the electrical resistivity method in the determination of the depth to bedrock (Asawa, 2009).

Table.2.5: Representative Values of Velocity of Seismic Refracted Waves in some Soils.

Material	**Velocity (m/s)**
Gravel, rubble or dry land	457 – 915
Wet sand	610 – 1830
Clay	915 – 2740
Water (depending on temperature and salinity)	1430 – 1680
Sea water	1460 – 1520
Sandstone	1830 – 3960
Shale	2740 – 4270
Chalk	1830 – 3960
Limestone	2130 – 6100
Salt	4270 – 5180
Granite	4570 – 5790
Metamorphic rock	3050 – 7010

Source: Asawa, 2009.

2.6.7 Electromagnetic Method (EM)

The electromagnetic method for the measurement of terrain resistivity uses induced current as illustrated in schematic form in Figure 2.13. A transmitter coil (Tx), energized with an alternating current at an audio frequency, is placed on the earth (assumed uniform) and a receiver coil (Rx) is located a short distance S away.

The time-varying magnetic field arising from the alternating current in the transmitter coil induces very small currents in the earth. These currents generate a secondary magnetic field (*Hs)* which is sensed together with the primary field (*Hp)* by the receiver coil.

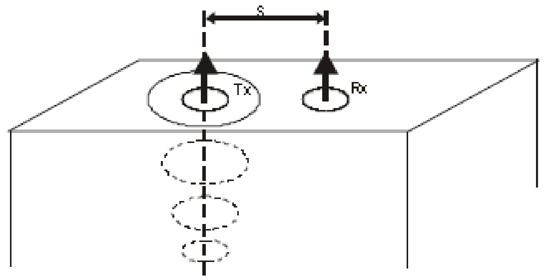


Figure 2.13: Schematic Diagram of the EM Method (Scott, et al. 1999)

Generally, this secondary magnetic field is a complicated function of the intercoil spacing (S), the operating frequency (*f*) and the ground conductivity (σ). However, under certain constraints the secondary magnetic field is a simple function of these variables. Apparent conductivity σ_a from the ratio of the secondary to the primary magnetic field is calculated as:

$$\sigma_a = \frac{4}{2\pi f \mu_\circ S^2}\left(\frac{H_s}{H_p}\right) \qquad (2.10)$$

σ_a = Apparent ground conductivity (mho/m)

H_s = Secondary magnetic field at the receiver coil; H_p = Primary magnetic field at the receiver coil; f = Frequency (Hz); $\mu_\circ$ = Permeability of the free space; S = Intercoil spacing

2.6.8 Use of the Resistivity Method for Groundwater Prospecting

Resistivity of a material is defined as the opposition to the flow of current in Ohms between opposite surfaces of a unit cube of material (Oseji, 2010). Electrical method utilizes direct current or low frequency alternating current to investigate the electrical properties of the subsurface. It is a technique used to study the shallow layer of the earth by sending direct electric current through a pair of electrodes and analysing the potential distribution it produces. From Ohm's law, resistance and resistivity can then be deduced.

It is possible to determine the resistivity of earth materials because electrical resistivity of earth materials varies over a wide range. The electrical resistivity method is particularly useful for soil testing, engineering purposes or hydrological checks. This method involves the use of artificially sourced current, which is introduced into the ground through a pair of electrodes (current electrodes) while the resulting potential difference is measured by another pair of electrodes called potential electrodes which may or may not be located within the current electrodes (Kearey and Brooks, 1991).

No geophysical method has yet surpassed the electrical resistivity method in groundwater studies. Akintorinwa, and Oluwole, (2018) noted that it has wild adoption in groundwater exploration. This is due to the fact that the field operation is easy, the equipment is portable, less filled pressure is required, it has greater depth of penetration, and it is accessible to modern communication systems (Ariyo and Adeyemi, 2009). The fundamental physical parameter used in the exploration and description of subsurface rock by the resistivity method is resistivity. The wide range of values in the resistivities of rocks is sometimes misleading and difficult to utilize. The resistivity of subsurface materials depends more on the pore volume including fractures, degree of saturation, weathering, and conductivity of the saturant than on the rock type.

In groundwater exploration, the resistivity method can determine the thickness of aquifer overlying resistive bedrock. The method is even capable of determining even the quality of groundwater i.e. whether the water is saline, brackish, fresh or contaminated with toxic wastes.

The geophysical literature contains papers (Oseji, 2010; Ekwe *et al.,* 2010; Eze and Ugwu, 2010; Anizoba et al., 2015; Otutu and Oviri, 2010; Ariyo and Adeyemi, 2009; and Alile *et al.,* 2008; Ayuni *et al.,* 2018; Moh and Prayogo, 2019) showing ample evidence for the successful use of the method in groundwater prospecting.

Meheni *et al.,* (1995) used resistivity prospecting to investigate the shallow structure of the ground. He used Wenner prospecting techniques for mapping lateral variations in resistivity. He found that electrical resistivity is very sensitive to granularity and porosity changes.

A multi-electrode resistivity data acquisition system was used by Dahlin (1996) which shows that 2D resistivity surveying can form a powerful geological mapping tool, for use in engineering and environmental applications, including hydrogeological mapping. He found that pseudosection plotting provides control over data quality, and thus is presented along with depth sections as a quality indicator. Pseudosection can also be used in qualitative interpretation.

A research by Bayewua et al., (2018) was carried out at Olabisi Onabanjo University campus, Ago-Iwoye, Southwestern Nigeria with the aim of evaluating groundwater potential and aquifer protective capacity of the overburden units in the area. The study concluded that study area ground potential ranges from low to high, while the protective capacity rating of the study area shows a poor, weak and moderate protective capacity rating. Seven VES stations had poor protective capacity; sixteen (16) VES station showed weak protective capacity and only one (1) VES station indicated a moderate protective capacity rating.

Ekwe, *et al.*, (2010) performed geoelectrical measurements using the vertical electrical sounding (VES) method to determine aquifer characteristics of Oduma. The authors delineated three geologic groups and acquired eight VES results using the Schlumberger configuration. The results were processed using RESIST software. Their interpreted results show ranges for transmissivity, hydraulic conductivity, depth to water tables and aquifer thickness for major areas within their studied area. The authors however recommended the use of SAS 400 (Lund imaging system) to be able to map areas with high density of fractures.

Ariyo and Adeyemi. (2009) explained the usefulness of the electrical resistivity method, most especially vertical electrical sounding in locating weathered/fractured zones that are the major source of groundwater in south-western Nigeria. The authors utilised twenty-eight VES locations within the study area and their interpreted result gave an overview of various aquifers that are present in the study area which are weathered/fractured basement and the groundwater situation of these hard rock units. They therefore suggested that geophysical methods, most especially the electrical resistivity method should form an integral part of groundwater exploration programs in solving complex geo-hydrological problems associated with groundwater occurrence and resource development.

Alile *et al.*, (2010) applied the VES method to decipher the existing subsurface stratification and groundwater occurrence status in a location in Edo State, Nigeria. Interpretations from their results indicate that the area has an abundant groundwater potential which was field-confirmed by the existence of productive boreholes against the standing history of abortive boreholes, resulting from failed drilling attempts within the study area. Their study however revealed the possibility of having a maximum drill depth to water table of 260m.

Oseji (2010) did geoelectric investigation of groundwater resources and aquifer characteristics in a location in Delta State, Nigeria. The author acquired VES data from ten locations evenly distributed within the study area and plotted the apparent resistivity values against the half current electrode spacing. The study revealed 4 prominent layers of near surface aquifer that are not confined with the best layer for groundwater development at a depth between 35.00m – 45.00m within the second layer.

Ehirim and Ebeniro (2010) also conducted a hydrogeophysical research in Enugu-Agidi, almost a kilometre from Awka town using Schlumberger electrode configuration. A total of 30 VES points from 30 different locations in Enugu-Agidi were acquired and analysed. The study revealed only two confined aquifers along traverses one at VES 2 and VES 3 and shallow unconfined aquifers in the entire traverses. However, the authors concluded that the quality and sustainable yields could be obtained only from the confined aquifer in the area when intercepted at a depth that is highly localized.

In the research done by Usma*n et al.,* (2015), hydro-geophysical investigation was conducted to ascertain aquifer characteristics in thirteen (13) communities in Nteje, Anambra East Local Government and environs. The study discovered four to five geo-electric units, one unconfined aquifer and three or four confined aquifers with the aquifer thickness greater at the NE and NW because of more clusters of the peak contours. The authors in their quest to verify the sustainability of groundwater in the area concluded that regional water project should be sited at Umeri because of its high values of transmissivity and aquifer thickness.

Nfor *et al.* (2007) in their study to determine the extent and distribution of groundwater resources in parts of Anambra State investigated forty five (45) boreholes across eighteen (18) Local Government Areas in Anambra State. Pre-drilling geophysical surveys were conducted at each of the sites by using Schlumberger array and consequently, the results identified four different geological formations with varying water storage and yielding capacities. However, the study observed that out of the four geological formations (Alluvial Plain Sands, Ogwashi-

Asaba Formation, Ameki/Nanka Sands and Imo Shale) the Imo shale because of its composition has the poorest water storing and yielding capacities. In conclusion, the study stated that lithology and other secondary factors like nearness to the recharge source and topography influence the extent and distribution of groundwater within the study area.

2.7 Groundwater Exploitation/ Overexploitation

Increased water demands associated with population increase and urbanisations have led to over exploitation of groundwater resources, which most times result to water level decline in both deep and shallow aquifers. The rate of discharge should not exceed the rate of recharge. Naturally, water discharges from aquifers at a rate which is controlled mostly by the amount of recharge. This discharged water from the aquifers feeds surface water and evapotranspiration.

Adequate outflows from aquifers are very important in preventing seawater intrusion, maintaining lake levels and also sustaining stream base flows. In groundwater exploitation, emphasis should be based on how to effectively recharge aquifers in order to avoid overexploitation. Overexploitation which creates hygienic and geotechnical problems, occurs when groundwater abstraction exceeds available groundwater recharge from surface water/ rainfall contributions. Once a particular aquifer in a given area is overexploited, the effective stresses in the aquifers change due to pressure reduction, thus, initiating mobility in fine grained, unconsolidated silt and clay aquifers (Magara, 1978). This is the reason why most boreholes, wells and even drainage channels fail. The storage capacity of aquifers is reduced because of the rapid movement of the sediments caused by overexploitation. Porosity also tends to reduce after overexploitation because of the plastic deformation suffered by the unconsolidated rocks. However, an increase in pore pressure with a decrease in effective stress is achieved by injecting water into the geological formation which sequentially leads to the expansion of the injected formation (Gambolati and Teatini, 2015).

Overexploitation of groundwater resources encourages the inflow of saline waters, thus distorting the quality of drinking water as well as the crops and the fertility of the soil. Groundwater Mining and Over-drafting are two terms used in groundwater exploitation to explain the excess withdrawal of water from an aquifer. Mining, another name for overexploitation occurs when groundwater is removed from an aquifer over a period of time, at a rate that exceeds the rate of natural recharge. However, Over-drafting occurs whenever pumping exceeds the Safe Sustainable Yield (SSY: The quantity of groundwater that can be safely and continuously withdrawn without unacceptable reduction/depletion in the aquifer storage reserve.).

It is important to note that if Mining and Over-drafting continue unchecked, the water reservoir will be depleted. Other damaging consequences will expose aquifers to contamination and also likely to affect the ground structures and infrastructures. These consequences include; land subsidence, progressively higher water costs, creation of fractures that will extend to the surface and reactivation of pre-existing faults with a major reduction of its mechanical properties and rapid increase in hydraulic conductivity (El-Gawadet al., 2017; Gambolati and Teatini, 2015).

2.8 Groundwater Quality Vulnerability and Degradation

The importance of groundwater for potable supplies has made it most expedient that aquifers should be given adequate protection. However, population increase and urbanisation is posing serious threat to groundwater quality. Orakwe (2010) pointed out that groundwater quality vulnerability and degradation may be attributed to human aided activities such as leakages from sewers, infiltration ponds for wastewaters, septic tanks, abandon wells, solid waste landfills and so on. This is because there is no formal way of waste disposal in Nigeria, also most pit toilets and soak-away pits are always in close proximity to wells and borehole. Consequently, the attenuation capacity of most soils and the geological strata between the source of the pollution and the water bearing aquifer accelerates groundwater quality degradation.

WHO (2006) in a study stated that the more logical approach towards assessing the possibility of groundwater pollution was to presume that it is the interaction between the pollutant load that infiltrates down to the subsurface environment as a result of human activity and the pollution vulnerability, which is determined by the characteristics of the geological strata between the aquifer and the earth surface. The study went further to ascertain what to bear in mind when assessing the possibility of groundwater pollution;

The vulnerability of all aquifers to persistent and mobile pollutants occurs in the long term.

Aquifers that are less vulnerable are not easily susceptible to pollution, but once polluted, are more difficult to restore.

In all pollution vulnerability assessments, uncertainty is always inherent. Obvious factors may be concealed and subtle differences may also become impossible to differentiate, if complex assessment systems are developed. Vulnerability of an aquifer was subdivided into five definite classes in Table 2.6., while Morris *et al.,* (2003) identified the hydrogeological environments and their susceptibility to groundwater pollution in Table 2.7.

Table 2.6: Broad Classification of Aquifer Vulnerability

Vulnerability Class	Definition
Extreme	Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
High	Vulnerable to many pollutants, except those highly absorbed and/or readily transformed, in many pollution scenarios
Moderate	Vulnerable to some pollutants, but only when continuously discharged or leached
Low	Only vulnerable to the most persistent pollutants in the long term, when continuously and widely discharged or leached
Negligible	Confining beds are present and prevent any significant vertical groundwater flow

Source: Foster *et al.*, 2002

Table 2.7: Hydrogeological Settings and their associated Groundwater Pollution Vulnerability

Hydrogeological setting and aquifer type		Typical travel times to water- table	Attenuation potential of aquifer	Pollution vulnerability
Alluvial and coastal plain sediments	Unconfined Semi-confined	Weeks-months Years-decades	High-moderate High	Moderate low
Intermontane valley-fill and volcanic systems	Unconfined Semi-confined	Months-years Years-decades	Moderate Moderate	Moderate Moderate-low
Consolidated sedimentary aquifers	Porous sandstone Karstic limestone	Weeks-years Days- weeks	Moderate Low	Moderate-high Extreme
Coastal limestones	Unconfined	Days- weeks	Low- moderate	High- extreme
Glacial and minor alluvial deposits	Unconfined	Weeks- years	Moderate-low	Moderate-high
Extensive volcanic sequences	Lava Ash/Lava Sequences	Day-months Months- years	Low High	High- extreme Low
Weathered basement	Unconfined Semiconfined	Days- weeks Weeks- years	Low Moderate	High- extreme Moderate
Loessic plateaux	Unconfined	Weeks- months	Low-moderate	Moderate-high

Source: (Morris *et al.*, 2003)

Most cities in civilised countries have central sewage systems unlike what is obtainable in Nigeria. The tremendous increase in population, which has resulted to a lot of informal settlements, has continued to mount pressure on groundwater and its quality. Anambra state is not an exception, with a meagre land size of 4,887sq.km and an estimated population (as at 2017) of more than 8million, makes it the second most populous state (after Rivers State) in both the Southeast and Southsouth regions (https://nigerianfinder.com). With little or no appropriate waste disposal system and the incessant drilling of boreholes/wells without necessarily checking the proximity to each other and to nearby soak-away pits and latrine. It becomes obvious that groundwater quantity and quality will be jeopardized in most communities within the State. However, it is expected that some areas in the State will be more susceptible to pollution than others, hence the need to develop a risk model chart for groundwater resources in the study area. This will help to ascertain or describe the degree of vulnerability of groundwater to pollution as a function of the amount and type of recharge, the groundwater flow system and the hydrogeological structure within the study area.

2.9 Aquifer Parameters that Influence Yield

The primary function of any aquifer is to store and transmit groundwater; however, the following aquifer properties are very significant in the study of groundwater hydrology.

i. Hydraulic conductivity or Coefficient of Permeability (K)

Hydraulic conductivity is symbolically represented as K, which is a property of rock that describes the ease with which water can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and on the degree of saturation. An aquifer is isotropic if the hydraulic conductivity is the same in all directions at a single point, but becomes anisotropic if the hydraulic conductivity changes with direction. The Hydraulic conductivity (K) is equal to the discharge (m^3/s) per unit area (m^2) of soil mass under unit hydraulic gradient. Hydraulic conductivity has the dimension of velocity (L/T) and it is usually expressed as cm/s, m/s, m/day because the discharge per unit area is equal to the velocity. However, hydraulic conductivity is determined in the field either from pumping tests or from aquifer parameters estimated from geophysical data.

From geophysical data, saturated hydraulic conductivity, k_{sat}, describes water movement through saturated media.

$$\mathbf{K_c} = \frac{\mathbf{1}}{\boldsymbol{\rho}} \qquad (2.11)$$

Where $\mathbf{K_c}$ is the calculated hydraulic conductivity

$\boldsymbol{\rho}$ is the resistivity of the saturated layer

ii. Transmissivity (T)

Transmissivity is a measure of the capability of the aquifer to transmit groundwater through a unit width of the aquifer under a unit hydraulic gradient. It can also be said to be the ease at which water can be extracted from an aquifer. Transmissivity is usually low if there is a substantial resistance to groundwater flow through the geologic formations.

It is directly proportional to hydraulic conductivity (K) and aquifer thickness (b). Expressing K in m/day or cm/s and b in m, the transmissivity (T) is found in units' m^2/day or cm^2/s or l/day/m. However, Transmissivity (T) has dimensions (L^2/T) with S.I metric unit as m^2/s.

$$\mathbf{T = Kb} \qquad (2.12)$$

The transmissivity (T) of aquifer is related to the field hydraulic conductivity (K) by the equation above.

According to Niwas and Singhal (1981) in a porous medium

$$\mathbf{T_c = K_c\, b} \qquad (2.13)$$

Where

$\mathbf{T_c}$ = Calculated transmissivity (m^2/day) from VES data.

$\mathbf{K_c}$ = Calcluated hydraulic conductivity (m/day) from VES data.

b = Thickness of saturated layer (m).

Transmissivity is also determined in the field either from pumping tests or from aquifer parameters estimated from geophysical data. Any aquifer with transmissivities greater than 0.015 m^2/s is very prolific and good for well development.

iii. Storage Coefficient (S)

Storage coefficient or Storativity is the volume of water released from storage, or taken into storage by the aquifer, per unit of aquifer storage area per unit change in hydraulic head. The water yielding capacity of an aquifer is expressed in terms of its storage coefficient. It is dimensionless because it is a ratio of the volume of water released from original storage volume. In confined aquifer, (S) is the result of compression of the aquifer and expansion of the confined water when the head (pressure) is reduced during pumping while in unconfined aquifers; (S) becomes the same as the specific yield of the aquifer. The Storage coefficient which ranges from 0.005 to 0.00005 in confined aquifer is determined from pumping tests of wells.

iv. Specific Yield (S_y)

Specific yield (S_y) is one of the aquifer characteristics that determine the volume of stored water in an aquifer. It is defined as the ratio of the volume of water that a saturated rock/aquifer will yield by gravity (or by pumping from wells) to the total volume of the saturated rock/aquifer. It can simply be said to be the actual volume of water that can be extracted by the force of gravity from a unit volume of aquifer (Table 2.8)

S_y is expressed mathematically by the equation;

$$\boldsymbol{S_y = \frac{V_w}{V} \times 100}\% \tag{2.14}$$

Where, $\mathbf{V_w}$ = Volume of water in a unit volume of earth materials ($\mathbf{L^3}$)

V = Unit volume of earth materials ($\mathbf{L^3}$)

Specific yield can be calculated from specific retention by use of porosity data from geophysical logs;

$$\boldsymbol{n} = \boldsymbol{S_y} + \boldsymbol{S_r} \qquad (2.15)$$

Where, **n** = porosity; $\boldsymbol{S_r}$ = Specific retention

Table 2.8: Specific Yield Value for Various Geologic Materials

Material	**Specific Yield (%)**
Gravel, coarse	21
Gravel, medium	24
Gravel, fine	28
Sand, coarse	30
Sand, medium	32
Sand, fine	33
Silt	20
Clay	6
Sandstone, fine grained	21
Sandstone, medium grained	27
Limestone	14
Dune sand	38
Loess	18
Peat	44
Schist	26
Siltstone	12
Till, predominantly silt	6
Till, predominantly sand	16
Till, predominantly gravel	16
Tuff	21

Source: Morris and Johnson, 1967

v. Specific Retention (Sr)

Specific Retention (Sr) is the ratio of the volume of water retained in an unconfined aquifer by capillary forces during gravity drainage of the aquifer. Specific retention and specific yield (Table 2.9) depend upon the shapes and sizes of particles, pores distribution and compaction of the geological formation. Thus, the specific retention increases with decreasing grain size.

Table 2.9: Geologic Materials with Their Corresponding Porosity, Specific Yield and Specific Retention Values

Material	Porosity (%)	Specific Yield (%)	Specific Retention (%)
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (unconsolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (young)	11	8	3

Source: Heath, 1983

vi. Leakage Factor (B)

Leakage factor as determined by the pumping test data of a semi-confined aquifer (symbol L; m), is the ratio of the semi-pervious layer conductance and the semi-confined aquifer transmissivity. It provides information on the permeability of the pumped strata and the resistivity of the overlying strata to vertical flow. Leakage factor is expressed in meter because of its L dimension through the following expression;

$$L = \sqrt{K'D'c} \tag{2.16}$$

Where,

$K' =$ Hydraulic conductivity of the aquitard for vertical flow (m/day)

D'= saturated thickness of the aquitard (m);

c = D'/K': hydraulic resistance of the aquitard (day)

vii. Leakage Coefficient (K/D)

Leakage coefficient as determined by the pumping test data of a semi-confined aquifer. It is the ratio of the vertical hydraulic conductivity (K’) of a semi-pervious layer to the saturated thickness (D’) of the semi-pervious layer. It is measured in day^{-1}. Leakage coefficient specifies the speedy vertical flow of groundwater through a semi-pervious layer under a unit vertical hydraulic gradient across the layer. The inverse of the leakage coefficient is called the Hydraulic Resistance (C).

2.10 Well Hydraulics

The basic principle of test pumping a well involves applying a stress to an aquifer by extracting groundwater from the well and measuring the aquifer response to that stress by monitoring drawdown as a function of time. This is usually done when the groundwater level has returned to normal after well development. Pumping test is carried out under controlled conditions to examine water chemistry and to determine well yield, well efficiency and aquifer parameters. However, for proper understanding of the principles of well hydraulic, it is important to list and define some relevant terms;

i. **Well yield:** This is a measure of the quantity of water that can be extracted from the well over a period of time. It is measured in $[L^3T^{-1}]$.

ii. **Specific capacity:** is a measure of well performance per unit of drawdown. This answers the question on whether the well will provide an adequate water supply, because as the amount of drawdown increases at constant higher rates of pumping, the maximum yield of the well will ultimately be ascertained. Specific capacity is calculated by dividing pumping rate over drawdown (Q/S). That is;

$$\mathbf{S_c} = \frac{\mathbf{Q}}{\mathbf{h_0 - h}} = \frac{\mathbf{Q}}{\mathbf{SWL - PWL}} \tag{2.17}$$

Where, $\mathbf{S_c}$ is the specific capacity ($[L^2T^{-1}]$; m²/day); **Q** is the pumping rate ($[L^3T^{-1}]$; m³/day)

$\mathbf{h_0 - h}$ or **SWL – PWL** is the drawdown ([L]; m)

iii. **Static Water Level (SWL):** This the equilibrium level of water in well (confined or unconfined aquifer) when no water is being extracted from the aquifer through pumping or free flow.

iv. **Pumping or Dynamic Water Level (PWL):** This is the water level when pumping is in progress.

v. **Drawdown (s):** This is the length difference between the SWL (water table or potentiometric) and the PWL.

vi. **Cone of Depression:** This occurs during pumping test, when water extraction from the well becomes greater than the rate of recharge, the level of the water table will be drawn down in the shape of an inverted cone.

vii. **Observation Well:** This is a non-pumping well basically used for observing the elevation of the water table or the piezometric pressure. Water-quality samples are equally obtained from the well. It serves as a measuring point for passive drawdown.

viii. **Potentiometric Surface (Piezometric Surface):** This is the depth to water in well penetrating a confined aquifer or the theoretical surface representing the hydraulic head of the water table in an unconfined aquifer.

ix. **Area of Influence:** This is the area of the well over which the depression can be detected during pumping. The outer limit of the cone of depression.

x. **Open Wells:** Also known as dug wells are the most convenient and cost-effective way of groundwater exploitation in both shallow and low-yielding unconfined aquifers. They are usually constructed in circular or rectangular shape.

xi. **Tube Wells:** These are wells constructed by installing a pipe through different geological formations comprising water-bearing and non-water-bearing layers below the ground surface. Well screens are usually placed in the water bearing aquifer while the casing pipes are placed in the non-water-bearing layers.

xii. **Filter Points:** This is a type of shallow tube well (<15m deep) that consist of a well screen and a short casing pipe that is mostly seen in deltaic regions, where gravel and coarse sand are the major components of the aquifer formations. Water is mostly withdrawn manually from this type of well.

xiii. **Drawdown Curve:** This is the shape of the potentiometric surface.

xiv. **Residual Drawdown (Recovery Curve):** This curve is noticed when a well after pumping, comes to equilibrium with the natural aquifer conditions as the water level in the well recovers or it is the drawdown after pumping has stopped before full recovery.

xv. **Falling Head Condition:** Vigorous pumping and the resultant drawdown of a well.

xvi. **Rising Head Condition:** Recovery of the well and aquifer following the pumping stoppage.

xvii. **Unsteady Radial Flow (Transient Flow Conditions):** In isotropic- homogeneous aquifer conditions, groundwater flow to well is assumed to be the same (radial) from all directions. Consequently, the flow is unsteady and drawdown is a function of time and distance or location.

xviii. **Steady Radial Flow (Steady State Flow Conditions):** Also in isotropic – homogeneous aquifer conditions where flow to well is assumed to be equal (radial) in all directions. The flow to pumping well is steady, while the head and cone of depression are at equilibrium between pumping rate and aquifer properties. Thus, the head and cone of depression are not a function of time.

xix. **Isotropic:** If the hydraulic conductivity is independent of the direction of measurement at a point in a geologic formation, the formation is isotropic at that point.

xx. **Anisotropic:** If the hydraulic conductivity varies with the direction of measurement at a point in a geologic formation, the formation is anisotropic at that point.

xxi. **Homogeneous Aquifer:** An aquifer is said to be homogeneous if the hydraulic conductivity is independent of position within the aquifer.

xxii. **Heterogeneous Aquifer:** An aquifer is Heterogeneous if the hydraulic conductivity is dependent on position within the aquifer.

2.11 Estimating Hydraulic Properties of Aquifers Using Pumping Test

Proper assessment of aquifer hydraulic properties is required for efficient management and development of groundwater resources. The estimation of hydraulic properties of aquifer like; transmissivity (T), hydraulic conductivity (K), storage coefficient (S) etc., provide vital quantitative information on the hydraulic response of the aquifer to recharge and pumping. So many methods like; slug tests, pumping test, bail tests, tracer tests and geo-electrical methods are used in estimating aquifer hydraulic properties. Pumping test, though uneconomical and time consuming happens to be a more precise method for obtaining the hydraulic parameters of an aquifer. Meanwhile, the major challenge associated with pumping test is the difficulty in keeping the discharge rate constant since it varies slightly with time due to discharge head increase and voltage fluctuation associated with supply of electric power to the pump motor (Rao *et al*., 2015).

Test pumping provides very useful qualitative and quantitative information which determines whether the well yield will be sufficient for its anticipated purpose. Different analytical methods are employed in the analysis of the data obtained from aquifer tests but the choice of method largely depends on aquifer conditions, type of test to be carried out and acceptable assumptions. Some of these methods include; Theis-type-curve matching, Cooper-Jacob straight-line and Theis recovery etc. These methods are based on the assumption that aquifers are homogeneous in nature. Conversely, the assumption tends to question the validity of the pumping test analysis because aquifers are known to be heterogeneous to some extent (Rao *et al*., 2015).

Drawdown data obtained from pumping test are interpreted with the analytical method and used for estimation of aquifer hydraulic properties.

2.11.1 Steady Radial Flow to a Well

Steady Radial Flow is assumed to occur in isotropic – homogeneous aquifer conditions where flow to well is to be equal (radial) in all directions. Consequently the flow to pumping well is steady which implies that the drawdown is a function of location.

- **Confined Aquifers**

Available equations for estimating aquifer hydraulic properties in a confined aquifer, under steady radial flow are based on the following assumptions (Kasenow, 2010);

The aquifer is confined

The aquifer has infinite aerial extent

The aquifer is homogeneous, isotropic and of uniform thickness

The piezometric surface is horizontal prior to start of pumping

The aquifer is pumped at a constant discharge rate

The pumping well fully penetrates the aquifer and thus receives water by horizontal flow

All flow is radial towards the well and Darcy's law is valid

Groundwater has a constant viscosity and density

It is important to use more than one piezometer during pumping test in order to avoid drawdown errors due to well losses at the abstraction well. Meanwhile, according to the assumptions earlier stated, the flow in figure 2.14 is expressed by applying Darcy's law to derive the flow equation that relates drawdown with pumping, thus;

$$\mathbf{Q = Aq} \tag{2.18}$$

Where **Q** = Discharge; **A** = Area of a cylinder($\mathbf{2\pi rb}$); **q** = Velocity of flow ($-\mathbf{K}\frac{\partial \mathbf{h}}{\partial \mathbf{r}}$)

Meanwhile from Darcy's Law $$\mathbf{q = -K\frac{\partial h}{\partial r}} \tag{2.19}$$

By eliminating A and q from equation (2.18)

Gives; $$\boldsymbol{Q = -2\pi rKb}\frac{\partial \mathbf{h}}{\partial \mathbf{r}} \tag{2.20}$$

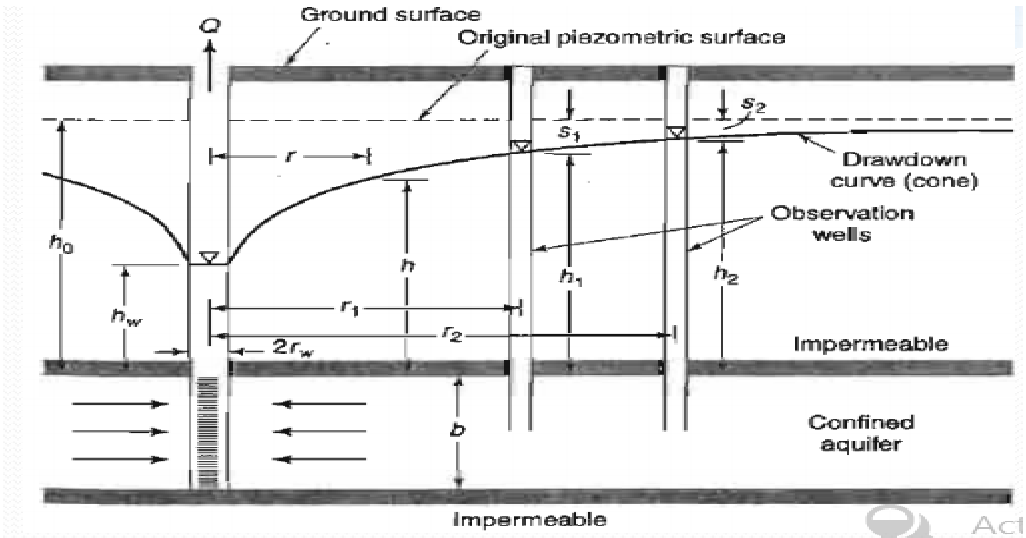


Figure 2.14: Cross-section of a pumped confined aquifer

From Figure 2.14; let $\mathbf{h = h_w}$ at $\mathbf{r = r_w}$ **;** $\mathbf{h = h_0}$ at $\mathbf{r = r_0}$**,** yields

Rearranging and Integration gives;

$$\mathbf{\frac{Q}{2\pi Kb}\int_{r_w}^{r_0}\frac{1}{r}dr = \int_{h_w}^{h_0}dh} \tag{2.21}$$

Thus, $$\frac{Q}{2\pi Kb}\ln(\frac{r_0}{r_w}) = h_0 - h_w \quad (2.22)$$

Therefore, $$Q = \frac{2\pi Kb(h - h_w)}{\ln(^{r}/_{r_w})} \quad (2.23)$$

The equation (2.23) is known as the equilibrium or Thiem Equation and can be used to estimate transmissivity.

However, transmissivity can be estimated from Drawdown measurement from the field from the equation below;

$$\frac{Q}{2\pi Kb}\ln(\frac{r_2}{r_1}) = s_1 - s_2 \quad (2.24)$$

$$T = Kb = \frac{Q}{2\pi(s_1 - s_2)}\ln(\frac{r_2}{r_1}) \quad (2.25)$$

Meanwhile,

K = Hydraulic conductivity

b = Aquifer thickness

$\mathbf{r_1}$, $\mathbf{r_2}$ = Distances from the two respective observation wells to the pumping well

$\mathbf{h_1}$, $\mathbf{h_2}$ = Heads of the respective observation wells

$\mathbf{s_1}$, $\mathbf{s_2}$ = Drawdown at the respective observation wells

- **Unconfined Aquifers**

The basic assumptions for estimating aquifer hydraulic properties in a steady state flow to well in unconfined aquifers are the same with that of the confined aquifer except that the aquifer must be unconfined.

Flow in figure 2.15 is also expressed by applying Darcy's law to derive the flow equation that relates drawdown with pumping, thus from equation 2.18;

$$\mathbf{Q = Aq}$$

Thus, from Darcy's Law and continuity equation;

$$\mathbf{Q = -2\pi rKh\frac{\partial h}{\partial r}} \tag{2.26}$$

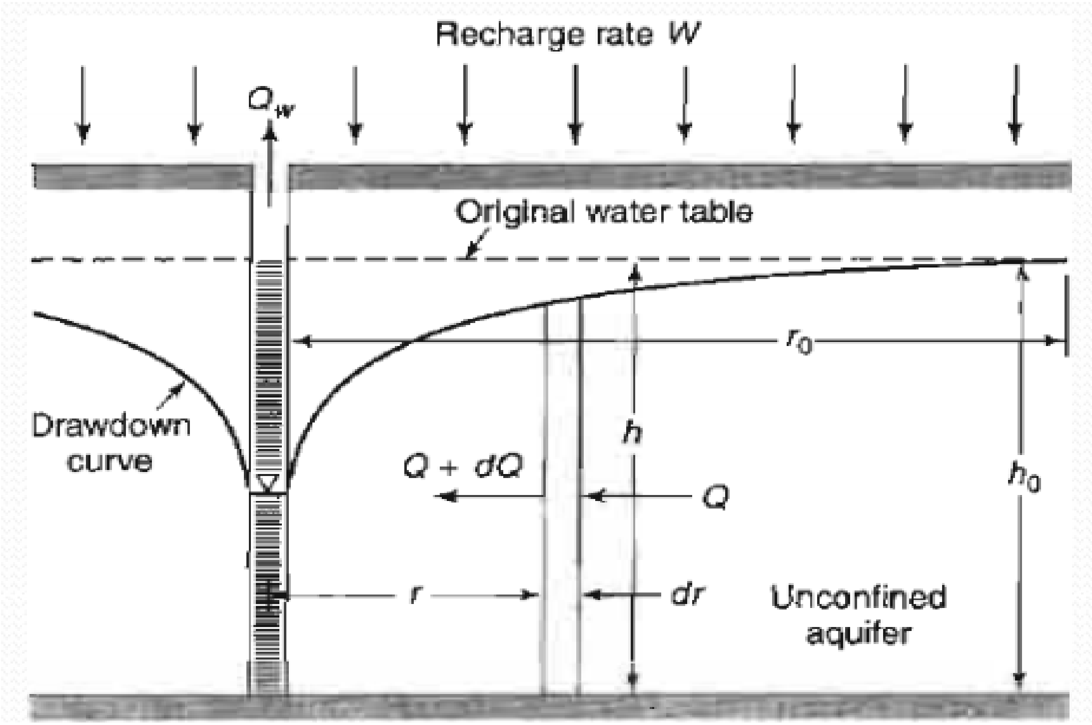


Figure 2.15: Cross-section of a pumped unconfined aquifer (steady-state flow)

From the figure 2.15 let $\mathbf{h = h_w}$ at $\mathbf{r = r_w}$; $\mathbf{h = h_0}$ at $\mathbf{r = r_0}$**,** yields

Rearranging and Integration,

$$\mathbf{\frac{Q}{2\pi K}\int_{r_w}^{r_0}\frac{1}{r}dr = \int_{h_w}^{h_0} hdh} \tag{2.27}$$

Thus, $$\mathbf{\frac{Q}{2\pi K}\ln\left(\frac{r_0}{r_w}\right) = \frac{h_0^2 - h_w^2}{2}} \tag{2.28}$$

Therefore, $\mathbf{Q = \pi K \frac{h_0^2 - h_w^2}{\ln(^{r_0}/_{r_w})}}$ (2.29)

$$\mathbf{Q = \pi K \frac{h_2^2 - h_1^2}{\ln(^{r_2}/_{r_1})}} \quad (2.30)$$

The equation (2.30) which is identical to the Theim equation is called Dupuit Formula. This formula is used to estimate Transmissivity in unconfined aquifer.

In estimating Transmissivity (T) from the equation (2.29) establish Q as the subject of the formula;

Thus,

$$\mathbf{Q = \frac{\pi K(h_2+h_1)(h_2-h_1)}{\ln(^{r_2}/_{r_1})}} \quad (2.31)$$

In unconfined aquifer, $\mathbf{T = K\frac{h_2+h_1}{2}}$ (2.32)

Hence, $\mathbf{K = \frac{Q}{\pi(h_2^2-h_1^2)} \ln(^{r_2}/_{r_1})}$ (2.33)

Meanwhile, Dupuit and Forchheimer assumed that;

The slope of water in pumped well in an unconfirmed aquifer is equal to the hydraulic gradient of flow.

Flow lines are horizontal and parallel to the impermeable layer.

However, in thick unconfined aquifers, drawdown (**s**) is negligible compared to $\mathbf{h_0}$**,** while $\mathbf{h_2 + h_1}$ is assumed to equal **2h**. Therefore; $(\mathbf{h_2^2 - h_1^2})$ = $(\mathbf{h_2 + h_1})(\mathbf{h_2 - h_1})$ and $\mathbf{h_2 - h_1}$ =$\mathbf{s_1 - s_2}$. From equation (2.31); **T** = $\mathbf{Kh_0}$.

In the figure 2.15; $\mathbf{h_2} = \mathbf{h_0 - s_2}$ and $\mathbf{h_1} = \mathbf{h_0 - s_1}$, consequently, substituting these values in the equation (2.33) and multiplying both sides of the equation by $\mathbf{2h_0}$ gives;

$$\mathbf{K} = \frac{\mathbf{Q\,ln(^{r_2}/_{r_1})}}{\mathbf{2\pi h_0}\left[\frac{(h_0^2 - 2s_2h_0 + s_2^2) - (h_0^2 - 2s_1h_0 + s_1^2)}{2h_0}\right]} \qquad (2.34)$$

Therefore Transmissivity is,

$$\mathbf{T = Kh_0} = \frac{\mathbf{Q}}{\mathbf{2\pi\{\left(s_1 - \frac{s_1{}^2}{2h_0}\right) - \left((s_2 - \frac{s_2{}^2}{2h_0})\right)\}}}\mathbf{ln(^{r_2}/_{r_1})} \qquad (2.35)$$

- **Leaky Aquifer**

There are two distinctive methods that are widely used in the analysis of steady state drawdown data in leaky aquifers in order to determine the aquifer characteristics. The two methods are the De Glee's method and Hantush- Jacob's method.

- **De Glee's Method**

De Glee (1930, 1951) derived the equations below based on the following assumptions; all the assumptions for steady radial flow to well conditions and the flow to well must be in steady state.

L > 3D

Thus; $$\mathbf{S_m} = \frac{\mathbf{Q}}{\mathbf{2\pi KD}}\mathbf{K_0(\frac{r}{L})} \qquad (2.36)$$

$$\mathbf{L} = \sqrt{\mathbf{KDc}} \qquad (2.37)$$

Where;

$\mathbf{S_m}$ = Steady state drawdown in a piezometer from distance 'r' from the well (L)

L = Leakage factor (L); Q = Discharge (L^3/T)

$\mathbf{c} = \frac{\mathbf{D'}}{\mathbf{K'}}$ **:** Hydraulic resistance of the aquitard (T)

$\mathbf{K'} =$ Hydraulic conductivity of the aquitard for the vertical flow (L/T)

$\mathbf{D'}$ = Saturated thickness of the aquitard (L)

$\mathbf{K_0(x)}$ = Hankel function (obtained from a table)

However, after some of the variables are plotted on a log-log paper, KD can be calculated by substituting the known value of Q and the values of $\mathbf{S_m}$ and $\mathbf{K_0}$(r/L) into equation (2.35). From substituting the calculated value of KD and the values of r and r/L into equation (2.36), **c** can be calculated, thus;

$$\mathbf{c = \frac{L^2}{KD} = \frac{1}{(r/L)^2} = \frac{r^2}{KD}} \tag{2.38}$$

- **Hantush-Jacob's method**

Hantush and Jacob (1955) modified the equation (2.36) as;

$$\mathbf{S_m \approx \frac{2.30Q}{2\pi KD}\left[\log 1.12\,\frac{L}{r}\right]} \tag{2.39}$$

The Hantush and Jacob's method can be used practically if only the following assumptions and conditions are fulfilled;

i. All the assumptions for steady radial flow to well conditions

ii. The flow to the well is in steady state

iii. L > 3D

iv. $\frac{\mathbf{r}}{\mathbf{L}} \leq 0.05$

When $\mathbf{S_m}$ is plotted against '**r**' on a semi-log paper, with **r** on the logarithmic scale, the resultant graph will be a straight- line within the range where r/L is small. However, in the range where r/L is large, the resultant graph will be curved as the zero-drawdown axis is asymptotically approached. Thus, the drawdown difference $\Delta\mathbf{S_m}$ per log cycle of **'r'** which is the slope of the straight portion of the curve (i.e., range where **r/L** is small) is expressed by (Hantush, 1956 and 1964),

$$\Delta \mathbf{S_m} = \frac{\mathbf{2.30Q}}{\mathbf{2\pi KD}} \tag{2.40}$$

Meanwhile, $\mathbf{S_m}$= 0 and r = $\mathbf{r_0}$ at the point of interception at the r- axis where drawdown is zero. Thus, equation (2.39) becomes;

$$\mathbf{0} = \frac{\mathbf{2.30Q}}{\mathbf{2\pi KD}}\left[\mathbf{log1.12}\frac{\mathbf{L}}{\mathbf{r}}\right] \tag{2.41}$$

Hence; $\mathbf{1.12}\frac{\mathbf{L}}{\mathbf{r_0}} = \frac{\mathbf{1.12}}{\mathbf{r_0}}\sqrt{\mathbf{KDc}} = \mathbf{1}$ (2.42)

And therefore; $\mathbf{c} = \frac{(\mathbf{r_0/1.12})^2}{\mathbf{KD}}$ (2.43)

2.11.2 Unsteady Radial Flow/ Non-equilibrium Well Pumping Equations

- Confined Aquifer

Unsteady radial flow (Transient Flow Conditions) is assumed to occur in an isotropic-homogeneous aquifer conditions where groundwater flow to well is the same (radial) from all directions. Consequently, the flow is unsteady and drawdown is a function of time and location.

$$\frac{\mathbf{1}}{\mathbf{r}}\frac{\partial \mathbf{h}}{\partial \mathbf{r}} + \frac{\partial^2 \mathbf{h}}{\partial \mathbf{r}^2} = \frac{\mathbf{S}}{\mathbf{T}}\frac{\partial \mathbf{h}}{\partial \mathbf{t}} \tag{2.44}$$

$\frac{\partial \mathbf{h}}{\partial \mathbf{t}}$ **=** change in head between $\mathbf{h_2}$ and $\mathbf{h_1}$ with time

S = Storage coefficient

r = Radial distance from the pumped well

T = Transmissivity

t = Time since pumping started

The equation (2.44) is the Laplace equation for unsteady radial flow (Transient flow). However, for Steady radial flow; $\frac{\partial h}{\partial t}$ **= 0.** This implies that there is zero change in the aquifer storage (Lohman, 1972), thus the Laplace equation;

$$\frac{1}{r}\frac{\partial h}{\partial r} + \frac{\partial^2 h}{\partial r^2} = 0 \qquad (2.45)$$

Theis Matching Curve Method

A solution for the non-equilibrium flow equations in radial coordinates was developed by Theis (1935) based on the analogy between groundwater flow and heat conduction thus;

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}du}{u} = \frac{Q}{4\pi T}W(u) = \frac{Q}{4\pi T}\left[-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \ ...\right] \qquad (2.46)$$

Where, **s** = Drawdown (L); **Q** = Constant well discharge (L^3/T)

W(u) = well function of u (dimensionless); **r** = distance from pumping well (L)

S = storativity (dimensionless); **t** = time since pumping begins (T)

T = transmissivity (L^2/T); **u** = auxiliary parameter (dimensionless)

$$u = \frac{r^2 S}{4Tt} \qquad (2.47)$$

The equation (2.46) is referred to as non-equilibrium or Theis equation. From the equation, '**u**' is the lower limit of integration which is expanded as a convergent serials and termed well function "**W(u)**" (see Table for values). The non-equilibrium equation is commonly applied in practice while estimating aquifers hydraulic properties through pumping test of wells. Researchers like Theis, Cooper and Jacob and Chow solved the mathematical difficulties associated with the application of the equation by developing simpler methods of analysis that can easily be used in the field from the non-equilibrium equation.

Table 2.10: Values of the function W(u) for various values of u

u	$W(u)$	u	$W(u)$	u	$W(u)$	u	$W(u)$
1×10^{-10}	22.45	7×10^{-8}	15.90	4×10^{-5}	9.55	1×10^{-2}	4.04
2	21.76	8	15.76	5	9.33	2	3.35
3	21.35	9	15.65	6	9.14	3	2.96
4	21.06	1×10^{-7}	15.54	7	8.99	4	2.68
5	20.84	2	14.85	8	8.86	5	2.47
6	20.66	3	14.44	9	8.74	6	2.30
7	20.50	4	14.15	1×10^{-4}	8.63	7	2.15
8	20.37	5	13.93	2	7.94	8	2.03
9	20.25	6	13.75	3	7.53	9	1.92
1×10^{-9}	20.15	7	13.60	4	7.25	1×10^{-1}	1.823
2	19.45	8	13.46	5	7.02	2	1.223
3	19.05	9	13.34	6	6.84	3	0.906
4	18.76	1×10^{-6}	13.24	7	6.69	4	0.702
5	18.54	2	12.55	8	6.55	5	0.560
6	18.35	3	12.14	9	6.44	6	0.454
7	18.20	4	11.85	1×10^{-3}	6.33	7	0.374
8	18.07	5	11.63	2	5.64	8	0.311
9	17.95	6	11.45	3	5.23	9	0.260
1×10^{-8}	17.84	7	11.29	4	4.95	1×10^{0}	0.219
2	17.15	8	11.16	5	4.73	2	0.049
3	16.74	9	11.04	6	4.54	3	0.013
4	16.46	1×10^{-5}	10.94	7	4.39	4	0.004
5	16.23	2	10.24	8	4.26	5	0.001
6	16.05	3	9.84	9	4.14		

Source: Wenzel, 1942

Data obtained from pumping wells in confined aquifers are better analyzed with the Theis solution called the Matching Curve method based on the following assumptions (Theis, 1935); aquifer is confined, homogeneous, isotropic and is of infinite extent; the flow to the well is in unsteady state; well completely penetrates (and get water from) the entire aquifer; well diameter is small making the well storage negligible.

Well is pumped at a constant rate before pumping, the potentiometric surface is horizontal.

Transmissivity is constant, water is removed from storage and discharge instantaneously with decline head.

Data like the pumping rate of well, distance between pumping well and observation well, and drawdown readings versus time are required for the Theis solution. However, Theis expressed the transient drawdown in equations (2.46) and (2.47) by introducing a graphical method that makes it possible to solve the two equations, thus, taking logarithms and rearranging the equations produces equations (2.48) and (2.49) respectively (Lohman, 1972).

$$\mathbf{log(\, s) = log[W(u)] + log\left[\frac{Q}{4\pi T}\right]} \tag{2.48}$$

$$\mathbf{log(\, t) = log\left(\frac{1}{u}\right) + log\left[\frac{r^2S}{4T}\right]} \tag{2.49}$$

Cooper- Jacob (Time Drawdown Method)

This method is widely referred to as Jacob's method and it is based on Theis analysis. However, from Theis analysis in equation (2.46), the term **'u'** can be seen to decrease as the time of pumping increases and as the distance of the piezometer from the well decreases. So, for drawdown observations made through piezometers close to the pumping well after prolong pumping, the terms beyond **ln u** in equation (2.46) become negligible. However, for values of $u < 0.001$, drawdown can be expressed (Cooper and Jacob, 1946):

$$\mathbf{s = \frac{Q}{4\pi T}\left[-0.5772 - ln\ \frac{r^2S}{4Tt}\right]} \tag{2.50}$$

Converting to logarithms and rearranging gives;

$$\mathbf{s = \frac{2.3Q}{4\pi T}\left[log\frac{2.25T}{r^2S}t\right]} \tag{2.51}$$

Thus the straight line equation;

$$\mathbf{s = \left[\frac{2.3Q}{4\pi T}log\frac{2.25T}{r^2S}\right] + \left[\frac{2.3Q}{4\pi T}\right]log\, t} \tag{2.52}$$

- **Unconfined Aquifer**

The commonly used equation for flow of water towards a pumping well in an unconfined aquifer was developed by Neuman and Witherspoon, 1969;

$$\mathbf{K_r}\ \frac{\partial^2 \mathbf{h}}{\partial \mathbf{r}^2} + \frac{\mathbf{K_r}}{\mathbf{r}} \times \frac{\partial \mathbf{h}}{\partial \mathbf{r}} + \mathbf{K_v} \frac{\partial^2 \mathbf{h}}{\partial \mathbf{z}^2} = \mathbf{S_s} \times \frac{\partial \mathbf{h}}{\partial \mathbf{t}} \qquad (2.53)$$

Where,

h = the saturated thickness of the aquifer (L); **r** = radial distance from the pumping well (L)

z = elevation above the base of the aquifer (L); specific storage (L^{-1})

$\mathbf{K_r}$ = radial hydraulic conductivity (L/T); $\mathbf{K_v}$ = vertical hydraulic conductivity (L/T)

T = time (T)

The Neuman solution is based on the following assumptions; aquifer is unconfined, homogeneous and is of infinite extent, but vadose zone has no influence on the drawdown.

Water is pumped initially from storage ($\mathbf{S_s}$) and drained later due to gravity ($\mathbf{S_y}$). Radial **K** or $\mathbf{K_r}$ can be different from vertical **K** or $\mathbf{K_v}$

Assume drawdown is negligible compared to saturated thickness

Neuman solution is valid only when drawdown is negligible compared to aquifer's thickness

The specific yield is at least 10 times the elastic storativity.

Thus, Neuman's solution is;

$$\mathbf{s} = \frac{\mathbf{Q}}{\mathbf{4\pi T}} \mathbf{W}(\mathbf{u_A}, \mathbf{u_B}, \mathbf{\Gamma}) \qquad (2.54)$$

Where;

$\mathbf{W}(\mathbf{u_A}, \mathbf{u_B}, \mathbf{\Gamma})$ is called the well function of the unconfined aquifer

Meanwhile, for early pumping time (early drawdown data) the equation below is used;

$$\mathbf{s} = \frac{\mathbf{Q}}{\mathbf{4\pi T}} \mathbf{W}(\mathbf{u_A}, \mathbf{\Gamma}) \quad \textbf{and} \quad \mathbf{u_A} = \frac{\mathbf{r^2 S}}{\mathbf{4Tt}} \qquad (2.55)$$

While the equation below is used for late pumping time (late drawdown data);

$$\mathbf{s} = \frac{\mathbf{Q}}{\mathbf{4\pi T}} \mathbf{W}(\mathbf{u_B}, \mathbf{\Gamma}) \quad \textbf{and} \quad \mathbf{u_B} = \frac{\mathbf{r^2 S_y}}{\mathbf{4Tt}} \qquad (2.56)$$

$$\Gamma = \frac{r^2 K_v}{b^2 K_h} \tag{2.57}$$

Where;

S = Storativity (dimensionless)

S_y = Specific yield (dimensionless)

r = Radial distance from pumping well (L)

b = Initial saturated thickness of aquifer (L)

K_h = Horizontal hydraulic conductivity (L/T)

- **Leaky Aquifer**

A leaky aquifer (semi-confined aquifer) is an aquifer that has both upper and lower boundaries as aquitards, or one boundary as aquitard and the other as aquiclude. During pumping in a leaky aquifer, groundwater flows vertically into the aquifer, while water is withdrawn from both the aquifer and the overlying aquitard, or the unconfined portion. Decrease in the potentiometric head in the aquifer produces a hydraulic gradient within the aquitard; consequently, the quantity of water moving downwards becomes proportional to the difference between the potentiometric head and the water table (figure 2.16).

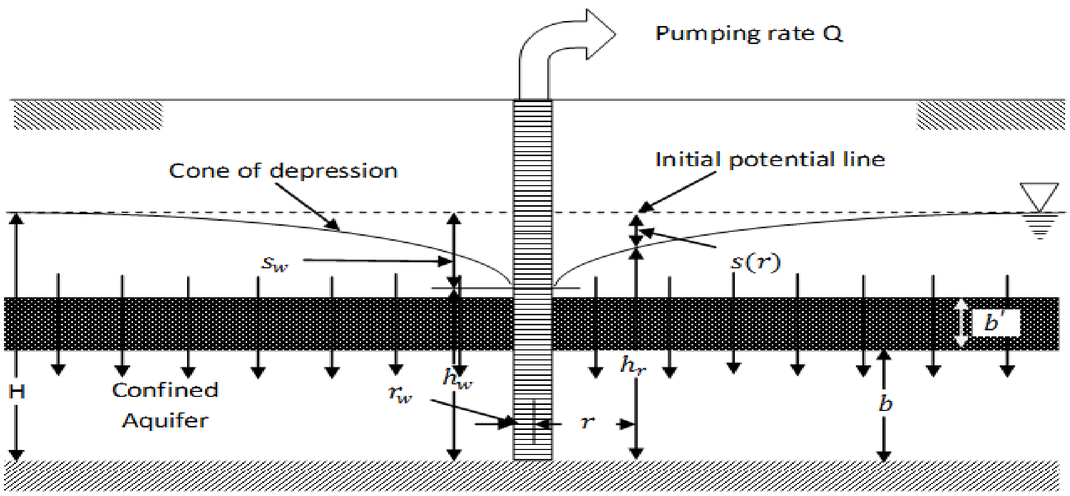


Figure 2.16: Cross- section of a pumped leaky aquifer

The unsteady radial flow for leaky aquifer is based on the following assumptions (Hantush and Jacob 1955; Hantush, 1956); aquifer and aquitard have infinite areal extent.

1. Aquifer is homogeneous, isotropic and of uniform thickness,
2. control well is fully or partially penetrating
3. flow to control well is horizontal when control well is fully penetrating
4. aquifer is leaky
5. flow is unsteady
6. water is released instantaneously from storage with decline of hydraulic head
7. diameter of control well is very small so that storage in the well can be neglected
8. aquitards have infinite areal extent, uniform vertical
9. aquitards are overlain or underlain by an infinite constant-head plane source
10. aquitards are incompressible such that changes in aquitard storage are negligible
11. flow in the aquitards is vertical
12. The aquifer is pumped at a constant discharge rate
13. The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow

The equation (2.58) represents the unsteady radial flow for leaky aquifer

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \times \frac{\partial h}{\partial r} + \frac{e}{T} = \frac{S}{T} \times \frac{\partial h}{\partial t} \qquad (2.58)$$

Where;

r = Radial distance from a pumping well (L)

e = Rate of vertical leakage (L/T)

The Hantush and Jacob (1955) presented a mathematical solution (most times referred to as Hantush Inflection- Point Method) for leaky aquifers based on two restrictive assumptions;

a. hydraulic head in unpumped aquifer remains constant

b. rate at which water moves downwards into pumped aquifer is proportional to hydraulic gradient within the aquitard.

Thus, $\mathbf{s} = \frac{\mathbf{Q}}{\mathbf{4\pi T}} \mathbf{W}(\mathbf{u}, \frac{\mathbf{r}}{\mathbf{B}})$ (2.59)

And $\mathbf{u} = \frac{\mathbf{r^2 S}}{\mathbf{4Tt}}$ (2.60)

Where;

$\mathbf{W}(\mathbf{u}, \frac{\mathbf{r}}{\mathbf{B}})$ = the well function for leaky confined aquifer

B = $\sqrt{\frac{\mathbf{Tb'}}{\mathbf{K'}}}$ = the leakage factor (L)

$\mathbf{b'}$ = aquitard thickness (L)

$\mathbf{K'}$ = vertical hydraulic conductivity of the aquitard (L/T)

Q = pumping rate/ Discharge (L^3/T)

r = radial distance from pumping well to observation well (L)

s = drawdown (L)

S = storativity (dimensionless)

t = elapsed time since start of pumping (T)

T = transmissivity (L^2/T)

Other available methods for analyzing data of unsteady- state flow in leaky aquifer include;

Walton curve- fitting method which neglects the aquitard storage just like the Hantush inflection- point method

Hantush curve- fitting method and Neuman and Witherspoon ratio method. These two methods take aquitard storage into account.

2.12 Multiple Well Systems

When the cone of depression of a pumping well overlaps with cone of depression of other nearby wells, all the wells will be affected by pumping of that well and the cone of depressions of these wells will interfere. Consequently, the rate of drawdown in each well will increase. This phenomenon is referred to as well interference. However, the actual drawdown, which will be more than the drawdown calculated for the individual wells can be calculated using the principle of superposition of linear system (Figure 2.17).

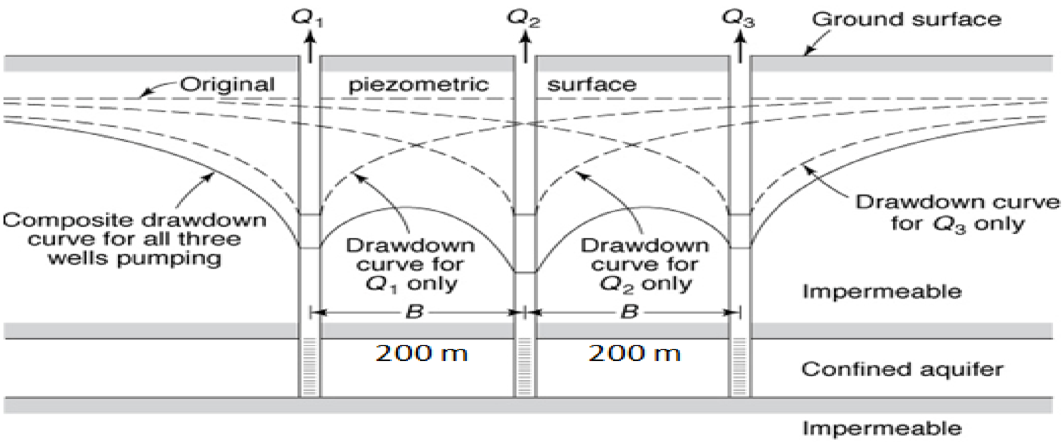


Figure 2.17: Individual and composite drawdown curves for three wells in a line.

From the principle of superposition of linear system, drawdown at any point in the area of influence caused by the discharge of some wells in close proximity is equal to the sum of all the drawdown caused by each individual well, thus;

$$\mathbf{s = s_1 + s_2 + s_3 + \cdots + s_n} \tag{2.61}$$

Where; s = total drawdown at a given point

$\mathbf{s_1, s_2, s_3, s_n}$ = drawdown at the point caused by the discharge of wells 1, 2, 3…, n respectively.

Meanwhile, it is economically advisable that in the course of groundwater exploitation of aquifers, distances between adjacent wells must be greater than the radii of influences of those wells to prevent negative effects on groundwater levels and storage. However, this phenomenon can be useful in most areas with shallow groundwater by drying swamps and lowering groundwater levels.

2.12.1 Wells Flow near Aquifer Boundaries

The assumption that the aquifer is of infinite areal extent is no longer valid when water is pumped from a well near an aquifer boundary. The aquifer boundaries can either be an impermeable or a constant head boundary. However, the principle of superposition is used to implement the effect of aquifer boundary by introducing imaginary wells, or image wells at different locations. These wells create the same effect as boundary and can transform an aquifer of finite extent into one that appears like infinite extent. More image wells are created if there is more than one boundary. In practice, it is important that image wells are added in pairs until a negligible influence on the sum of all image-well effects is noticed (Kruseman and de Ridder, 1994).

- **Well Near an Impermeable Boundary**

Figure 2.18a shows a well near an impermeable boundary. In order to find out the actual drawdown by considering an imaginary pumping well at a distance equal to the distance between the pumping well and the image pumping well as shown in Figure 2.18b.

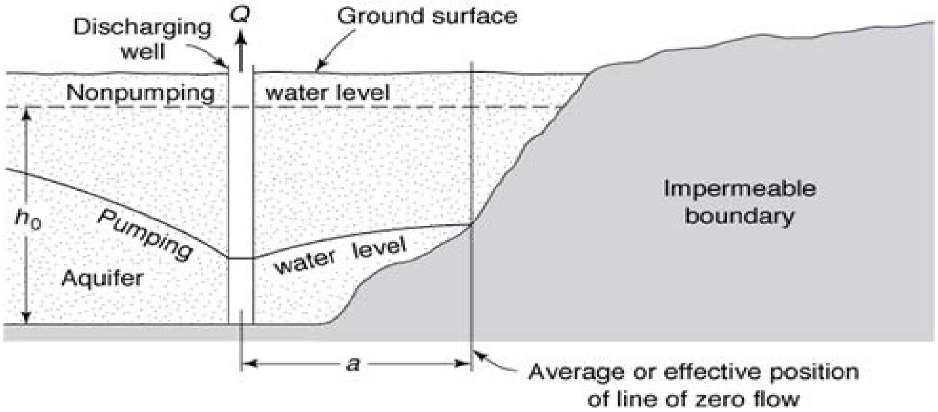


Figure 2.18a: Sectional View of Discharging Well Near an Impermeable Boundary

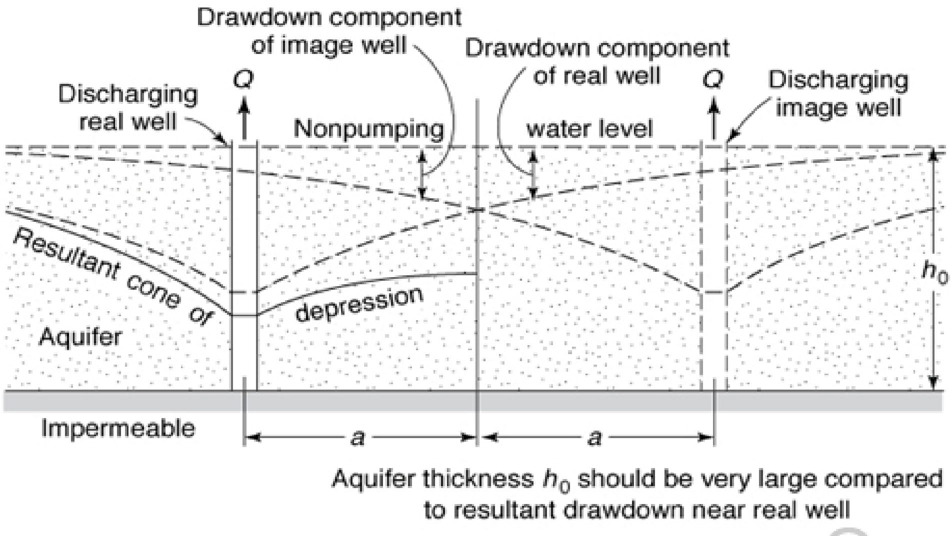


Figure 2.18b: Sectional View of the Equivalent Hydraulic System in an Aquifer with Infinite Areal Extent.

The following equations are important in solving problems associated with discharging well near impermeable boundary

$$\mathbf{h_0^2 - h^2 = \frac{Q}{\pi K} \ln\left(\frac{R}{r_1}\right) + \frac{Q}{\pi K} \ln\left(\frac{R}{r_2}\right)} \tag{2.62}$$

Therefore;

$$\mathbf{h_0^2 - h^2 = \frac{Q}{\pi K} ln\left(\frac{R^2}{r_2 r_1}\right)} \tag{2.63}$$

The **steady state flow** equation for pumping well in a confined aquifer near an impermeable boundary is;

$$\mathbf{s = \frac{Q}{2\pi T} ln\left(\frac{R}{r_p}\right) + \frac{Q}{2\pi T} ln\left(\frac{R}{r_i}\right) = \frac{Q}{2\pi T}\left[ln\left(\frac{R}{r_p}\right) + ln\left(\frac{R}{r_i}\right)\right]} \tag{2.64}$$

Where; $\mathbf{r_i}$ and $\mathbf{r_p}$ are distance from pumping real well and image well respectively.

Therefore, $$s = \mathbf{\frac{Q}{2\pi T} ln\left(\frac{R^2}{r_p r_i}\right)} \tag{2.65}$$

For unsteady state flow the equation is;

Theis Method

$$\mathbf{s = \frac{Q}{4\pi T} W(u_p) + \frac{Q}{4\pi T} W(u_i) = \frac{Q}{4\pi T}[W(u_p) + W(u_i)]} \tag{2.66}$$

$$\mathbf{u_p = \frac{r_p^2 S}{4Tt}} \quad ; \quad \mathbf{u_i = \frac{r_i^2 S}{4Tt}}$$

Jacob's method

$$\mathbf{s = \frac{2.3Q}{4\pi T} log_{10}\left(\frac{2.25Tt}{r_p^2 S}\right) + \frac{2.3Q}{4\pi T} log_{10}\left(\frac{2.25Tt}{r_i^2 S}\right)} \tag{2.67}$$

Thus; $$\mathbf{s = \frac{2.3Q}{4\pi T}\left[log_{10}\left(\frac{2.25Tt}{r_p^2 S}\right) + log_{10}\left(\frac{2.25Tt}{r_i^2 S}\right)\right]} \tag{2.68}$$

Therefore;

$$\mathbf{s} = \frac{\mathbf{2.3Q}}{\mathbf{4\pi T}}\left[\mathbf{log_{10}}\left(\frac{\mathbf{2.25Tt}}{\mathbf{S}}\right)^{\mathbf{2}}\frac{\mathbf{1}}{\mathbf{r_p^2 r_i^2}}\right] \tag{2.69}$$

2.13 Partially-Penetrating Wells

Mostly, partially penetrating wells are installed in aquifers that have very broad thickness that is greater than the intake of the well. The partially penetrated well does not receive water horizontally, thus defying the general assumption that wells receive water horizontally. The partial penetration induces some curved upward/downward flow lines that tends to be more than that of a fully penetrated well as shown in Figure 2.19. With the increase in flow velocity around the well caused by the partial penetration, there is a resultant extra head loss with its effect inversely related to the distance from the well. However, the effect becomes negligible at a distances; $\mathbf{r} > \mathbf{2D}\sqrt{\mathbf{K_h}/\mathbf{K_v}}$ if the aquifer is anisotropy on the vertical axis (Kruseman and de Ridder, 1994)

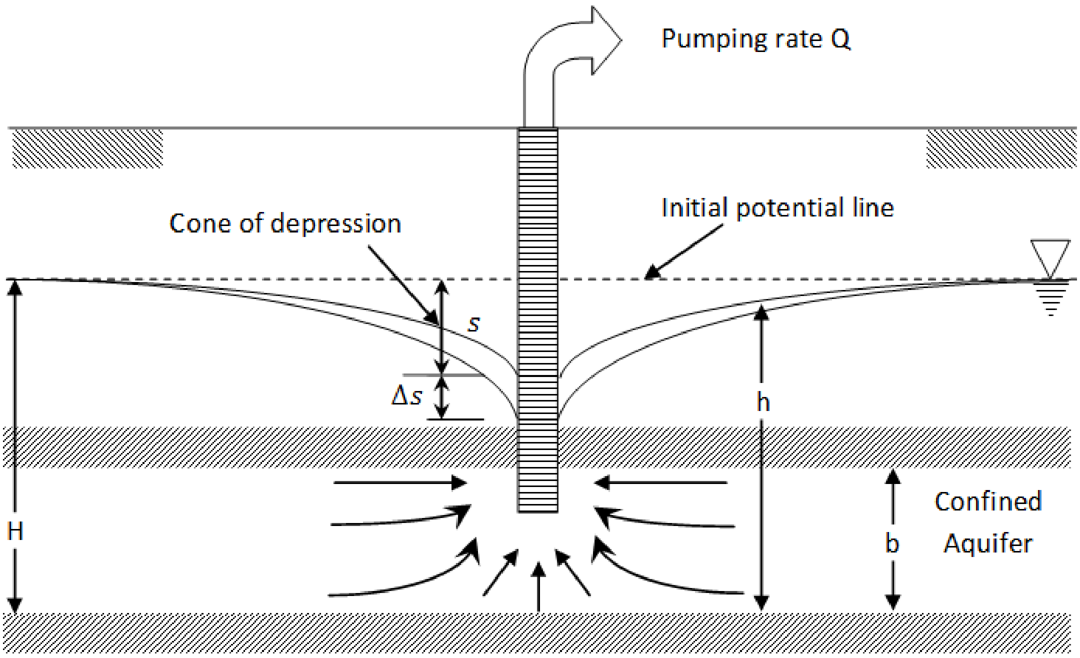


Figure 2.19: Partial Penetrated Well

For solving problem associated with different aquifers with different conditions, the following methods are employed;

- **Steady-State Flow (Confined aquifers)**

Huisman's correction method I

Huisman's equation is used to correct steady-state drawdown in piezometer at r < 2D. See Figure 2.20 for the equation parameters. However, this method is not applicable within the well surrounding, hence, Huisman's correction method II must be used instead.

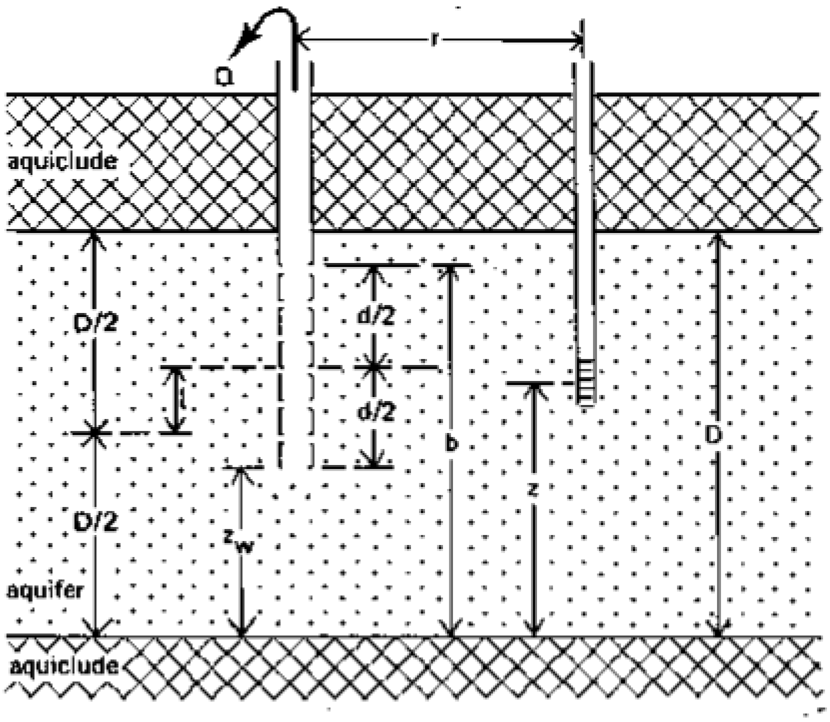


Figure 2.20: Parameters of the Huisman Correction Method for Partial Penetration (Kruseman and de Ridder, 1994)

$$(s_m)\text{partially} - (s_m)\text{fully} = \frac{Q}{2\pi KD} \times \frac{2D}{\pi d} \sum_{n=1}^{\infty} \frac{1}{n} \left[\sin\left(\frac{n\pi b}{D}\right) - \sin\frac{n\pi z_w}{D}\right] \cos\left(\frac{n\pi z}{D}\right) K_0\left(\frac{n\pi r}{D}\right) \quad (2.70)$$

Where,

$(\mathbf{s_m})\mathbf{partially}$ = observed steady-state drawdown

$(\mathbf{s_m})\mathbf{fully}$ = steady-state drawdown that would have occurred if the well had been fully penetrated

$\mathbf{z_w}$ = distance from the bottom of the well screen to the underlying aquiclude

b = distance from the top of the well screen to the underlying aquiclude

z = distance from the middle of the piezometer screen to the underlying aquiclude

d = length of the well screen been fully penetrating

In the application of the above equation, all assumptions concerning steady- state flow in confined aquifer and following extra assumptions/ condition must be fulfilled.

The well partially penetrated the aquifer thickness and does not receive water horizontally.

r must be greater than $\mathbf{r_{ew}}$ = effective radius of the pumped well

Huisman's correction method II

This method is in conformity with all the assumptions/conditions for the method I except that;

$\mathbf{r = r_{ew}}$ **.** Consequently, it is expressed as;

$$(\mathbf{s_m})\mathbf{partially} - (\mathbf{s_m})\mathbf{fully} = \frac{\mathbf{Q}}{\mathbf{2\pi KD}}\left(\frac{\mathbf{1-P}}{\mathbf{P}}\right)\mathbf{ln}\,\frac{\boldsymbol{\varepsilon}\mathbf{d}}{\mathbf{r_{ew}}} \qquad (2.71)$$

Where;

P = the penetration ratio **d/D**

d = length of the well screen

e = amount of eccentricity = **l/D**

l = distance between the middle of the well screen and the middle of the aquifer

$\boldsymbol{\varepsilon}$ = function of P and e (obtained from a table)

- **Unsteady-state flow (Confined aquifers)**

Hantush's modification of the Theis method

Hantush's modification of the Theis method is based on the conditions that;

All flow to the well is in an unsteady state

Pumping time is relatively short

However, all the assumptions for an unsteady- state flow in confined aquifers remain valid excerpt that the well partially penetrated the aquifer and does not receive water through horizontal flow.

The drawdown in a piezometer at **"r"** within a relatively short pumping time $\mathbf{t} < \left[\left((\mathbf{2D - b - a})\right)^{\mathbf{2}}(\mathbf{s_s})\right]/\mathbf{20K}$ is;

$$\mathbf{s} = \frac{\mathbf{Q}}{\mathbf{8\pi K(b-d)}}\mathbf{E}\left(\mathbf{u}, \frac{\mathbf{b}}{\mathbf{r}}, \frac{\mathbf{d}}{\mathbf{r}}, \frac{\mathbf{a}}{\mathbf{r}}\right) \qquad (2.72)$$

Where,

$$\mathbf{E}\left(\mathbf{u}, \frac{\mathbf{b}}{\mathbf{r}}, \frac{\mathbf{d}}{\mathbf{r}}, \frac{\mathbf{a}}{\mathbf{r}}\right) = \mathbf{M(u, B_1)} - \mathbf{M(u, B_2)} + \mathbf{M(u, B_3)} - \mathbf{M(u, B_4)} \qquad (2.73)$$

$$\mathbf{u} = \frac{\mathbf{r^2 S_s}}{\mathbf{4Kt}} \qquad (2.74)$$

$\mathbf{S_s} = \frac{\mathbf{S}}{\mathbf{D}}$ = aquifer's specific storage

$\mathbf{B_1}$ **= (b+a)/r** (represents the symbols b, d and a as shown in Figure 2.21)

$\mathbf{B_2}$ **= (d+a)/r**

$\mathbf{B_3}$ **= (b-a)/r**

$\mathbf{B_4}$ **= (d-a)/r**

M(u, B) = $\int_{\mathbf{u}}^{\infty}\frac{\mathbf{e^{-y}}}{\mathbf{y}}\mathbf{erf}(\mathbf{B}\sqrt{\mathbf{y}})\mathbf{dy}$ (obtained from tables of values)

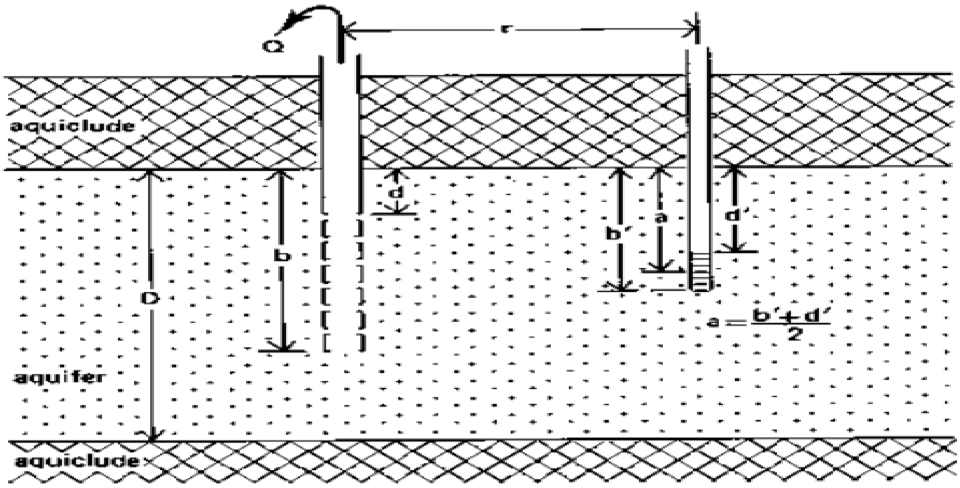


Figure 2.21: Parameters of the Hantush modification of the Theis and Jacob methods for partial penetration (Kruseman and de Ridder, 1994)

- **Unsteady- State Flow (Unconfined anisotropic aquifers)**

Streltsova's curve-fitting method

Streltsova (1974) developed equation for the early-time drawdown behaviour in a partially penetrated unconfined anisotropic aquifer as shown in Figure 2.22. The equation is based on the following assumptions/conditions;

a. The aquifer is unconfined, homogeneous, anisotropic, and of uniform thickness around the area influenced by the pumping test
b. The aquifer has a seemingly infinite areal extent
c. The piezometric surface over the area to be influenced by the pumping test is horizontal before pumping begins
d. Discharge rate is constant during pumping test
e. The well storage can be neglected
f. The entire thickness of the aquifer is not penetrated by well
g. The aquifer shows delayed water-table response
h. Water flow to well is in an unsteady state

i. $\frac{S_Y}{S_A} > 10$

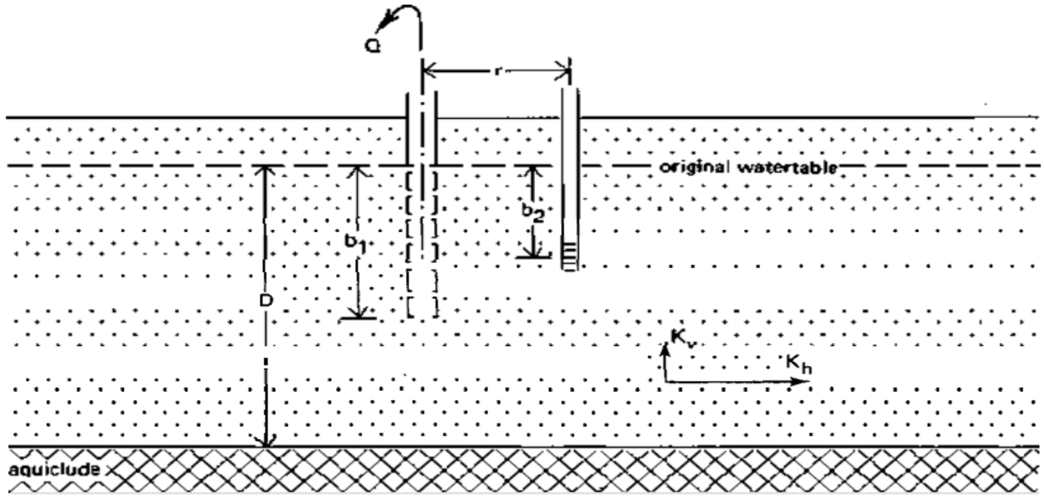


Figure 2.22: Cross-Section of an Unconfined Anisotropic Aquifer Pumped by a Partially Penetrating Well (Kruseman and de Ridder, 1994)

- **Unsteady-state flow(Leaky aquifers)**

Weeks's modifications of the Walton and the Hantush curve-fitting methods.

Weeks (1969), modified the Walton and Hantush curve fitting method by establishing a drawdown equation in partially penetrated leaky aquifers for t > DS/2K, thus;

$$\mathbf{s} = \frac{\mathbf{Q}}{\mathbf{4\pi KD}}\left[\mathbf{W}(\mathbf{u}, \mathbf{r/L}) + \mathbf{f_s}\left(\frac{\mathbf{r}}{\mathbf{D}}, \frac{\mathbf{b}}{\mathbf{D}}, \frac{\mathbf{d}}{\mathbf{D}}, \frac{\mathbf{a}}{\mathbf{D}}\right)\right] \quad (2.75)$$

Or

$$\mathbf{s} = \frac{\mathbf{Q}}{\mathbf{4\pi KD}}\left[\mathbf{W}(\mathbf{u}, \boldsymbol{\beta}) + \mathbf{f_s}\left(\frac{\mathbf{r}}{\mathbf{D}}, \frac{\mathbf{b}}{\mathbf{D}}, \frac{\mathbf{d}}{\mathbf{D}}, \frac{\mathbf{a}}{\mathbf{D}}\right)\right] \quad (2.76)$$

Where,

$\mathbf{W}(\mathbf{u}, \mathbf{r/L})$ **=** Walton's well function for unsteady-state flow in fully penetrated leaky aquifers confined by incompressible aquitards.

$\mathbf{W}(\mathbf{u}, \boldsymbol{\beta})$ **=** Hantush's well function for unsteady-state flow in fully penetrated leaky aquifers confined by compressible aquitards

r, b, d, a = Geometrical parameters shown in Figure 2.22

2.14 Groundwater Quality

Groundwater constitutes the major source of domestic, agricultural and industrial uses of water. However, the quality of groundwater and its availability as economic resources is very important to human existence and of global concern. That is why it is within the mandate of the Sustainable Development Goals (SDGs) programme of the WHO/UNICEF.

The Groundwater quality concerns the physical, chemical, and biological characteristics, which when polluted or contaminated affects the water quality. Groundwater pollution occurs when pollutants released on the ground find their way down into groundwater. It can also occur naturally due to surface water intrusion or due to the presence of unwanted constituents or impurities in the composition of the water bearing aquifer (Phillips *et al*., 2013). Most studies have shown that groundwater is mostly threatened by human activities (Adelana *et al*., 2008). Thus, population explosion, urbanization and industrialization have contributed greatly towards groundwater quality deterioration. In areas with shallow aquifers, the bacteriological and physico- chemical properties of groundwater are usually polluted by domestic, agricultural and industrial waste (Edet *et al*., 2011).

The general mentality is that groundwater is free of pathogens that are widely found in surface water, hence, it’s odorless, colorless and clean and of high quality without any specific taste. This is why water packaging factories in Anambra state, largely depend on groundwater resources as their major source of water in the production of bottled/packaged drinking water.

Consequently, one of the set objectives of this study, which is aimed at comparing the groundwater quality in the study area with the Nigeria standard for drinking water quality (Table 2.11) was carried out.

Table 2.11: Nigerian Standard for Drinking Water Quality

	PHYSICAL. PARAMETERS	**NIG STD**
1.	Appearance	Clear
2.	Temperature ^{0}C	Ambient
3.	Colour (TCIJ)	15
4.	Turbidity (NTU)	5
5	Odour	**Nil**
	CHEMICAL PARAMETERS	
1.	pH	6.5-8.5
2.	Conductivity uS/cm	1000
3	Total Dissolved solids mg/1	500
4.	Salinity mg/1	500
5	Chloride ($C1^-$) mg/1	250
6	Carbonate ($CO^{2-}{}_3$)mg/l	500
7	Bicarbonate (HCO_3^-) mg/1	500
8	Total hardness mg/1	500
9	Calcium (Ca^{2+}) mg/1	200
10	Magnesium (Mg^{2+}) mg/1	250
11	Potassium (K^+) mg/1	250
12	Sulphate ($SO4^{2-}$) mg/1	100
13	Nitrite (NO_2^-) mg/1	0.2
14	Nitrate (NO_3^{2-}) mg/1	50
15	Iron (Fe^{2+}) mg/1	0.3
16	Manganese (Mn^{2+}) mg/1	0.2
17	Copper (Cu^{2+}) mg/1	1.0
18	Residual Chlorine (CI_2) mg/1	0.25
	BACTERIOLOGICAL PARAMETERS	
1	Total Coli form / 100 ml H_20	**10**
2	Feacal Coli form /100ml H_20	0

Source: Nigerian Standard for Drinking Water Quality, 2015.

2.15 Summary of Related Literature on Groundwater Prospecting

Several work have been done in groundwater prospecting, for instance, Ritz*et al.*(1999) used electrical resistivity tomography (ERT) to investigate the electrical properties of a lateritic weathering mantle. The field survey was conducted along two profiles providing continuous coverage. Colour modulated sections of resistivity versus depth were plotted, giving an approximate image of the subsurface structure. Three layers were investigated. The near-surface topsoil comprising under-saturated lateritic material is highly resistive. The intermediate layer with low resistivities contains clays including small quantities of water. The third, highly resistive layer reflects the granitic basement. The results show and suggest that Electrical Resistivity Tomography can be used as a fast and efficient exploration tool to map the thick lateritic weathering mantle in tropical basement areas with hard rock geology.

Ekwe, *et al.*,(2010) performed geo-electrical measurements using the vertical electrical sounding (VES) method to determine aquifer characteristics of Oduma. The authors delineated three geologic groups and acquired eight VES results using the Schlumberger configuration. The results were processed using RESIST software. Their interpreted results show ranges for transmissivity, hydraulic conductivity, depth to water tables and aquifer thickness for major areas within their studied area. The authors however recommended the use of SAS 400 (Lund imaging system) to be able to map areas with high density of fractures.

Ariyo and Adeyemi. (2009) explained the usefulness of the electrical resistivity method, most especially vertical electrical sounding in locating weathered/fractured zones that are the major source of groundwater in south-western Nigeria. The authors utilised twenty-eight VES locations within the study area and their interpreted result gave an overview of various aquifers that are present in the study area which are weathered/fractured basement and the groundwater situation of these hard rock units. They therefore suggested that geophysical methods, most especially the electrical resistivity method should form an integral part of groundwater exploration programs in solving complex geo-hydrological problems associated with groundwater occurrence and resource development.

Alile *et al.*, (2010) applied the VES method to decipher the existing subsurface stratification and groundwater occurrence status in a location in Edo State, Nigeria. Interpretations from their results indicate that the area has an abundant groundwater potential which was field-confirmed by the existence of productive boreholes against the standing history of abortive boreholes, resulting from failed drilling attempts within the study area. Their study however revealed the possibility of having a maximum drill depth to water table of 260m.

Oseji (2010) did geo-electric investigation of groundwater resources and aquifer characteristics in a location in Delta State, Nigeria. The author acquired VES data from ten locations evenly distributed within the study area and plotted the apparent resistivity values against the half current electrode spacing. The study revealed 4 prominent layers of near surface aquifer that are not confined with the best layer for groundwater development at a depth between 35.00m – 45.00m within the second layer.

Ehirim and Ebeniro (2010) also conducted a hydro-geophysical research in Enugu-Agidi, almost a kilometre from Awka town using Schlumberger electrode configuration. A total of 30 VES points from 30 different locations in Enugu-Agidi were acquired and analysed. The study revealed only two confined aquifers along traverses one at VES 2 and VES 3 and shallow unconfined aquifers in the entire traverses. However, the authors concluded that the quality and sustainable yields could be obtained only from the confined aquifer in the area when intercepted at a depth that is highly localized.

In the research done by Usma*n et al.*, (2015), hydro-geophysical investigation was conducted to ascertain aquifer characteristics in thirteen (13) communities in Nteje in Anambra State. The study discovered four to five geo-electric units, one unconfined aquifer and three or four confined aquifers with the aquifer thickness greater at the NE and NW because of more clusters of the peak contours. The authors in their quest to verify the sustainability of groundwater in the area concluded that regional water project should be sited at Umeri because of its high values of transmissivity and aquifer thickness.

Nfor *et al.* (2007) determined the extent and distribution of groundwater resources in parts of Anambra State, the researchers investigated forty five (45) boreholes across eighteen (18) Local Government Areas in Anambra State. Pre-drilling geophysical surveys were conducted at each of the sites by using Schlumberger array and consequently, the results identified four different geological formations with varying water storage and yielding capacities. However, the study observed that out of the four geological formations (Alluvial Plain Sands, Ogwashi-Asaba Formation, Ameki/Nanka Sands and Imo Shale) the Imo shale because of its composition has the poorest water storing and yielding capacities. In conclusion, the study stated that lithology and other secondary factors like nearness to the recharge source and topography influence the extent and distribution of groundwater within the study area.

Mohamaden et al., (2017) conducted a study in the northeast of Qattara Depression, Western Desert, Egypt. Using a combination of geo-electrical resistivity method and GIS. The results of the study revealed that the subsurface section consists of three geo-electrical units. The first unit is composed of surface Quaternary wadi deposits with resistivity values ranging from 248 to 1378 Ohm.m. and thickness ranging from 5.9 to 34.6 m. The second geo-electrical unit is composed of sandstone of Moghra Formation (Lower Miocene) with depth ranges from 5.9 to 34.6 m and its resistivity values range from 23 to 188 Ohm.m. This unit represents the main aquifer in the study area. The third geo-electrical unit is composed of claystone of Qattrani

Formation with depth ranging from 106 to 174.4 m and resistivity values range from 0.5 to 9 Ohm.m.

A study on the geophysical data at East Sadat City, Egypt was conducted by Araffa et al., (2019), three geophysical techniques such as resistivity, seismic refraction, and GPR were applied to delineate the depth to the groundwater surface, subsurface stratigraphy and subsurface structures which control the configuration and distribution of the groundwater aquifer. Five (VES) stations were measured by using Syscal-R2 instrument of electrode separation ranging from AB/2 = 1–500 m to reach depth of investigation about 150 m. The results of quantitative interpretation of the VES data indicate that the subsurface sequence composed of six geo-electric units

2.16 Gaps in Literature

From the previous mentioned literature, this research attempted to fill up the following gaps in research works.

1. Previous studies have failed to provide detailed database of groundwater prospect of the study area, despite the fact that Nfor *et al.* (2007) determine the extent and distribution of groundwater resources in parts of Anambra State using forty five (45) boreholes across eighteen (18) Local Government Areas in Anambra State, this is barely enough for detailed mapping of the ground water prospect of the study area. Hence this study hopes to provide detailed database by using 207 VES points. This will reduce spatial error in varying from one data point to another as a result of using few data points used by previous studies.
2. Previous studies have produced groundwater prospect for the state using VES, however these studies considered few towns or LGA, and also failed to incorporate the groundwater flow direction, the groundwater yielding potentials and the groundwater characterization. Also previous studies done on soil erodibility were centred on the top

soil, vegetation, erosion agents etc. The studies were limited to spatial occurrences of erosion. However, this study will provide data on the soil erodibility as a result of subsurface characteristics.

3. Previous studies have developed groundwater potential map, this is however based on one or two Local Government Areas in the state, this study however provided elaborate data covering almost the entire State. In addition, previous studies have failed to provide risk model map of groundwater resources for the study area, the knowledge gap was also filled by this study

4. No generalized geological and statistical model do exist for the study area, this study therefore provided a statistical model that relates apparent resistivity and hydraulic conductivity.

CHAPTER THREE

METHODOLOGY

3.1 Study Area

The study area is the southern part of Anambra State (see figure 3.1) and it lies within longitude 6º40´0´´E and 7º20´0´´E and Latitude 5º45´0´´N and 6º20´0´´N. The area cuts across all the five geological formations dominant in the state namely; Nsukka Formation (Mastrichtian – Danian), Imo Formation (Paleocene), Ameki Formation (Eocene), Ogwashi - Asaba Formation (Oligocene- Miocene) and Benin Formation (Pliocene- Recent) and it is within the tropical rainforest belt of Nigeria having two distinct seasons: wet season (April- October) and dry season (November – March). The mean temperature which prevails over this region varies between 27 ºC – 28 ºC which most times peak to 35 ºC between January and April. This region also witnesses a mean annual rainfall of about 2000 mm with maximum monthly rainfall during the peaks ranging from 270 mm – 360 mm (Odumodu and Ekenta, 2012).

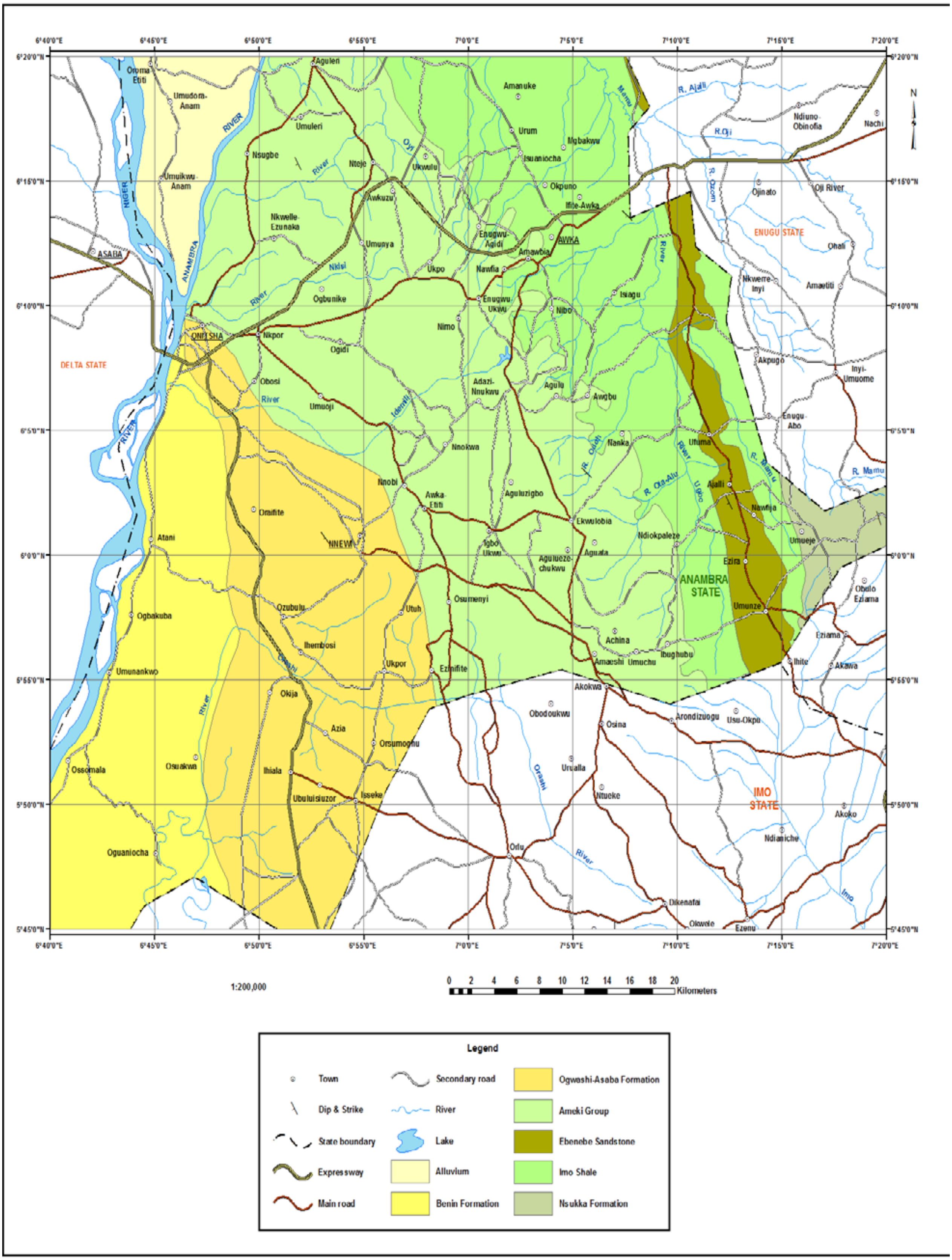


Figure 3.1: Geologic map of the Study Area

3.2 Geophysical Survey of the Study Area

The geophysical survey was conducted in order to establish the various formations in the study area and also to identify both the aquifer presence and distribution. Aquifer characteristics were also determined during the geophysical survey.

The following field equipment was used for the survey:

- ABEM Terrameter Self Averaging System (SAS) 1000C which displays apparent resistivity values digitally as computed from Ohm’s law. This device was powered by a 12.5V DC power source.
- Booster
- Four stainless steel current and potential electrodes
- Four single core cable reels for current and potential electrodes
- Hammers for coupling electrodes into the ground
- Measuring tapes for marking out electrode spacing
- Phones
- GPS for measuring for spatial location (latitude and longitude) and elevation for chosen points

3.2.1 Instrumentation and Data Acquisition

For the geophysical assessment of groundwater in the study area, the Schlumberger configuration (vertical electrical sounding) in electrical resistivity survey was used based on various advantages which include high signal to noise ratio array; excellent vertical resolution and good depth sensitivity; reduced manpower and time requirement and acquisition of data within a very short time.

Stray current in industrial areas and telluric currents that are measured with long spread, affect Schlumberger array less than they affect Wenner array.

Near-surface, lateral in-homogeneities affect Schlumberger measurements less than they affect the Wenner measurements.

The interpretation techniques are more fully developed and more diversified for Schlumberger sounding curves than Wenner sounding curves.

For Schlumberger configuration

$$\boldsymbol{\rho_a} = \frac{\pi\left[\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2\right]R}{MN} \qquad \textbf{(3.1)}$$

Where

ρ_a = Apparent resistivity

AB = distance between the current electrodes

MN = distance between the potential electrodes

R = resistance of the layer (Ohm)

Constant

3.3 Field Procedure

3.3.1 Geo- electrical Survey

The Vertical Electrical Sounding, (VES) is a field technique used in geophysical survey to observe the variations of resistivity with depth. For homogenous and horizontally stratified earth, VES results represent only resistivity variation across the layers up to the maximum depth of probe. Practically, as the spacing between the current electrodes is increased about a centre, the total volume of earth included in the measurement also increased both vertically and horizontally. The field procedure involves measuring the apparent resistivity as the mid-point of the array is kept fixed while the distance between the current electrodes is progressively increased. Thus, after data acquisition, the apparent resistivity values are plotted against half the current electrode spacing on bi-logarithmic graph paper.

The Terrameter SAS 1000C used for this study was hired from the Department of Geology, Nnamdi Azikiwe University, Awka, because of its capacity to transmit a well- defined and regulated square wave, which minimizes induction effects and attenuation.

During the field procedure, two electrodes (current electrodes) made of stainless steel were driven into the soil at each end of the spread A and B (Figure 3.2) and were connected to the current sender of the Terrameter. The electrodes M and N (potential electrodes) were also driven into the soil and connected to the voltage receiver. At each position of A and B, the current was sent and the potential difference between M and N was measured. Also, the distances AB and MN were measured. The conventional Schlumberger technique, with half electrode spacing (AB/2) varying from 1m to 300m was mostly employed.

Following the placing and connection of all electrodes, resistance measurements were made beginning with the smallest spacing and progressing outward. The spacing for the array was taken such that the short separation between the inner two electrodes is usually 1/5th of the total length, because if the ratio of the distance between the current electrodes to that between the potential electrodes becomes too large, the potential electrodes must also be displaced outwards. Otherwise, the potential difference becomes too small to be measured with sufficient accuracy (Koefoed, 1979).

Meanwhile, since the aim of the electrical resistivity survey is to determine the depth of current penetration as a function of current electrode spacing, the measurements of both the current electrode spacing and that of the potential electrode spacing were taken manually. The ABEM Terrameter performs automatic recording of both voltage and current, stacks the results, computes the resistance in real time and digitally displays it. Hence, to convert the resistance reading to an apparent ground resistivity, a geometric factor was applied to the data, based on the Schlumberger configuration used in the study. A total of two hundred and seven **(207)** vertical electrical sounding points (VES points) were acquired across the study area (see Figure 3.3), in order to study the variations in the resistivity distribution of the soil with depth.

From the field data, the apparent resistivity, which is a function of AB/2 (half the current electrode spacing) was calculated and interpreted with One Dimensional (IX1D) Interpex computer software, developed by Interpex Limited (http:www.interpex.com/ix1dv3_version.htm)

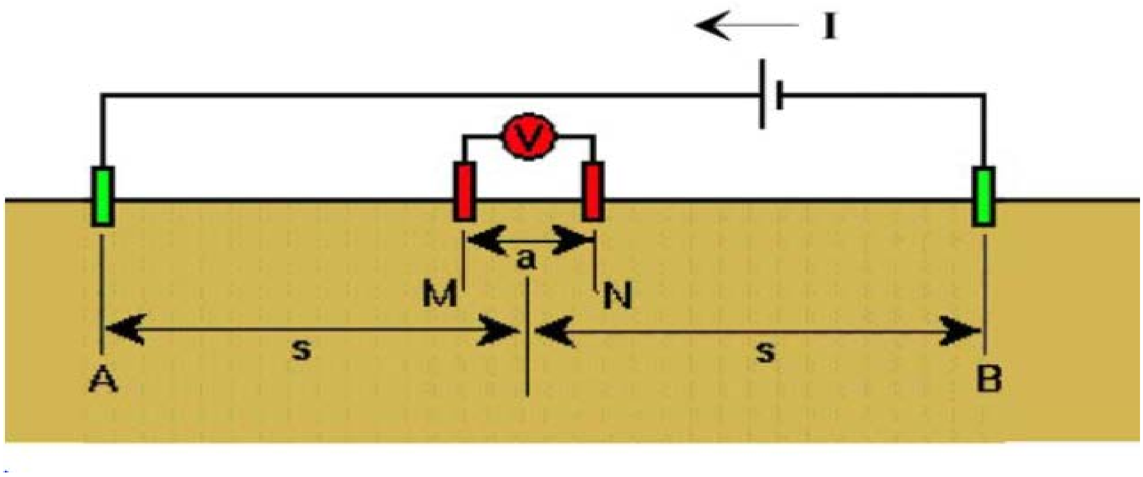


Figure 3.2: Sketch diagram of Schlumberger Configuration

The apparent resistivity values obtained in the field from each of the two hundred and seven **(207)** VES points were plotted against the corresponding half current electrode spacing in a bi-logarithmic graph. The smooth curves of best fit were traced and drawn through the points to generate curves often referred to as sounding curves (Figure 3.4).

Qualitative and quantitative interpretations of the sounding curves were carried out by an accurate and dependable method of identification and interpretation of sounding curves. The method involves the use of computer method in conjunction with the visual inspection for proper identification of the VES curves based on the shape of the various curves produced from the field data and hence infers the relative magnitudes of the different geo-electric layers.

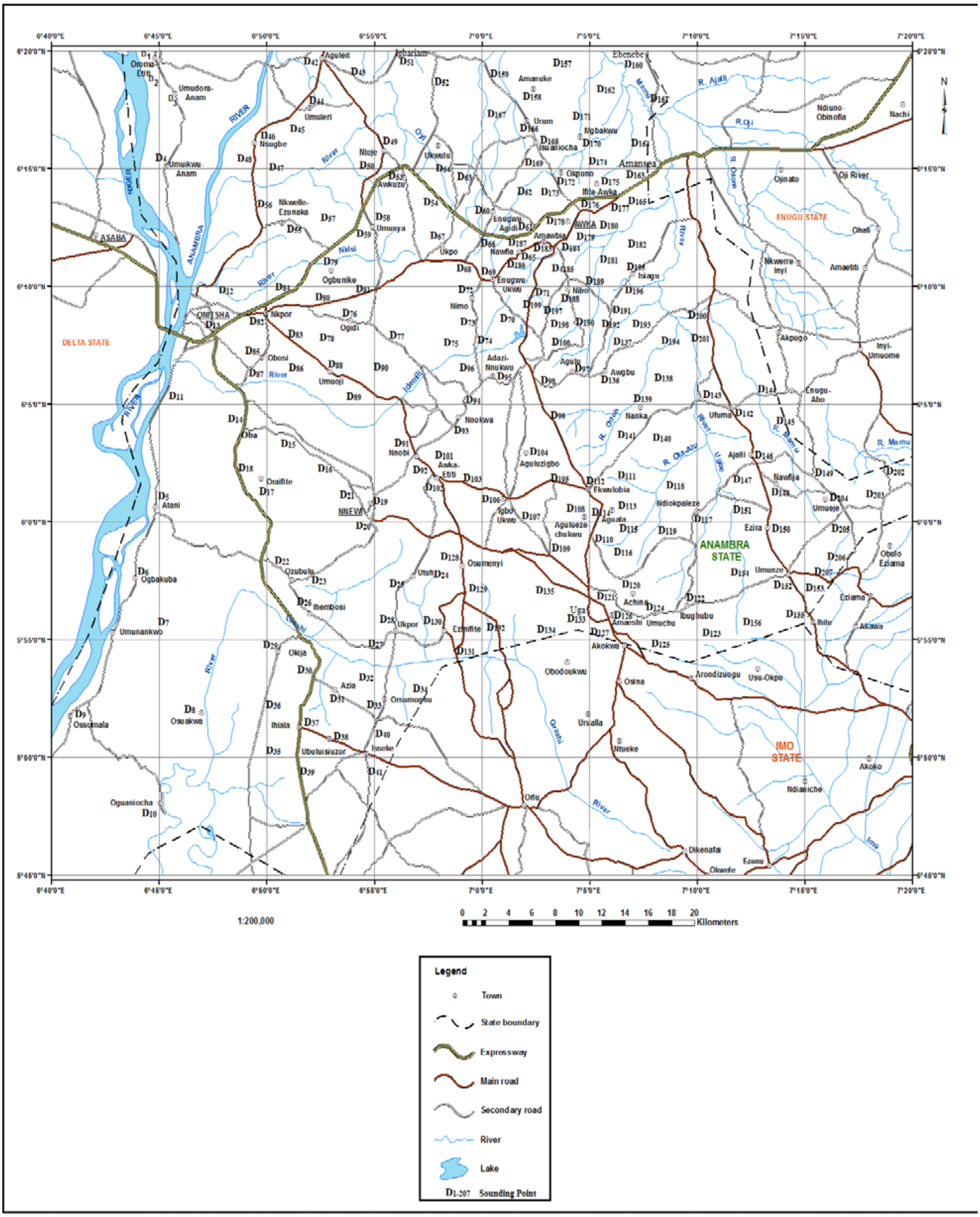


Figure 3.3: Map of the Study Area Showing VES point locations

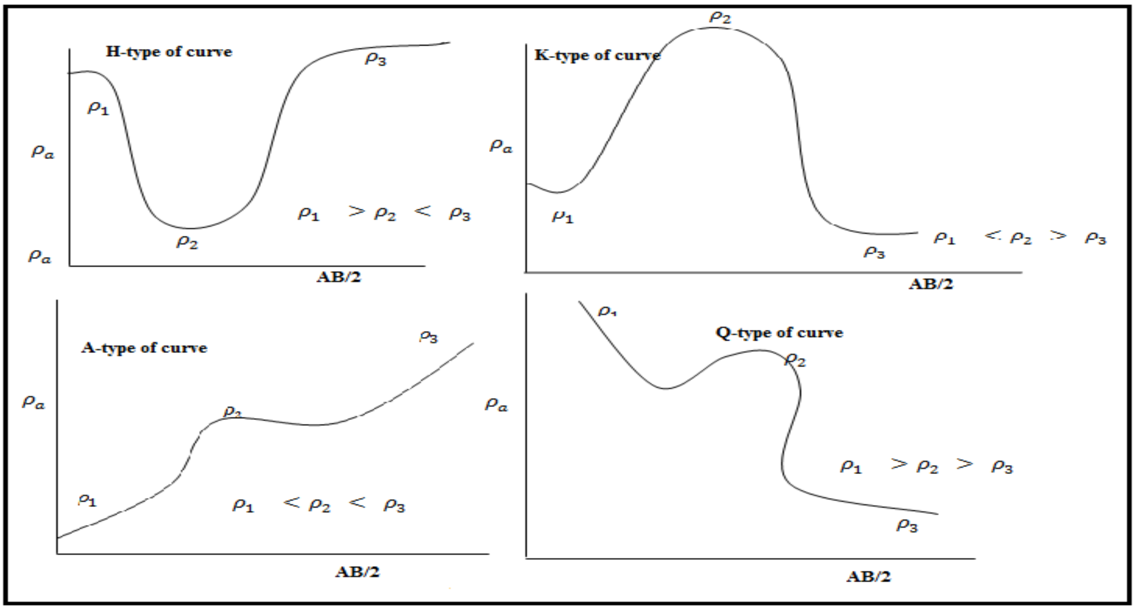


Figure 3.4: Classification of curve types (Keller and Frischnecht, 1966; Telford *et al.*, 1998)

3.3.2 Hydrogeology

The hydrogeological assessment was conducted in order to ascertain the implications of the geology as regards the water bearing aquifers, hydraulic properties of each of the aquifers, erodibility and the groundwater flow direction. Hydrogeological survey also helped in the groundwater quality assessment.

3.3.3 Water Quality

The fundamental task is to obtain samples that are representative, diagnostic, and characteristic of the aquifer and to analyse them with minimal change in composition. The water samples were collected using sterilized bottles and were properly stored and transported in an ice cooler before testing with due consideration for the effect of time on both the physico-chemical and bacteriological parameters. Samples were collected directly from the wellhead (with the sterilized 1 litre bottles) while water was being pumped from various boreholes within the study area. The sealed water samples were taken straight to the laboratory and subjected to physical, chemical and bacteriological analyses. Standard methods were applied during water sample analyses as shown in Table 3.1.

Table 3.1: Water Quality Analyses Methods

NO	PARAMETER	METHOD	INSTRUMENT
1.	Temperature	Insert the thermometer into the sample and read temperature.	Thermometer
2.	Colour	a) Enter the stored programme number for colour b) Rotate the ware bright dial until the small display shows respective warebright c) Place them one after the other into the cell holder and read result on the result display. The results will be read Platinum-Cobat units.	A Hach (microprocessor) single beam controlled spectrophotometer suitable for both laboratory and field use with caliberation of over 120 difference colorimetric measurements and RAM capacity generated caliberation.
3.	Turbidity	Same as in the colour test using the stored programme for turbidity.	Hach Spectrophotometer
4.	Electrical Conductivity	a) Press the power key and CND key b) Select the appropriate range c) Insert the probe into the sample solution d) Allow time for the reading to stabilize	Conductivity – F.D.S. meter with measured conductivity capacity levels up to 20mS/cm total dissolved solids up to 20g/l F.D.S and temperature from 0^0 to 100^0C
5.	pH	a) Standardize the instrument with two buffer solutions (pH = 4 and pH = 7) b) Rinse the electrode with deionized water c) Immerse the electrode in the sample to be tested d) read the result on the display	Portable Hach One (Electrode System) pH-meter consisting of combination reference electrode, reference solution cartridge and Hac One dispenser.
6.	Total hardness	Buffer sample to pH 10.1 and Manver 2 Hardness indicator to form a red complex with a portion the calcium and magnesium in the sample. React EDTA titrant first with free calcium and magnesium ions and then with those bound to the indicator to cause a change to blue colour at the end point.	Digital Titrator: a precision dispensing device fitted with concentrated titrants in compact container called cartridges which enables titrations to be made without the bulk and fragility of conventional burette.
7.	Calcium Hardness	Same as in Total Hardness but using CAL-VAR as indicator.	Digital Tirator
8.	Magnessium Hardness	The difference between Total hardness and Calcium Hardness	As with Total Hardness
9.	Silica as SiO_2	a) Enter the stored programme number for silica b) Rotate the ware bright dial until the small display shows the respective ware bright c) Pour water samples into cells d) Hold the reagents for the necessary time for the reaction to take place e) Place them one after the other (first the blank for zero sample) into cell holder and read the results on the small display.	Hach Spectrophotometer
10.	Iron (as Fe)	Same as Silica but reagents specific for iron	Hach Spectrophotometer
11.	Manganese	Same as above but using reagents specific for manganese	Hach Spectrophotometer
12.	Chloride	Same as above but using reagents specific for manganese	Hach Spectrophotometer
13.	Sulphate (SO_4)	Same as above but using reagents specific for sulphate	Hach Spectrophotometer
14.	Sulphides	Same as above but using reagents specific for sulphides	Hach Spectrophotometer
15.	Nitrates	Same as above but using reagents specific for nitrates	Hach Spectrophotometer
16.	Nitrites	Same as above but using reagents specific for nitrites	Hach Spectrophotometer
17.	Suspended solids	As for turbidity	Hach Spectrophotometer
18.	Acsenic	-	Hach Spectrophotometer
19.	Lead	-	Hach Spectrophotometer
20.	Chromium	-	Hach Spectrophotometer
21.	Mercury	-	Hach Spectrophotometer
22.	Alkalinity	Same as Hardness but using H_2SO_4 as titrant and fenolftalcine as indicator	Hach Digital titrator
23.	Acidity	Same as Hardness but using NaOH as titrant and indicator	Hach Digital titrator
24.	Total Dissolved Solids (TDS)	Same as for conductivity but pushing the key for T.D.S.	Hach Conductivity
25.	Microbiological	An estimate of the number of living bacteria may be obtained with plate count using nutrient agar medium	Hach Eture; Colony counter

Source: Orakwe, 2010.

3.4 Dar-Zarrouk Parameters

According to Maillet, 1974; Niwas and Singhal, 1981, the Dar-Zarrouk parameters are longitudinal conductance and transverse resistance. These parameters are characterized by a geologic unit of layer resistivity (ρ) and layer thickness (h). From these two properties, both the longitudinal conductance and transverse resistance for each layer can be derived. However, these Dar-Zarrouk parameters were estimated across the study area.

3.4.1 Longitudinal Conductance

Maillet, (1974); Niwas and Singhal, (1981) defined Longitudinal conductance as the sum of all the thickness/resistivity ratios of n-1 layers which overlie a semi-infinite substratum of resistivity, ρ_n, such that:

$$\boldsymbol{S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} \dots\dots\dots + \frac{h_{n-1}}{\rho_{n-1}}} \ (\boldsymbol{Ohm^{-1}}) \qquad \textbf{(3.2)}$$

Where,

$h_1, h_2, \dots h_{n-1}$ *are* the thickness and

$\rho_{1,2,\dots}\rho_{n-1}$ are the resistivity values of successive layers.

Hence:

$$\boldsymbol{S = \frac{h}{\rho} = h\sigma} \qquad (3.3)$$

Where,

$\boldsymbol{S}$ is longitudinal conductance and $\boldsymbol{\sigma}$ is conductivity.

The sum of all $\boldsymbol{S}(\sum {}^{\boldsymbol{h_i}}/_{\boldsymbol{\rho_i}})$ is called Dar-Zarrouk functions. When longitudinal conductance (S) increases in value from one sounding point to the next, it indicates an increase in the total thickness of the sedimentary section. The values of longitudinal conductance of the aquifer are classified based on its protective capacity into poor, weak, moderate and good (Henriet *et al.*, 1976; Oladapo *et al.*, 2004). Areas with poor and weak longitudinal conductance values are vulnerable to contamination from infiltration from contaminants such as dumpsite leachate and/or leakage of buried underground storage facility.

3.4.2 Transverse Resistance

This is the product of the layer's resistivity and its thickness. It is a geophysical parameter, proportional to product of the resistivity (ρ) and thickness (h) of the aquifer. For n-1 layers of resistivity (ρ_n),

$$T = h_1\rho_1 + h_2\rho_2 + h_3\rho_3 \ldots \ldots \ldots + h_{n-1}\rho_{n-1}\ (Ohm - m^2) \tag{3.4}$$

Where $\rho_{1,2,\ldots\ldots}\rho_{n-1}$ are the resistivity values and $h_1, h_2 \ldots h_{n-1}$ are the thickness of successive layers. The transverse resistance parameter for the saturated zone of the aquifer makes it possible to delineate the most favourable and prolific zones, with the objective of hydrogeological exploration. Hence:

$$T = h\rho \tag{3.5}$$

The sum of all (h_i) is called Dar Zarrouk variables. When the value of transverse resistance (T) increases from one sounding point to another, it means generally that the thickness of the resistive layer in the section (gravel, basalt etc) also increases. The increase in T might be caused by increase in the resistivity values. High transverse resistance assumes that the aquifer may likely have high transmissivity with quantifiable groundwater potentials characterized by high yield of the aquifer units.

3.5 Aquifer Characteristics/Parameters

3.5.1 Hydraulic Conductivity

Hydraulic conductivity, symbolically represented as K, is a property of soils and rocks that describes the ease with which a fluid (usually water) can move through pore spaces or fractures.

It depends on the intrinsic permeability of the material, the degree of saturation and on the density and viscosity of the fluid.

The hydraulic conductivity (K) of the layers across the area was estimated using equation generated by Heigold *et al.*, (1979);

$$\boldsymbol{K = 386.40R_{rw}^{-0.93283}} \quad \textbf{(3.6)}$$

Where, K = Hydraulic conductivity; R_{rw} = *Apparent r*esistivity of the layer.

3.5.2 Transmissivity/ Transmissibility

Transmissibility (or transmissivity) is a property closely related to hydraulic conductivity that describes the capacity of a specific water-bearing unit of a given thickness, such as an aquifer, to transmit water. Transmissibility is most simply defined as the effective hydraulic conductivity of an aquifer or other water-bearing unit multiplied by the thickness of that unit.

However, the aquifer transmissivity (T_a) of the aquifer layers across the area was estimated using the relation generated by Niwas and Singhal, 1981:

$$\boldsymbol{T_a = K_a h_a} \quad \textbf{(3.7)}$$

Where, $T_a =$ Aquifer transmissivity; K_a = Aquifer hydraulic conductivity; h_a= Aquifer thickness.

3.5.3 Erodibility/ Erodability

Erodibility (or erodability) property of the layer is determined with respect to the geoelectrical parameters generated within the study area. It is good to note that erodibility can be defined as the inherent yielding or non-resistance of soils and rocks to erosion. Hence, a high erodibility implies that the same amount of work exerted by the erosion processes leads to a larger removal of material. Because the mechanics behind erosion depend upon the competence and coherence of the material. Erodability is treated in different ways depending on the type of surface that is eroded. The erodability of the overburden layers within the study area were calculated using the equation by Freeze and Cherry, 1979:

$$\boldsymbol{K_z = \frac{b}{\left[\sum_{i=1}^{m}(b_i/K_i)\right]}} \qquad \textbf{(3.8)}$$

Where, $\boldsymbol{K_z}$ = erodibility or parallel flow within each lithologic layer; K_i= hydraulic conductivity of each individual layer of thickness; b_i =individual layer of thickness; b = Overall thickness of the sequence.

3.5.4 Reflection Coefficient and Fractured Contrast

Other parameters deduced within the study area are the reflection coefficient (RC) and fractured contrast (FC). The equations for calculating them were generated by Obiora *et al,* 2016 and are given as follows:

$$\boldsymbol{RC = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}}} \qquad \textbf{(3.9)}$$

$$\boldsymbol{FC = \frac{\rho_n}{\rho_{n-1}}} \qquad \textbf{(3.10)}$$

Where, RC = Reflection Coefficient; ρ_n= the resistivity of the nth layer; ρ_{n-1}= the layer resistivity overlying the nth layer; FC = Fractured Contrast

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Qualitative Interpretations of Geo-electrical Results

Two hundred and seven vertical electrical sounding (VES) curves obtained from the study area (Fig. 4.1) were interpreted qualitatively and they varied considerably across the study area. The results revealed that the study area has eleven (11) typical curve types (Appendix II) according to Telford *et al*., 1998, Anakwuba *et al*., 2014, and Anizoba *et al.*, 2015. The most predominant among these curve types in the study area are HK and KHK-curve types with 34.3% and 20.8% respectively, whereas the remaining 44.9% belongs to the other nine curve types within the study area (Fig. 4.2 and Appendix II). Generally, the generated resistivity curve types show typical H-curves (namely; KH, HK, KHK, H and HKH) which are quite common in a sedimentary environment for multilayer structures.

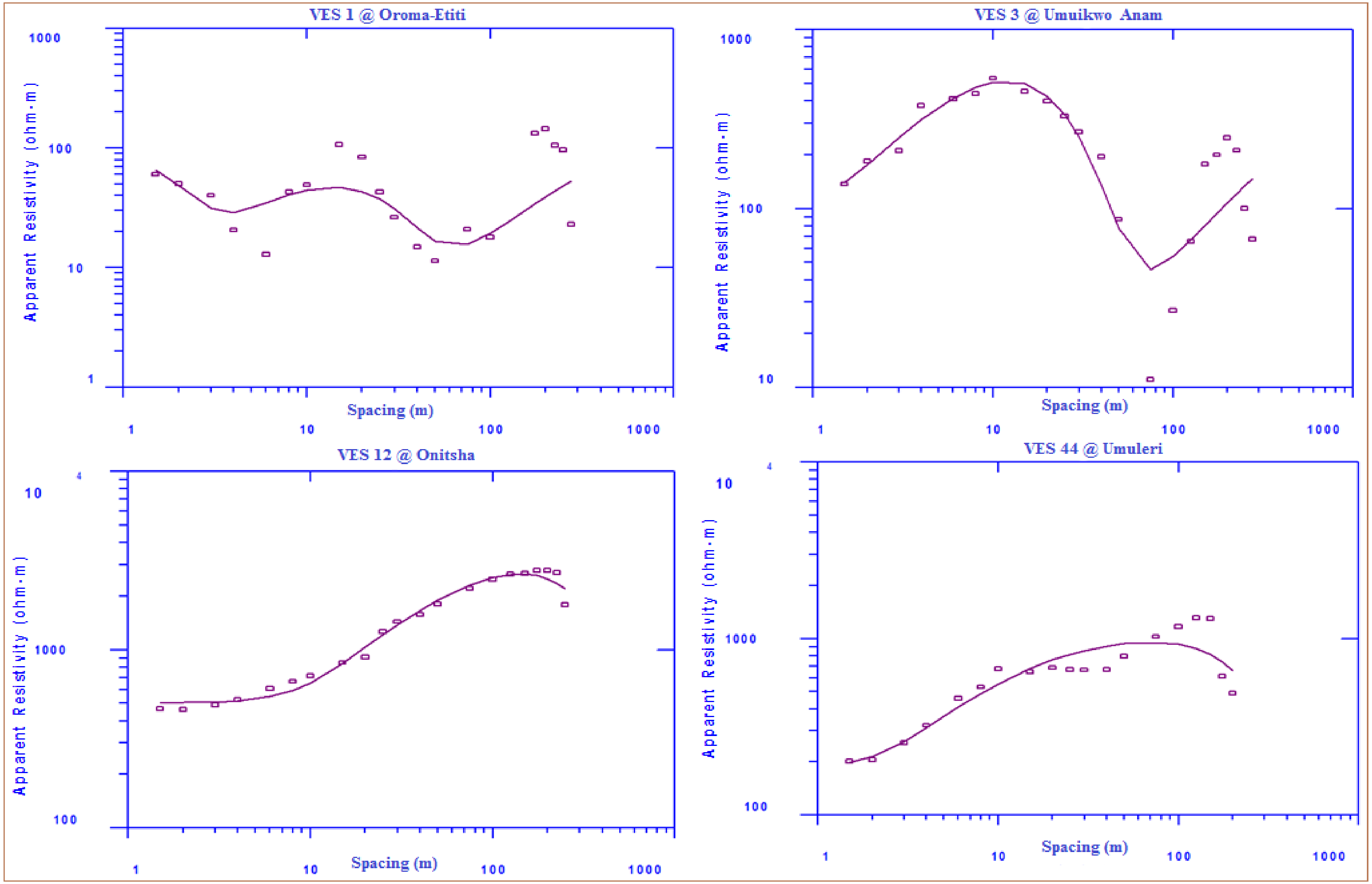
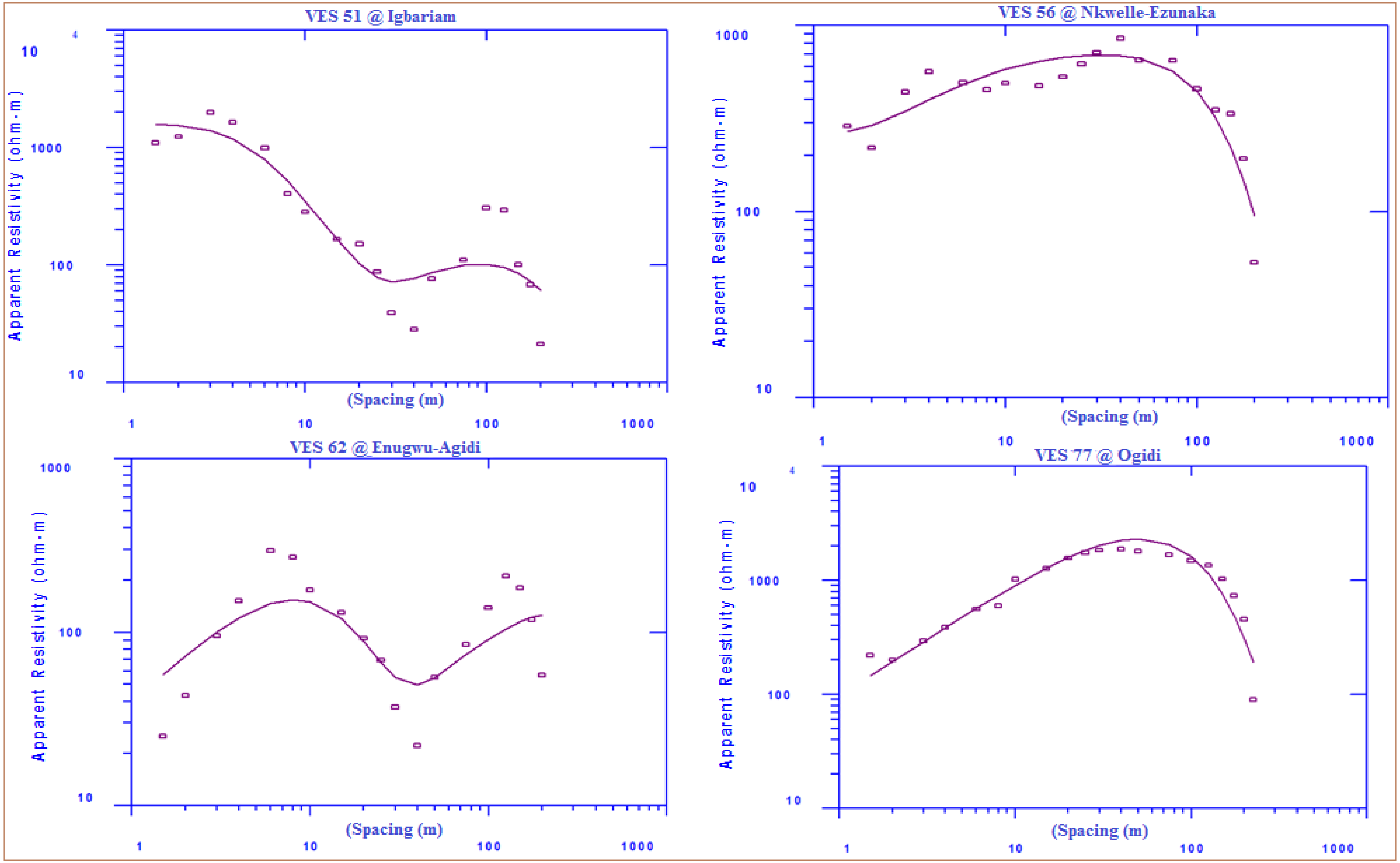
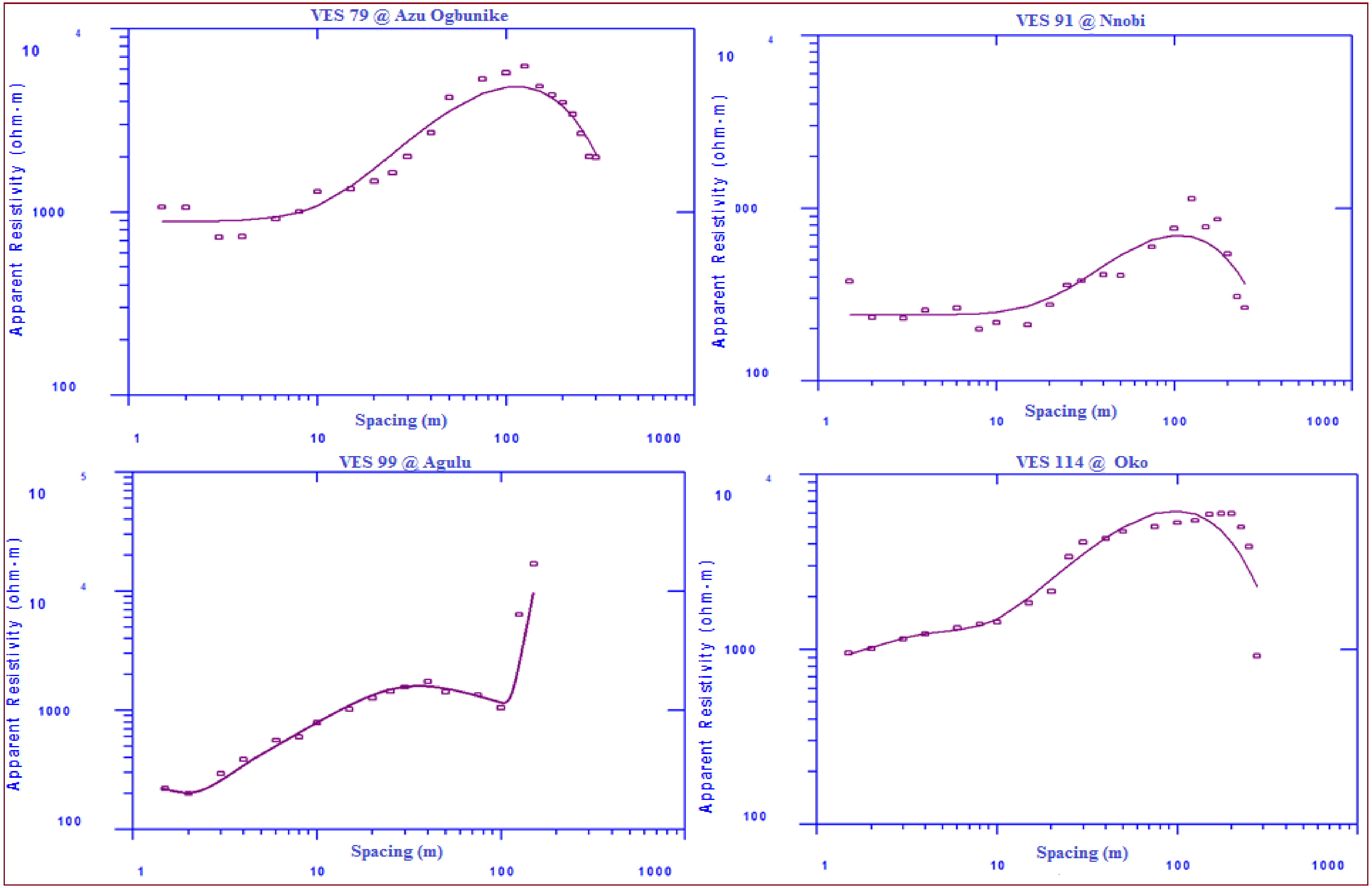


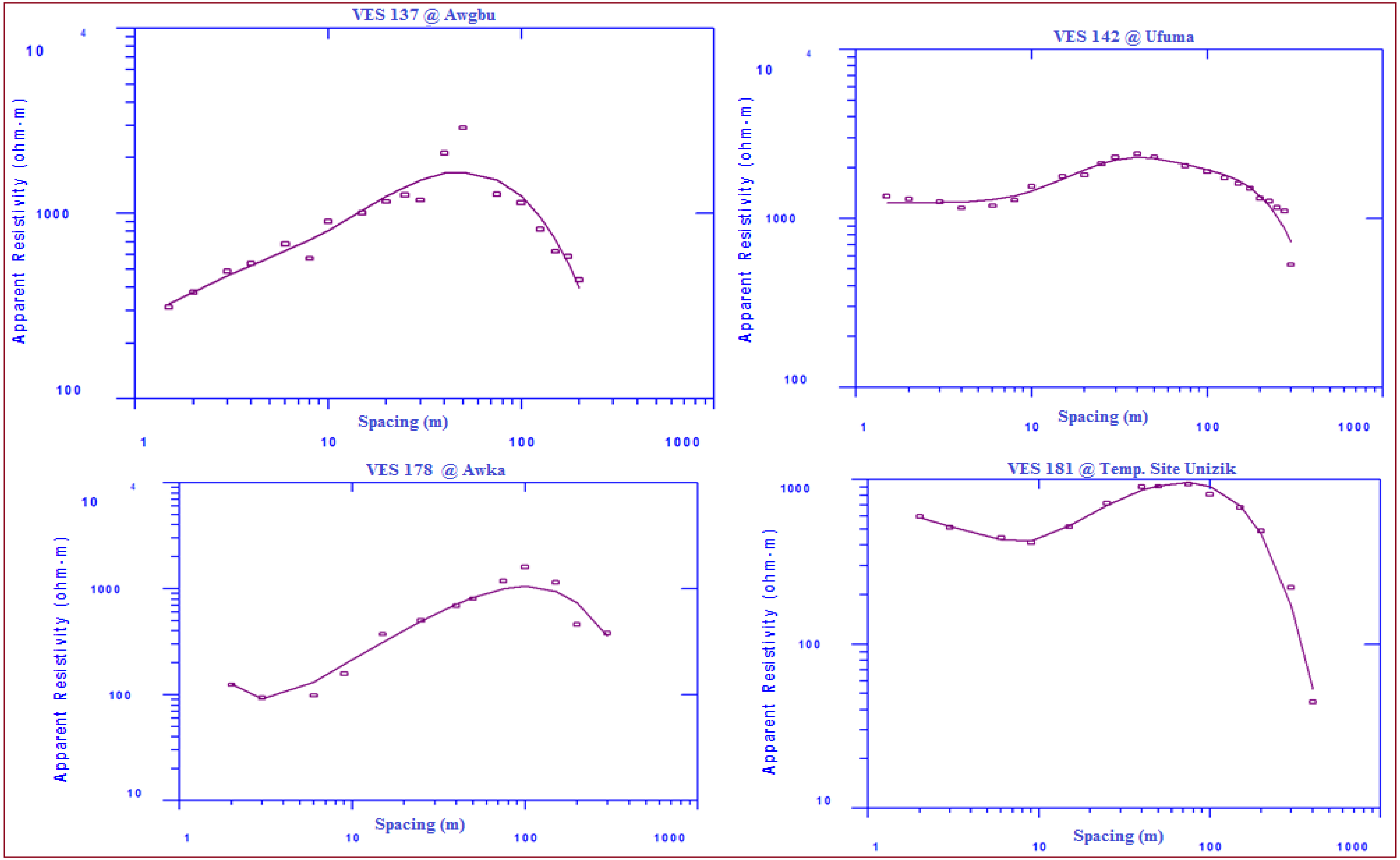
Figure 4.1(a-e): Representative of Vertical electrical sounding curves/ geo-electric curves within the study area


VES 51 @ Igbariam
VES 56 @ Nkwelle-Ezunaka
VES 62 @ Enugwu-Agidi
VES 77 @ Ogidi
Apparent Resistivity (ohm-m)
(Spacing (m))
1
10
100
1000
10
4

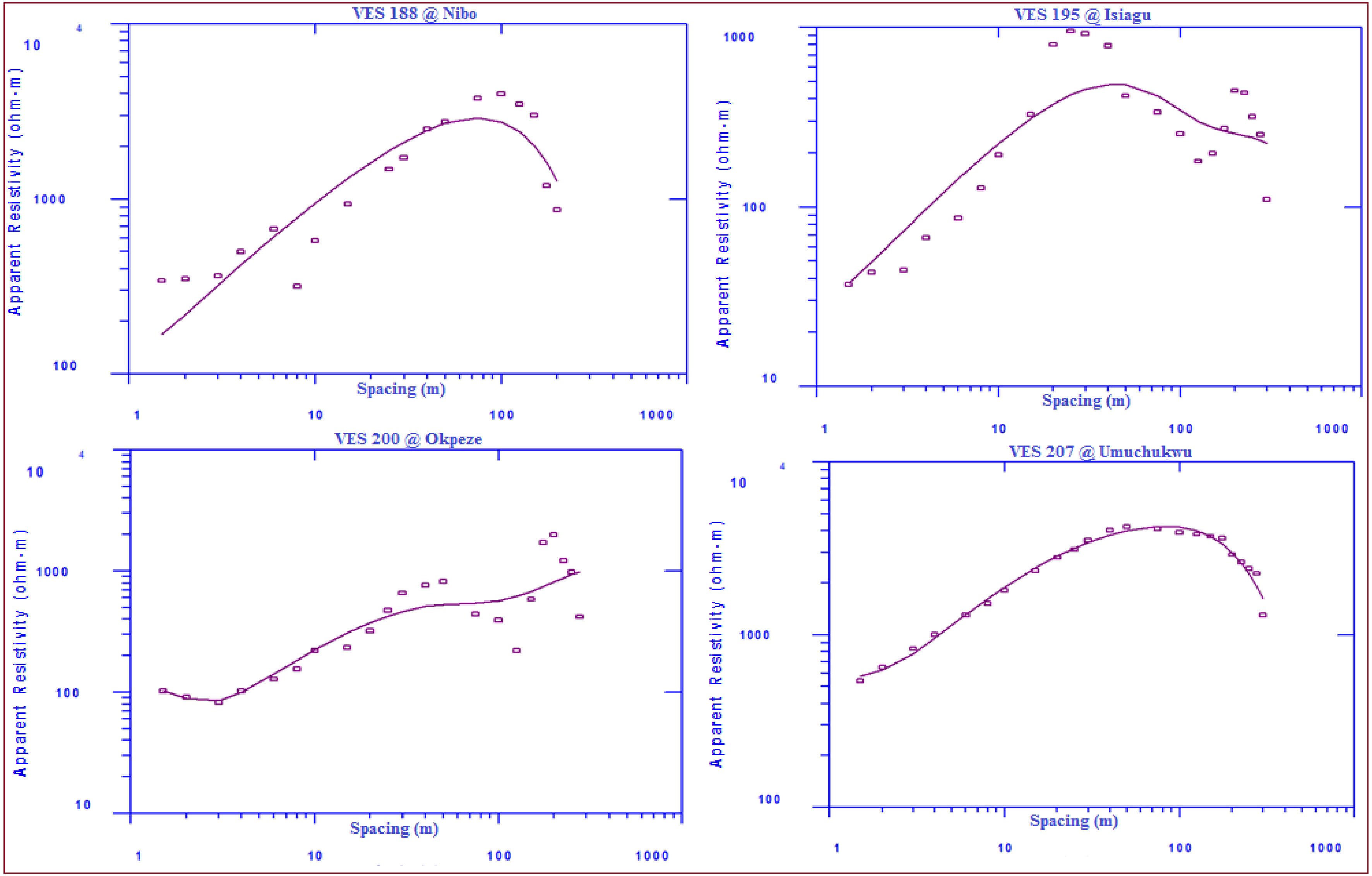
b.


VES 79 @ Azu Ogbunike
VES 91 @ Nnobi
VES 99 @ Agulu
VES 114 @ Oko
Apparent Resistivity (ohm-m)
Spacing (m)
1
10
100
1000

c.


VES 137 @ Awgbu
VES 142 @ Ufuma
VES 178 @ Awka
VES 181 @ Temp. Site Unizik
Apparent Resistivity (ohm-m)
Spacing (m)
1
10
100
1000
10^4

d.


VES 188 @ Nibo
Apparent Resistivity (ohm-m)
Spacing (m)
VES 195 @ Isiagu
Apparent Resistivity (ohm-m)
Spacing (m)
VES 200 @ Okpeze
Apparent Resistivity (ohm-m)
Spacing (m)
VES 207 @ Umuchukwu
Apparent Resistivity (ohm-m)
Spacing (m)

e.

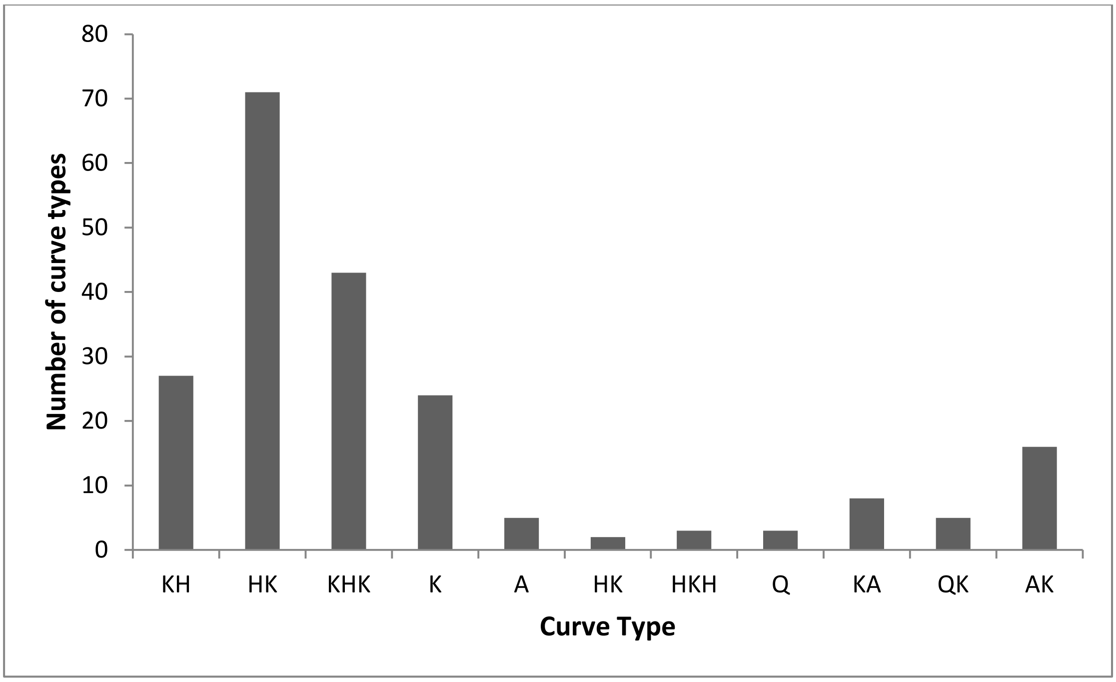


Fig. 4.2a: Bar Chart showing the various curve types within the study area

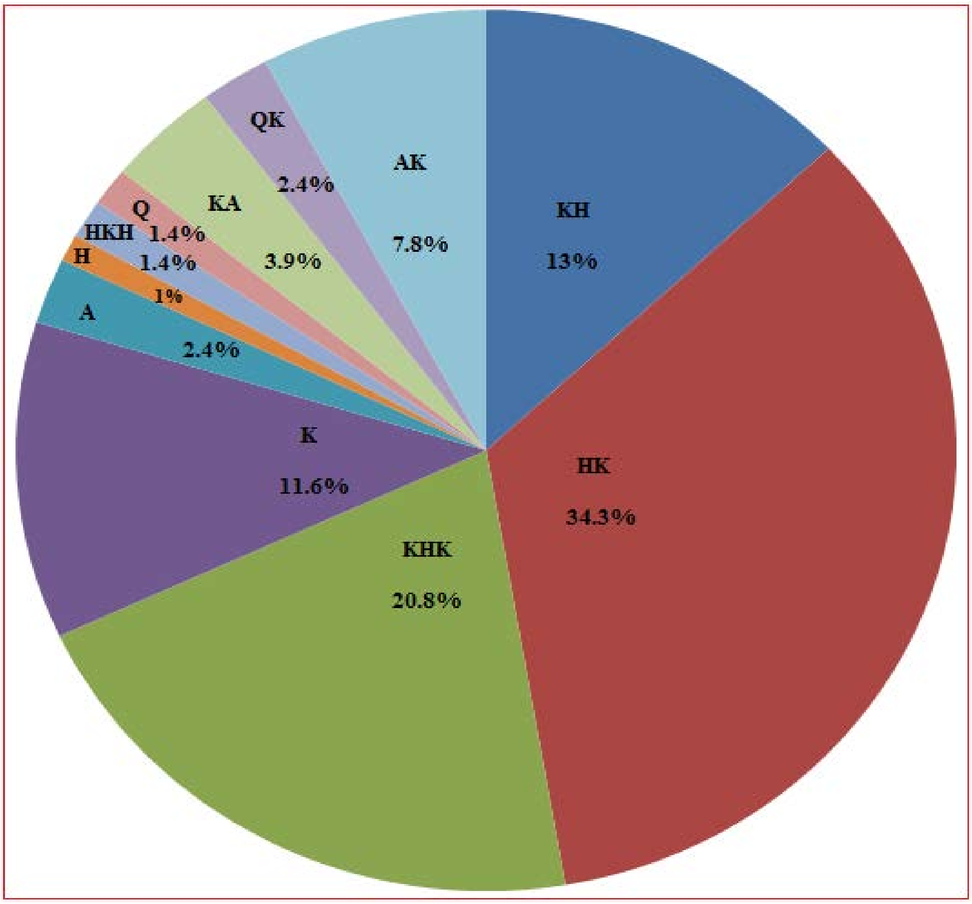


Figure 4.2b: Pie Chart showing the various percentages of curve types within the study area

4.2 Quantitative Interpretations of Geoelectrical Results

4.2.1 Interpretations of VES Results

The results of the VES interpretations within the study area show that there are four to six geo-electrical layers namely; top soil, shally-sand/clayey sand, sand, dry sandstone, water saturated sandstone, and shale (Fig. 4.3 and Appendix IIIa). In Alluvium terrain, the top layers thickness and resistivity range between 1.76 – 4.77m and 89.91 – 222.09Ωm respectively and they are characterized by lateritic sand (Appendix IIIa). The second layers thickness and resistivity range between 6.32 – 15.88m and 356.47 - 508.11Ωm respectively and they are delineated as mainly of shally sand/clayey sand (Appendix IIIa). The third layers thickness and resistivity range between 10.8 – 25.31m and 821.09 – 1127.25Ωm respectively and they are delineated as mainly of sand (Appendix IIIa). The forth layers thickness and resistivity range between 17.71 – 31.08m and 99.73 – 115.84Ωm respectively and they are delineated as mainly of shale (Appendix IIIa). The fifth layers thickness and resistivity range between 59.44 – 87.36m and 882.08 – 1824.08Ωm respectively and they are delineated as mainly of dry sand (Appendix IIIa). The sixth layers thickness and resistivity range between 22.29 – 28.71m and 600.07 – 886.43Ωm respectively and they are delineated as mainly of water saturated dry sand (Appendix IIIa). The last layers whose bases were not reached have their resistivity range between 10.11 – 18.91Ωm and they are delineated as shale (Appendix IIIa).

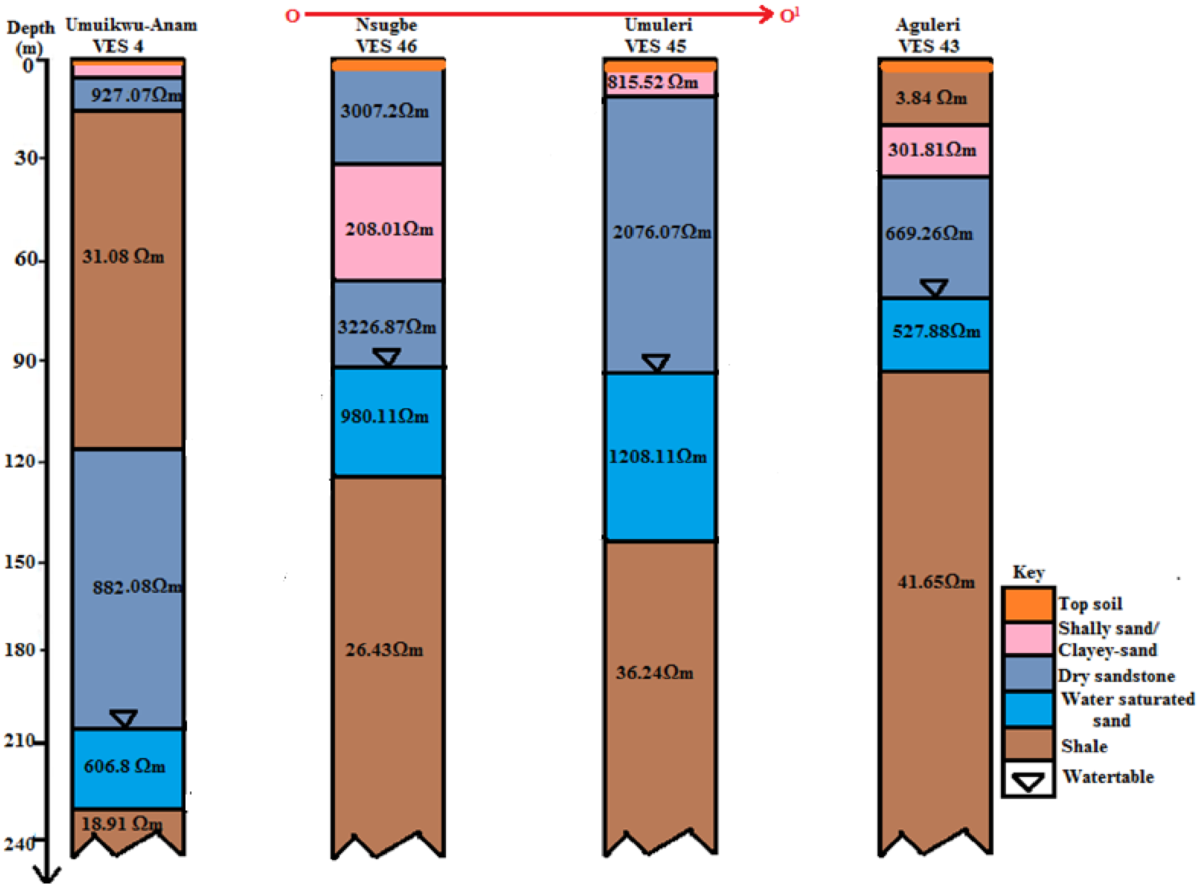


Figure 4.3a: Geo-electric sections along Profile O-O[1]

However, at the Benin Formation (Appendix IIIb), the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 276.08 - 1331.11Ωm and 30.45 - 64.75m across the area. For Ogwashi- Asaba Formation (Appendix IIIc), the resistivity and thickness of the prospective aquifer layers (water saturated sand) range 23.09 - 4960.07Ωm and 21.77 - 58.38m across the area. For Ameki Formation (Appendix IIId), the resistivity and thickness of the prospective aquifer layers (water saturated sand) range 284.80 – 8207.54Ωm and 21.45 – 56.35m across the area. For Imo Formation (Appendix III e-f), the resistivity and thickness of the prospective aquifer layers (water saturated sand) range 126.08 – 4620.14Ωm and 18.73 – 43.96m across the area; while for Nsukka Formation (Appendix IIIg), the resistivity and thickness of the prospective aquifer layers (water saturated sand) range 2470.51 – 5014.74Ωm and 23.02 – 35.42m across the area.

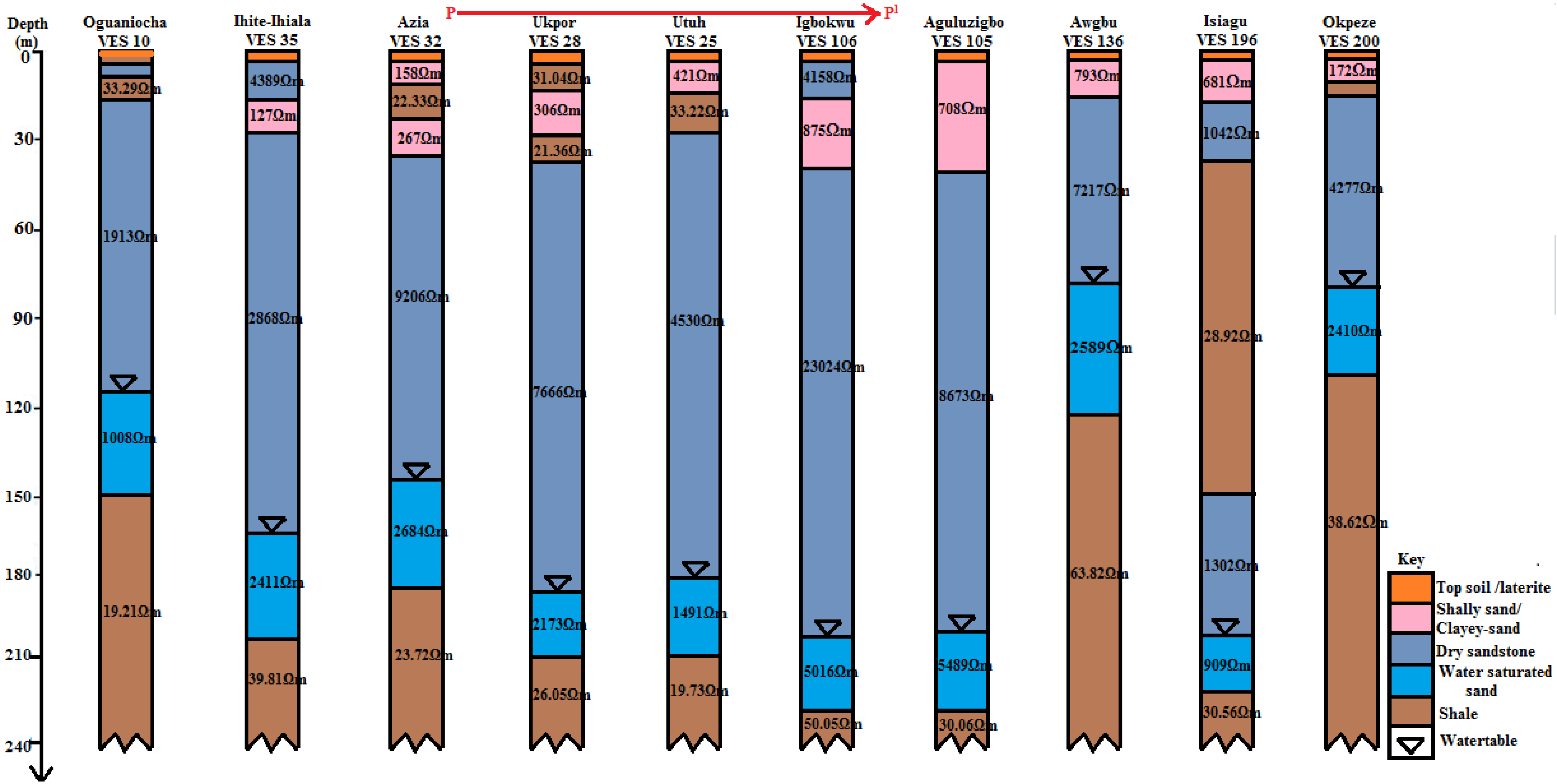


Figure 4.3b: Geo-electric sections along Profile P-P[l]

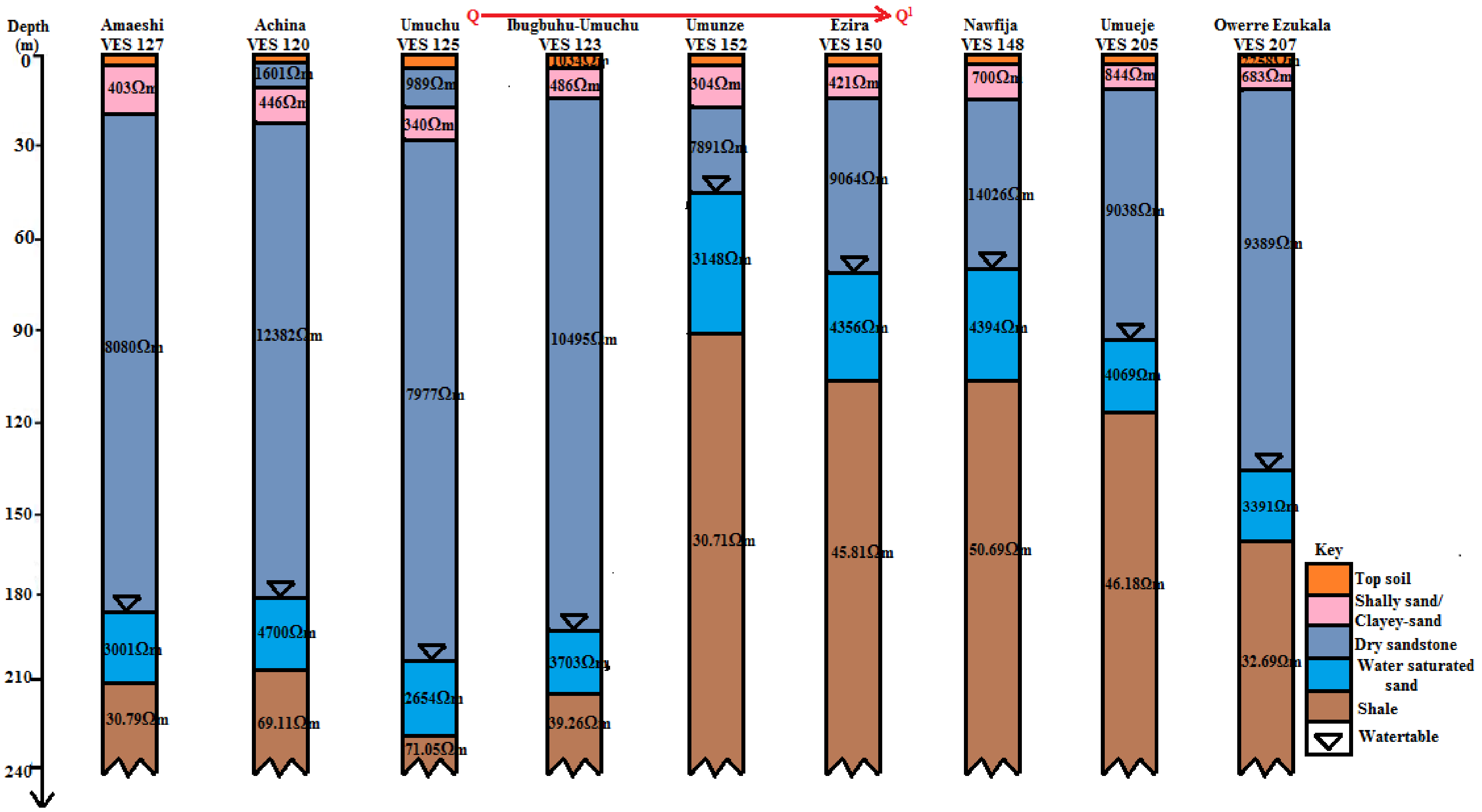


Figure 4.3c: Geo-electric sections along Profile Q-Q[l]

4.3 Correlation of Geo-electric Cross Sections

4.3.1 Geo-electric Correlation across Profile O-O^{l}

Fig. 4.4a shows a true variation of the different layers delineated along the profile O-O^{l} within the study area. The topsoil is relatively thin in most places, with resistivity values characteristically of lateritic soil. The topsoil resistivity value was found to vary between 89.91 Ohm-m to 7420.46 Ohm-m, while its thickness ranges between 1.91m to 3.79m. Thus, the aquiferous units (the water saturated units) there have thickness value of about 21.87 to 49.67m with true resistivity range of 527.88 to 1208.11 Ohm-m. Following this layer is shale with resistivity value of 18.91 – 41.65 Ohm-m. This layer happens to be the base where borehole will be terminated. Generally, the various layers vary from one VES point to other because of heterogeneous nature of the geological formations.

4.3.2 Geo-electric Correlation at Profile P-P^{l}

Fig. 4.4b shows a true variation of the different layers delineated along the profile P-P^{l} within the study area. The topsoil is also relatively thin in most places, with resistivity values characteristically of lateritic soil. The topsoil resistivity value was found to vary between 40.28 Ohm-m to 2068.09 Ohm-m, while its thickness ranges between 2.02m to 5.26m. Thus, the aquiferous units (the water saturated units) here have thickness value of about 21.77 to 42.05m with true resistivity range of 909.08 to 5488.71 Ohm-m. The last layer is the shale with resistivity value range of 19.21 – 63.82 Ohm-m.

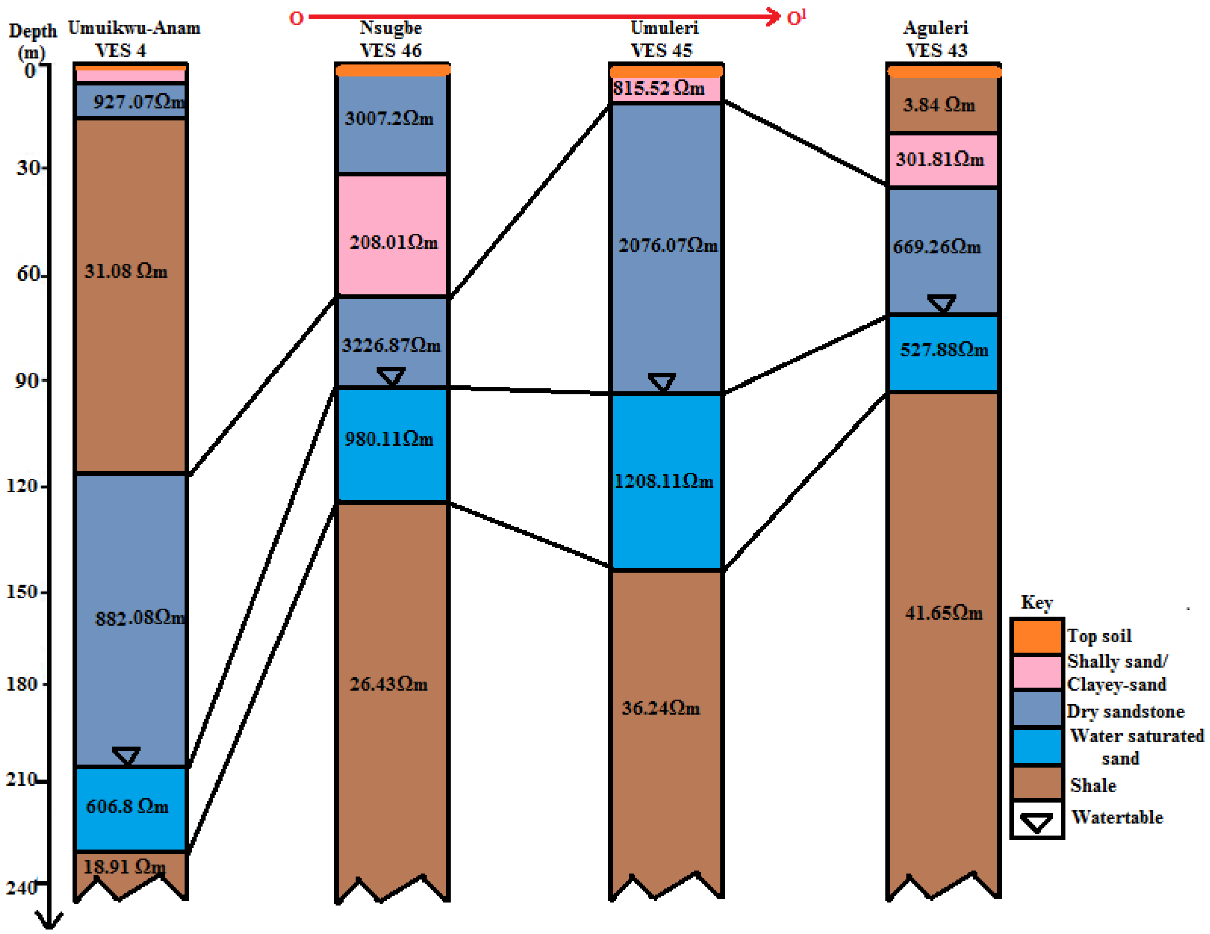


Figure 4.4a: VES correlation along Profile O-O^{l}

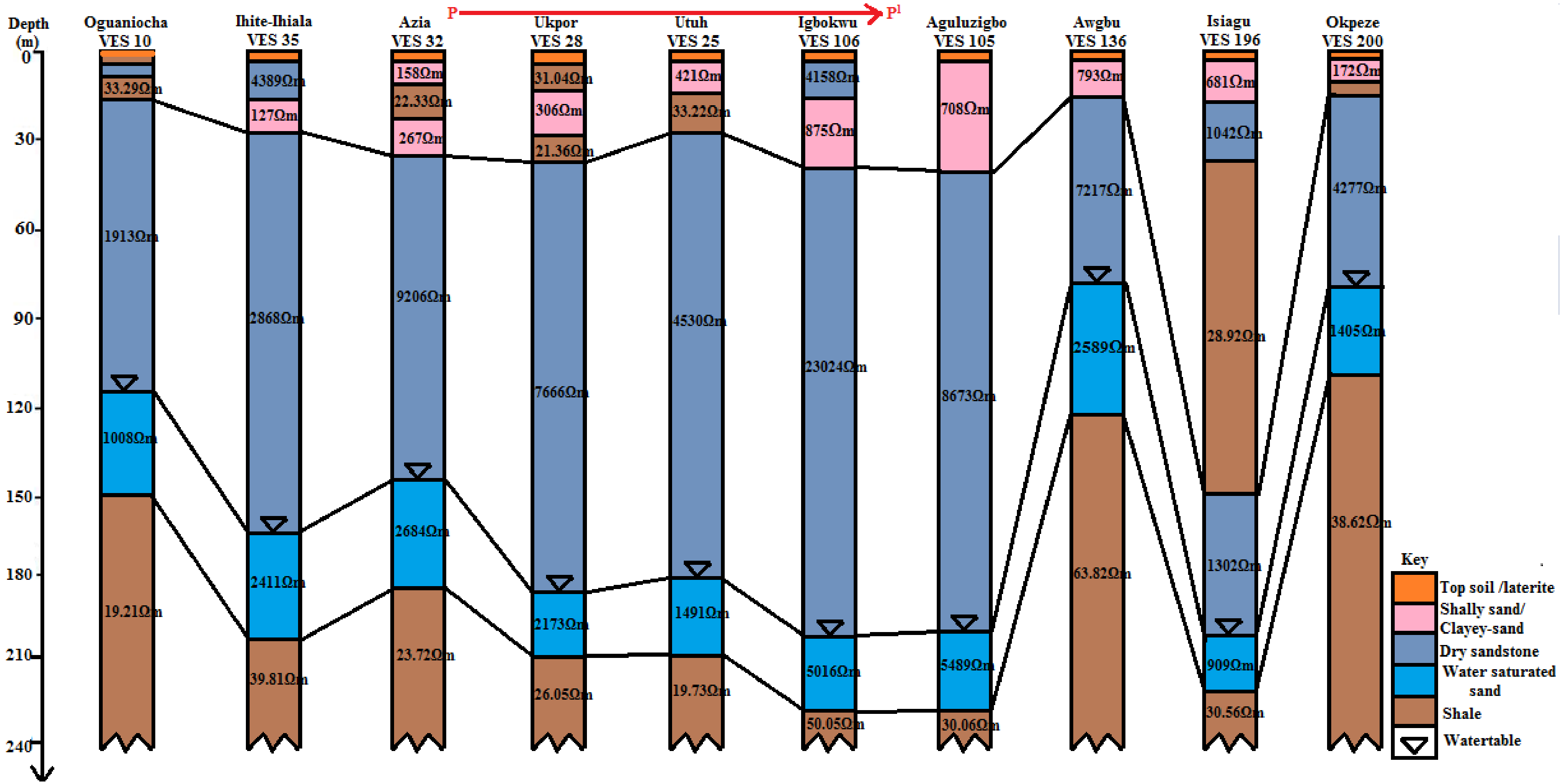


Figure 4.4b: VES correlation along Profile P-P[l]

4.3.3 Geo-electric Correlation at Profile Q-Q^l

Fig. 4.4c shows a true variation of the different layers delineated along the profile Q-Q^l within the study area. The topsoil is also relatively thin in most places, with resistivity values characteristically of lateritic soil. The topsoil resistivity value was found to vary between 300.08 Ohm-m to 2258.08 Ohm-m, while its thickness ranges between 2.83m to 4.88m. Thus, the aquiferous units (the water saturated units) here have thickness value of about 22.79 to 50.69m with true resistivity range of 2654.31 to 4700.03 Ohm-m. Following this layer is shale with resistivity value of 30.71 – 71.05Ohm-m.

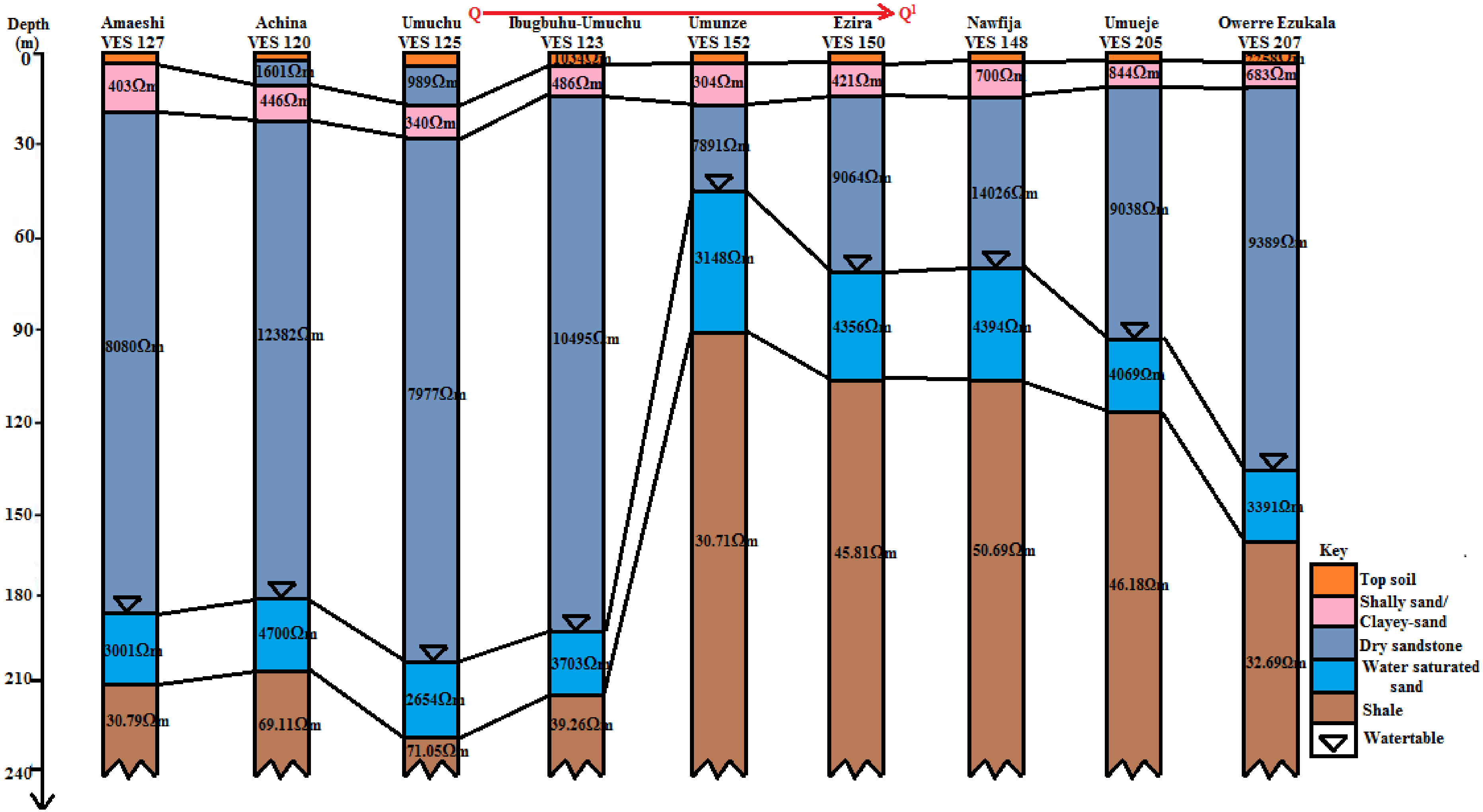


Figure 4.4c: VES correlation along Profile Q-Q[1]

4.3.4 : Correlation of Geo-electric section and Borehole section

The correlation of interpreted geo-electric section and lithologic section from the borehole located near some of the sounding stations across the study area (Fig.4.5), show that the overburden thicknesses in the lithologic sections are higher than those in geo-electric sections. In the underlying layers, the geo-electric units show suppression and merging of some lithologic units from the borehole. This is because geo-electric units are not the same as lithologic units. A given lithologic unit with variations in resistivity will give rise to so many geo-electric units. Hence, different lithologic units with similar resistivities would be merged as one geo-electric unit. Consequently, the water table between the geo-electric and borehole sections vary. At Ameshi, the depth of water saturated unit is 188.07m in the geo-electric section and 182.79m in lithologic unit. Also, at Umuchu, the depth of water saturated unit is 204.77m in the geo-electric section and 208.32m in lithologic unit. More so, at Umunze, the depth of water saturated unit is 48.89m in the geo-electric section and 43.58m in lithologic unit. Also, at Nibo, the depth of water saturated unit is 89.43m in the geo-electric section and 86.24m in lithologic unit. Following these layers are impermeable layers whose base were not reached and as such, the thicknesses were not deduced. In general, these geo-electric sections are highly correlated with the borehole section across the area (Fig. 4.5). This study shows a clear support or proof of the depth to aquifer in the study area.

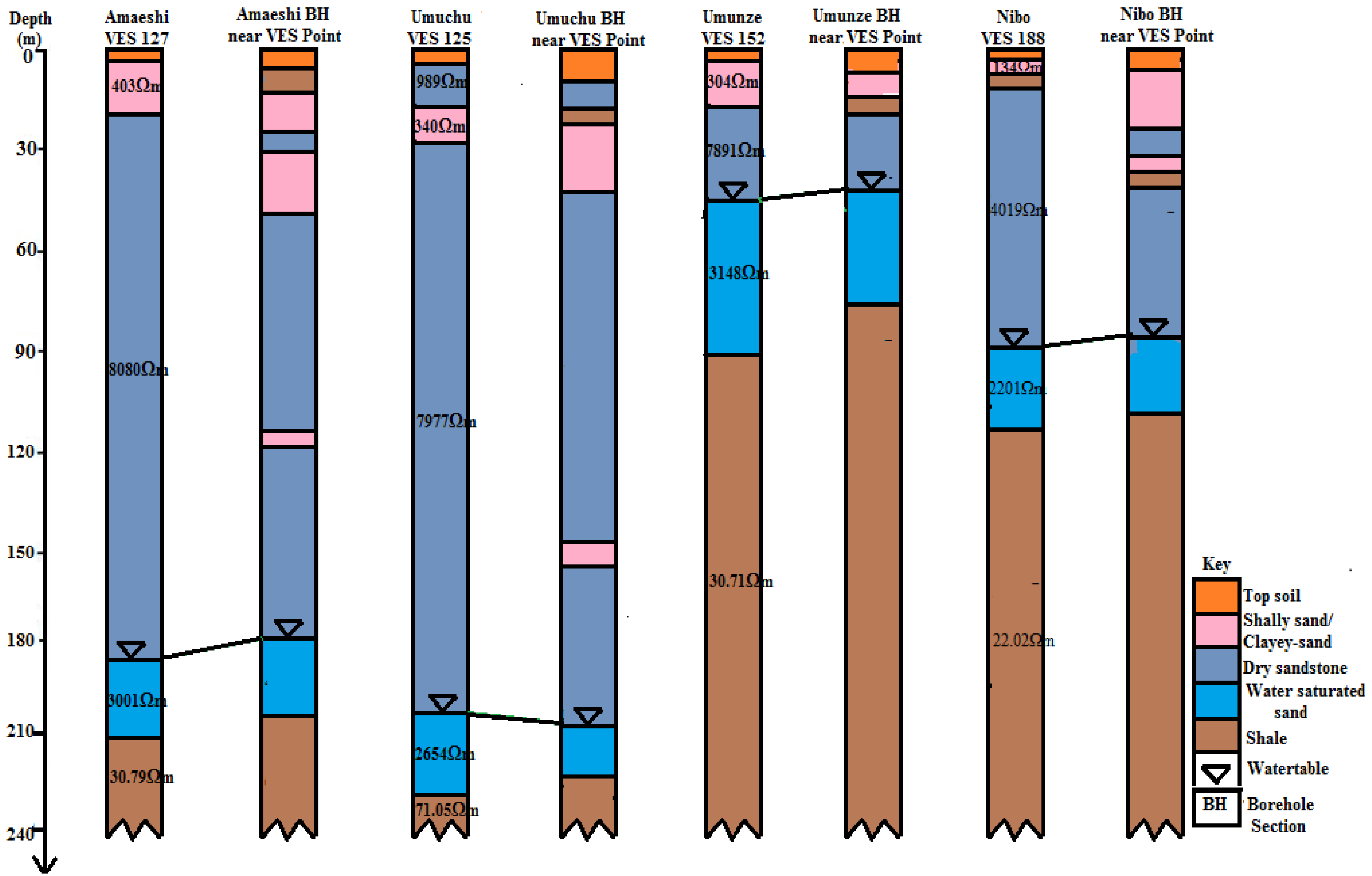


Figure 4.5: Comparison of geo-electric and borehole sections in the area

4.4 Estimation of Aquifer Characteristics/Parameters

The results for the computed aquifer parameters for the overburden and water saturated layer from interpreted VES data is presented in Appendix III. The obtained results show that the values of various parameters range from low to high within the area: longitudinal conductance (mhom); transverse resistance (m-ohms); reflection coefficient (no unit); fractured contrast (no unit) and others.

4.4.1 Overlying Layer Resistivity map

The results of the overlying layer resistivity obtained within the study area is presented in Appendix III. The obtained results show that the value of resistivity within the area is relatively high (490.92 to 30641.01 Ohm-m) and the interpreted layer is dry sandstone. The map showing overlying layer resistivity distributions across the area with contour interval of 1000 Ωm was produced (Fig. 4.6). This map signifies that the study area has different resistivity of the overlying layer with its trend direction in northeast-southwest (NE-SW) path. The Isothermal equation of the Overlaying layer resistivity contour map is given as:

$$\boldsymbol{\rho_{o\,(x,y)} = 572649.9268 - 12951.3226x - 12432.2480y} \quad \textbf{(4.1)}$$

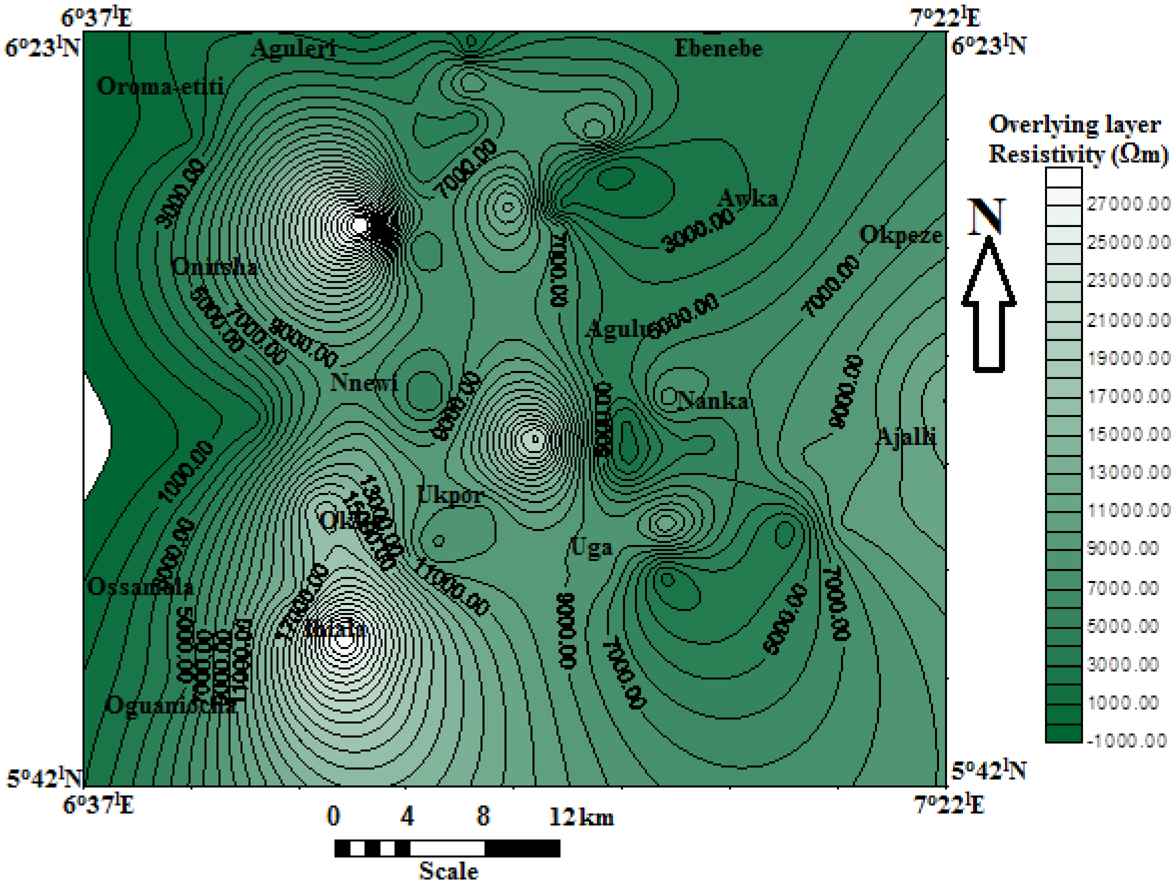


Figure 4.6: Distribution map for Resistivity of Overlying Layer in the study area (Contour Interval ~1000 Ωm)

4.4.2 Aquifer Resistivity map

The results of the aquifer resistivity obtained within the study area are presented in Appendix III – IV. The obtained results show that the value of resistivity within the area ranges from relatively low to relatively high (276.08 to 8207.54 Ohm-m). Some of these resistivity values obtained here aligned with some of those ones obtained by previous workers like Anakwuba *et al*. (2014), Anizoba *et al*. (2015), Chinwuko *et al*. (2015), and Osele *et al*. (2016); where their results revealed the extent of the aquifer resistivity values across and beyond the study area. The map showing aquifer resistivity distributions with contour interval of 600 Ωm was produced (Fig. 4.7). This map signifies that the study area has favourable resistivity for the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. The Isothermal equation for the Aquifer resistivity contour map is given as:

$$\rho_{a\,(x,y)} = 57.8208x - 28.6588y + 1898.8520 \tag{4.2}$$

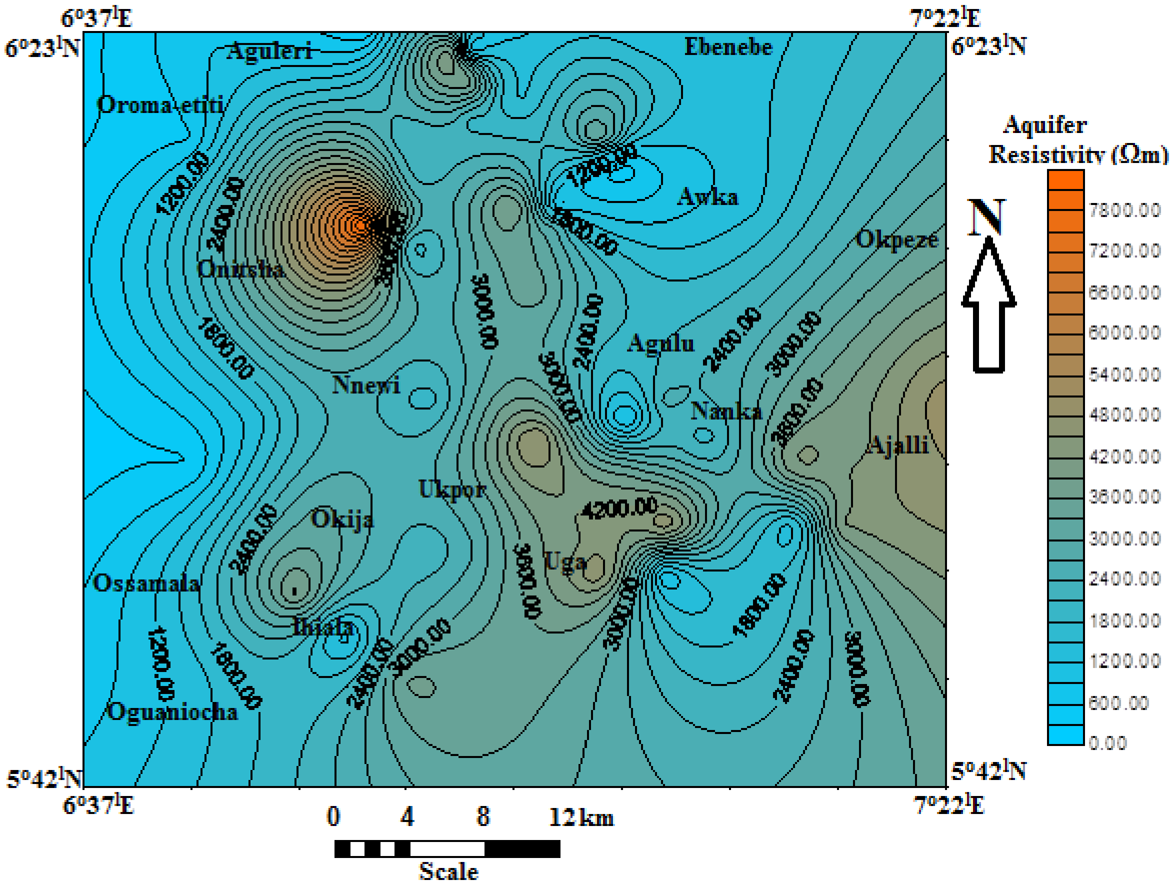


Figure 4.7: Aquifer Resistivity map across the study area (Contour Interval ~600 Ohm-m)

4.4.3 Aquifer Thickness map

The results of the aquifer thickness obtained within the study area is presented in Appendix III - IV. The obtained results show that the aquifer thickness values within the area ranged between relatively moderate and high (18.73 - 64.75m). Some of these aquifer thickness values obtained here aligned with some of those ones obtained by previous workers like Anakwuba *et al*. (2014), Anizoba *et al*. (2015), Chinwuko *et al*. (2015), and Osele *et al*. (2016); where their results revealed the extent of the aquifer thickness values across and beyond the study area. The distribution map of aquifer thickness (Fig. 4.8) with contour interval of 4m indicates that two distinct zones can be identified within the area. The light bluish colour which occurs at the eastern, northern and central parts of the map reveals the existence of relatively moderate thickness of the aquiferous unit (18.73 to 34m), while the yellowish colour at other parts corresponds to relatively high thickness of the water saturated unit (36 to 64.75m). The area is characterized by a thick and prolific aquiferous zone in line with Anakwuba *et al*. (2014) and Chinwuko *et al*. (2015). The Isothermal equation for the Aquifer thickness contour map is given as:

$$\boldsymbol{b}_{(x,y)} = \mathbf{44.0321 - 0.2677}\boldsymbol{x} - \mathbf{0.3120}\boldsymbol{y} \qquad \textbf{(4.3)}$$

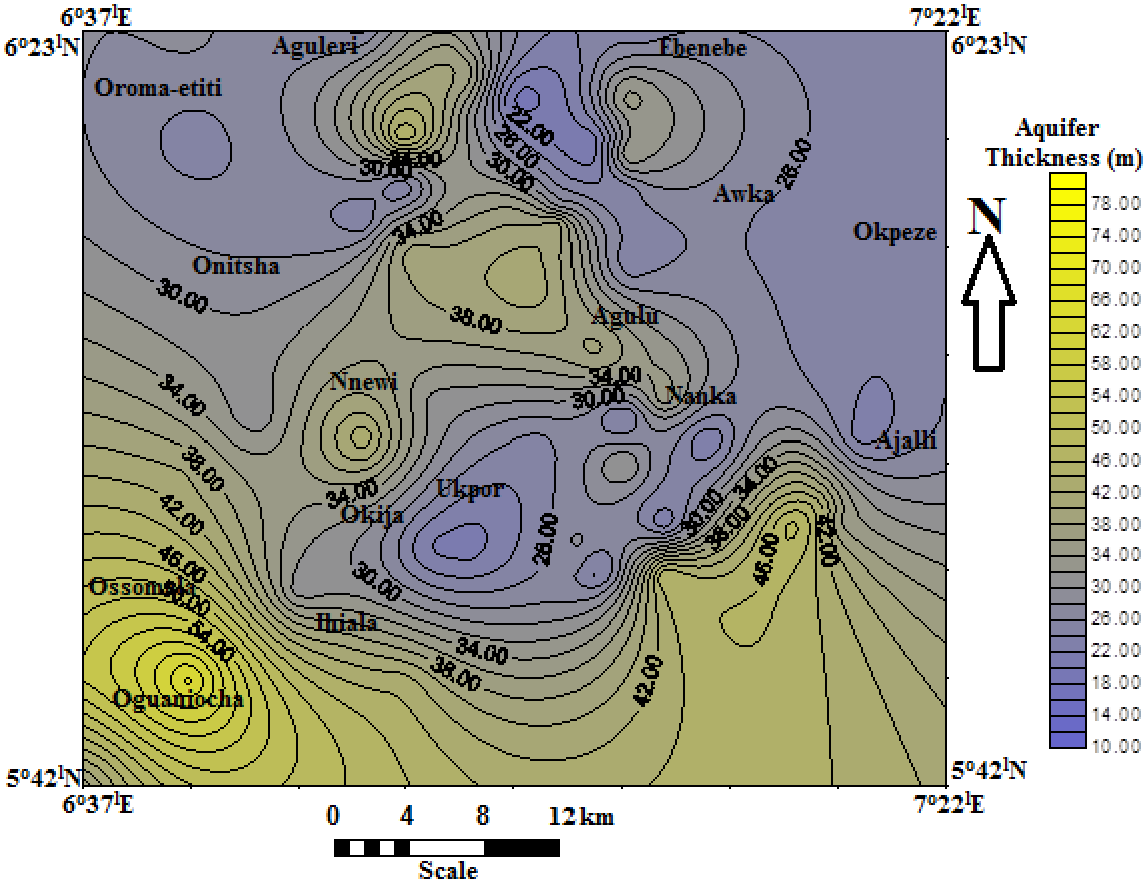


Figure 4.8: Aquifer Thickness map within the study area (Contour Interval ~ 4m)

4.4.4 Depth to Aquifer

The results of the depth to aquifer obtained within the study area are presented in Appendix III - IV. The obtained results show that the depth to aquifer values within the area range between relatively moderate and high (36.76 – 253.26 m). The distribution map of depth to aquifer (Fig. 4.9) with contour interval of 10m indicates that two distinct zones can be identified within the area. The bluish colour which occurs at the far southern and northern parts of the map reveals the existence of relatively moderate depth of the aquiferous unit (36.76 to 110 m), while the light brownish colour at other parts corresponds to relatively high depth of the water saturated unit (120 to 240m). The study area is characterized by a shallow and far depth to the aquifer which is in conformity with that of Anakwuba *et al*. (2014), Anizoba *et al*. (2015), Chinwuko *et al*. (2015), Osele *et al*. (2016), and others. The Isothermal equation for the Depth to Aquifer contour map is given as:

$$\boldsymbol{d_{a\,(x,y)} = 149.6551 - 0.3795x - 0.8106y} \qquad \textbf{(4.4)}$$

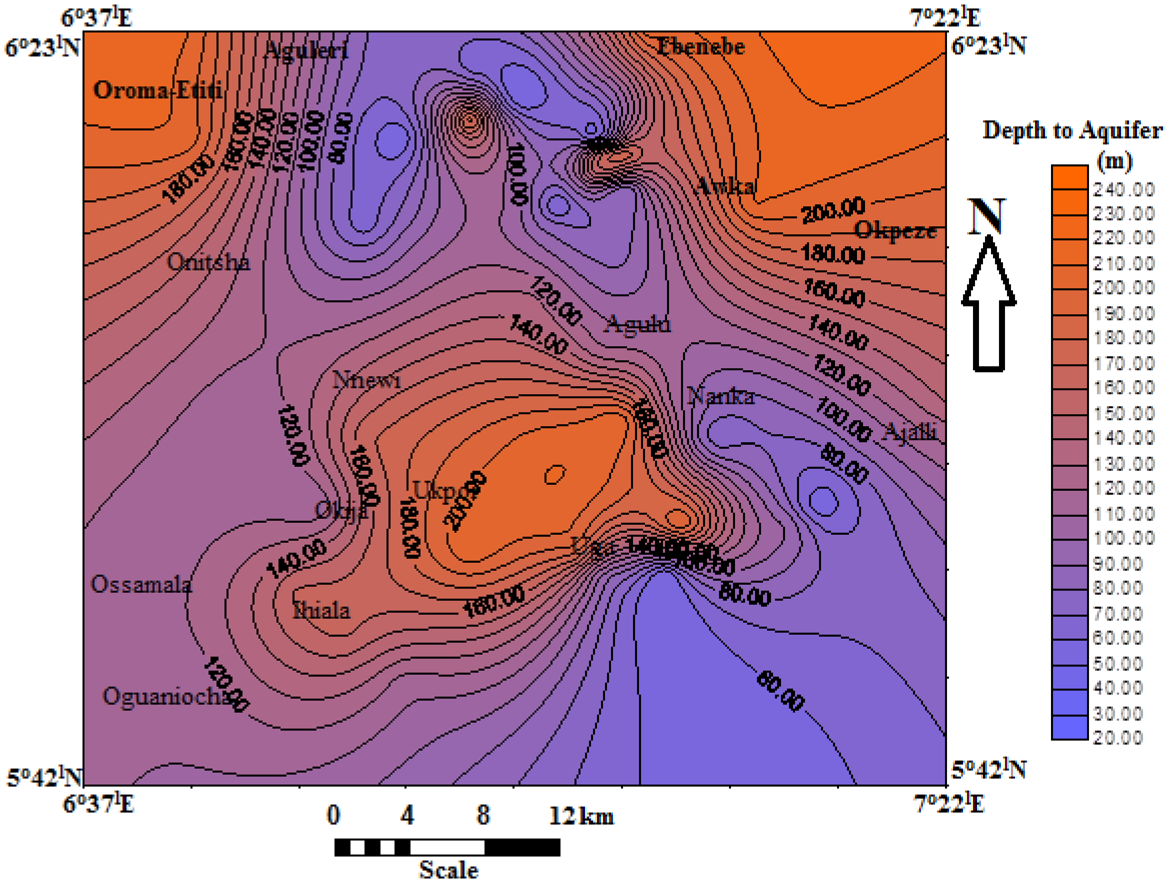


Figure 4.9: Aquifer Depth within the study area (Contour Interval ~ 10m)

4.4.5 Longitudinal Conductance of the Aquifer

The results of the longitudinal conductance of the aquifer obtained within the study area are presented in Appendix III - IV. The obtained results show that the value of longitudinal conductance within the area is relatively low (0.0030289 to 1.0364 mhom) and the interpreted layer is water saturated unit. The map showing longitudinal conductance distributions across the area with contour interval of 0.01 mhom was produced (Fig. 4.10). This map signifies that the study area has different longitudinal conductance of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. Fig. 4.10 depicts that the southwestern part of the area possess higher longitudinal conductance (0.10 – 1.0364 mhom) while at the other parts of the area, there are lower values of longitudinal conductance (0.003029 - 0.09 mhom). The Isothermal equation for the Longitudinal Conductance (Sa) contour map is given as:

$$S_{a\,(x,y)} = 0.001134x + 0.000042y + 0.045400 \quad (4.5)$$

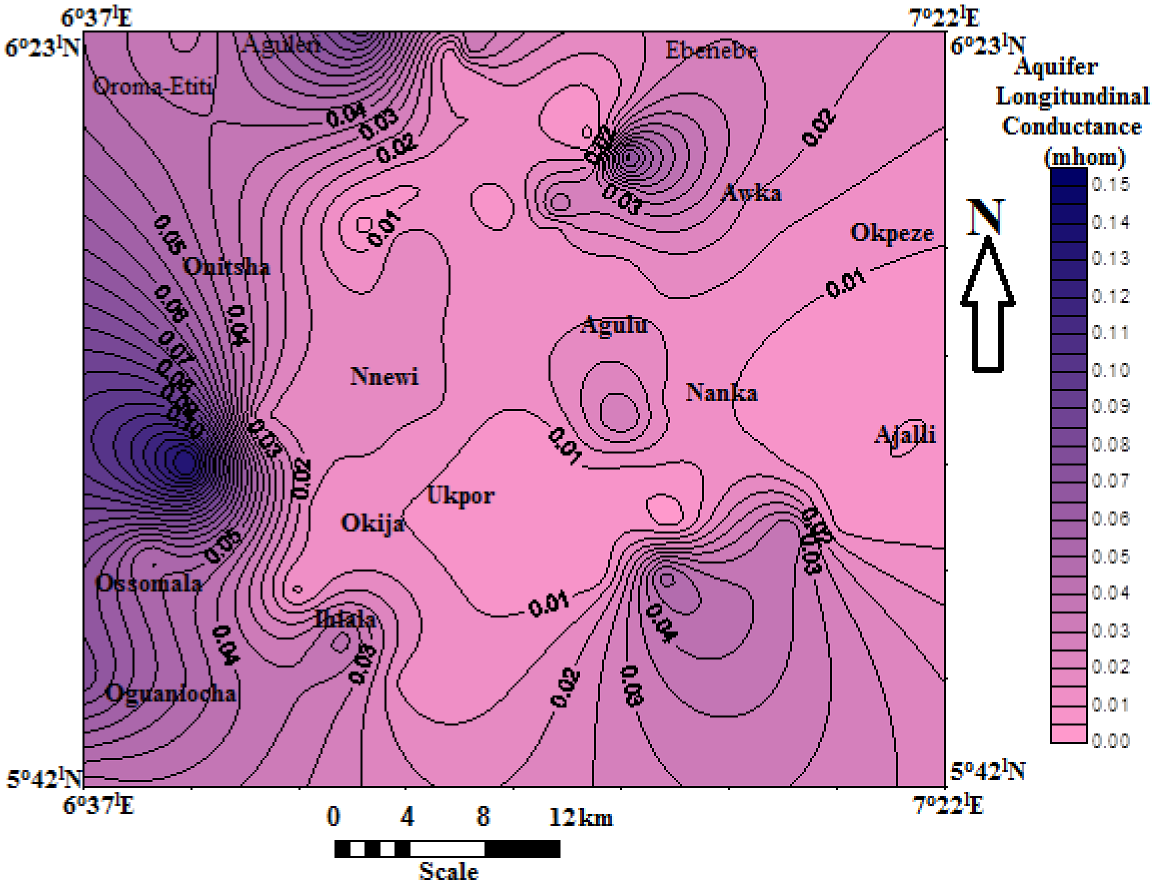


Figure 4.10: Aquifer Longitundinal Conductance within the study area (Contour Interval ~ 0.01 mhom)

4.4.6 Transverse Resistance of the Aquifer

The results of the transverse resistance of the aquifer obtained within the study area are presented in Appendix III - IV. The obtained results show that the value of transverse resistance within the area is relatively low (552.54 to 14003090.56 Ohm-m^2) and the interpreted layer is water saturated unit. The map showing transverse resistance distributions across the area with contour interval of 1000 Ohm-m^2 were produced (Fig. 4.11). This map signifies that the study area has various transverse resistance of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. Fig. 4.11 depicts that the southwestern and northern parts of the area possess lower transverse resistance (552.54 – 80000 Ohm-m^2) while at the other parts of the area, there are higher values of transverse resistance (90000 – 14003090 Ohm-m^2). The Isothermal equation for the Transverse Resistance contour map is given as:

$$T_{R\,(x,y)} = \mathbf{1408.3697}x - \mathbf{1063.6241}y + \mathbf{70910.6864} \qquad \textbf{(4.6)}$$

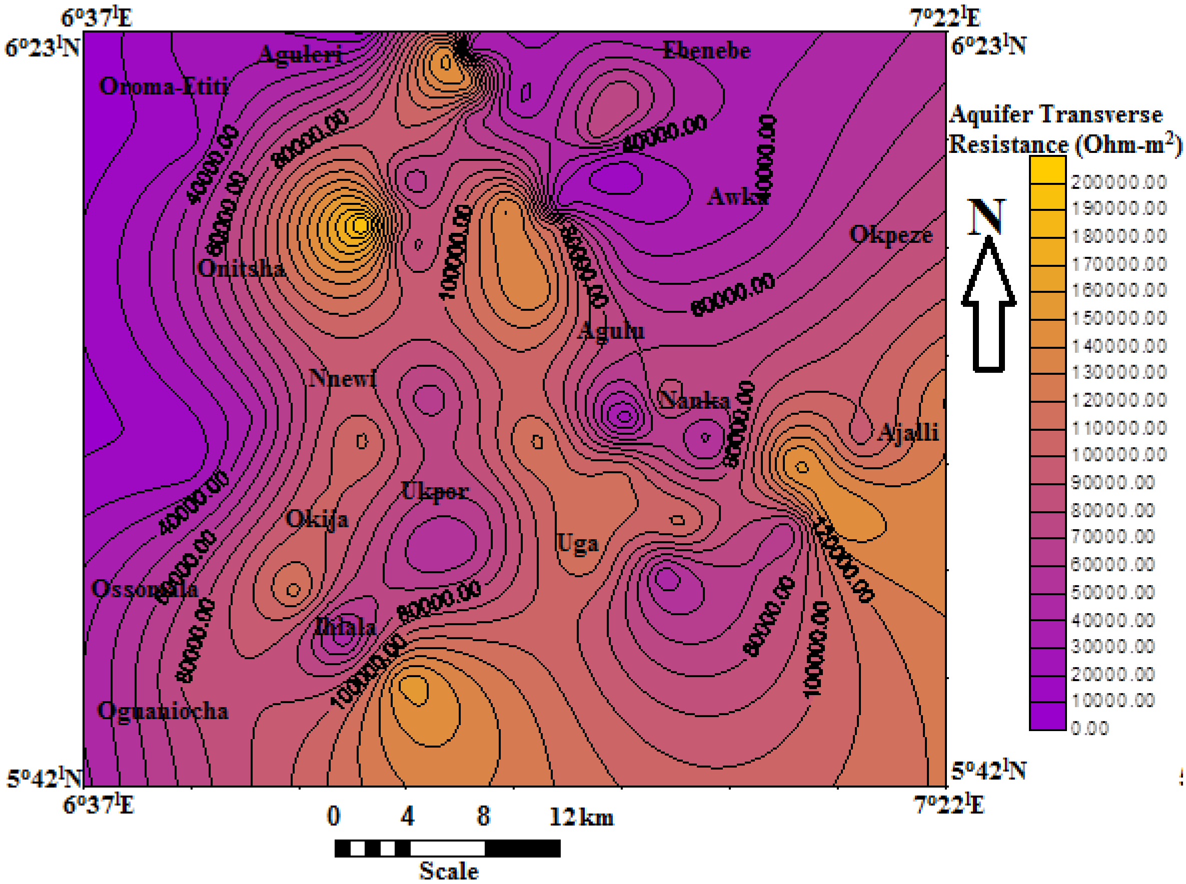


Figure 4.11: Aquifer Transverse Resistance within the study area (Contour Interval ~ 1000 Ohm-m^2)

4.4.7 Conductivity of the Aquifer

The results of the conductivity of the aquifer obtained within the study area are presented in Appendix III - IV. The obtained results show that the value of conductivity within the area is relatively low (0.0001218 to 0.0433088mho) and the interpreted layer is water saturated unit.

Some of these conductivity values obtained here align with some previous works such as Anakwuba *et al.* (2014), and Chinwuko *et al.* (2015). The map showing conductivity distributions across the area with contour interval of 0.0002mho were produced (Fig. 4.12). This map signifies that the study area has various conductivity of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. Fig. 4.12 depicts that the southwestern and northern parts of the area possess lower conductivity (0.0001218 – 0.0010 mho) while at the other parts of the area, there are higher values of conductivity (0.0011 – 0.0433 mho). The Isothermal equation for the Aquifer conductivity contour map is given as:

$$\boldsymbol{C}_{(x,y)} = \mathbf{0.0009728 - 0.0000276}\boldsymbol{x} - \mathbf{0.0000145}\boldsymbol{y} \qquad \textbf{(4.7)}$$

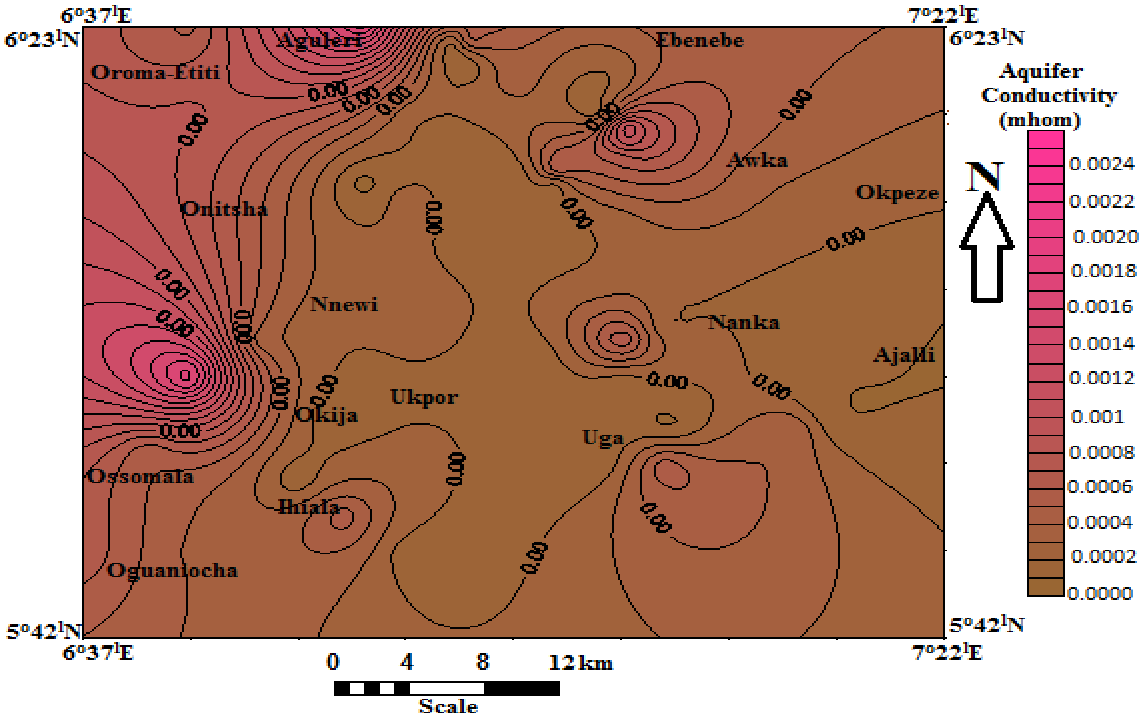


Figure 4.12: Aquifer Conductivity map within the study area (Contour Interval = 0.0002mho)

4.4.8 Hydraulic Conductivity of the Aquifer

The results of the hydraulic conductivity of the aquifer obtained within the study area are presented in Appendix III – IV. The obtained results show that the value of hydraulic conductivity within the area is relatively low (0.04392 to 15.61045959 m/day) and the interpreted layer is water saturated unit. The map showing conductivity distributions across the area with contour interval of 0.1m/day were produced (Fig. 4.13). This map signifies that the study area has various hydraulic conductivity of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. Fig. 4.13 depicts that the southwestern and northern parts of the area possess lower conductivity (0.04392 – 0.600 m/day) while at the other parts of the area, there are higher values of hydraulic conductivity (0.70 – 2.6 m/day). The Isothermal equation for the Hydraulic conductivity contour map is given as:

$$\boldsymbol{K}_{(x,y)} = \mathbf{0.35060 - 0.00993}\boldsymbol{x} + \mathbf{0.005240}\boldsymbol{y} \qquad \textbf{(4.8)}$$

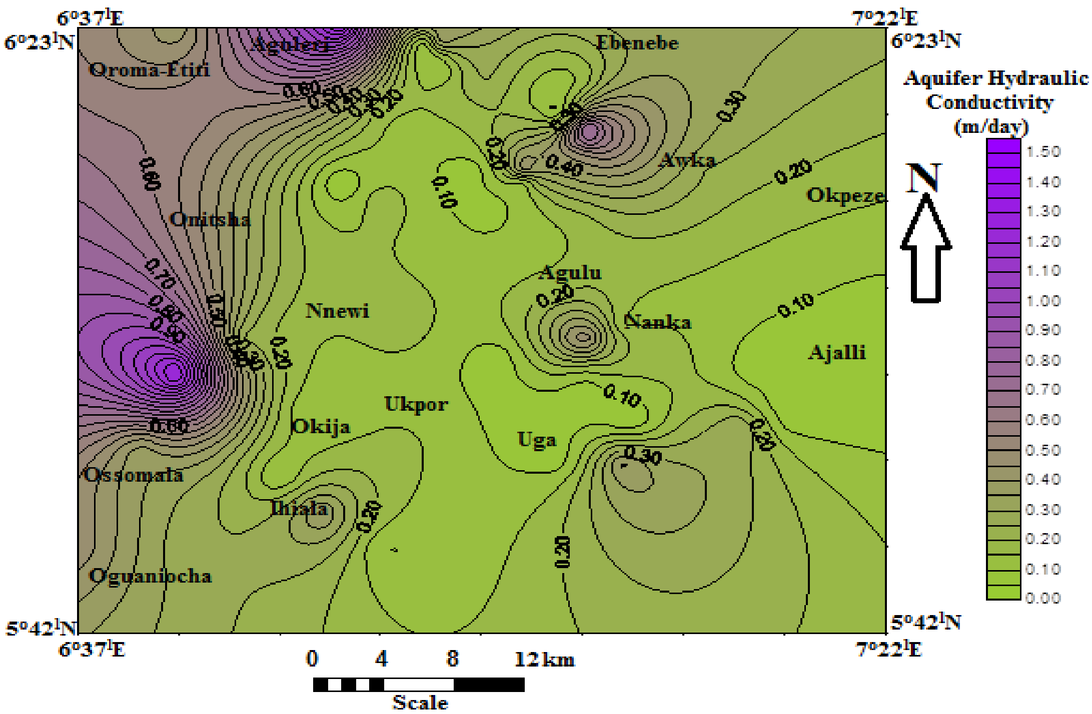


Figure 4.13: Aquifer Hydraulic Conductivity within the study area (Contour Interval ~ 0.1m/day)

4.4.9 Transmissivity of the Aquifer

The results of the transmissivity of the aquifer obtained within the study area are presented in Appendix III – IV. The obtained results show that the value of transmissivity within the area is relatively low (1.0918 to 373.5583 m^2/day) and the interpreted layer is water saturated unit..

The map showing transmissivity distributions across the area with contour interval of 2.5m^2/day was produced (Fig. 4.14). This map signifies that the study area has various transmissivity of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. Fig. 4.14 depicts that the southwestern and northern parts of the area possess lower conductivity (1.0918 – 22.50 m^2/day) while at the other parts of the area, there are higher values of transmissivity (25.00 – 52.50 m^2/day). The Isothermal equation for the Transmissivity contour map given as;

$$T_{(x,y)} = 16.3653 - 0.4087x - 0.0150y \qquad (4.9)$$

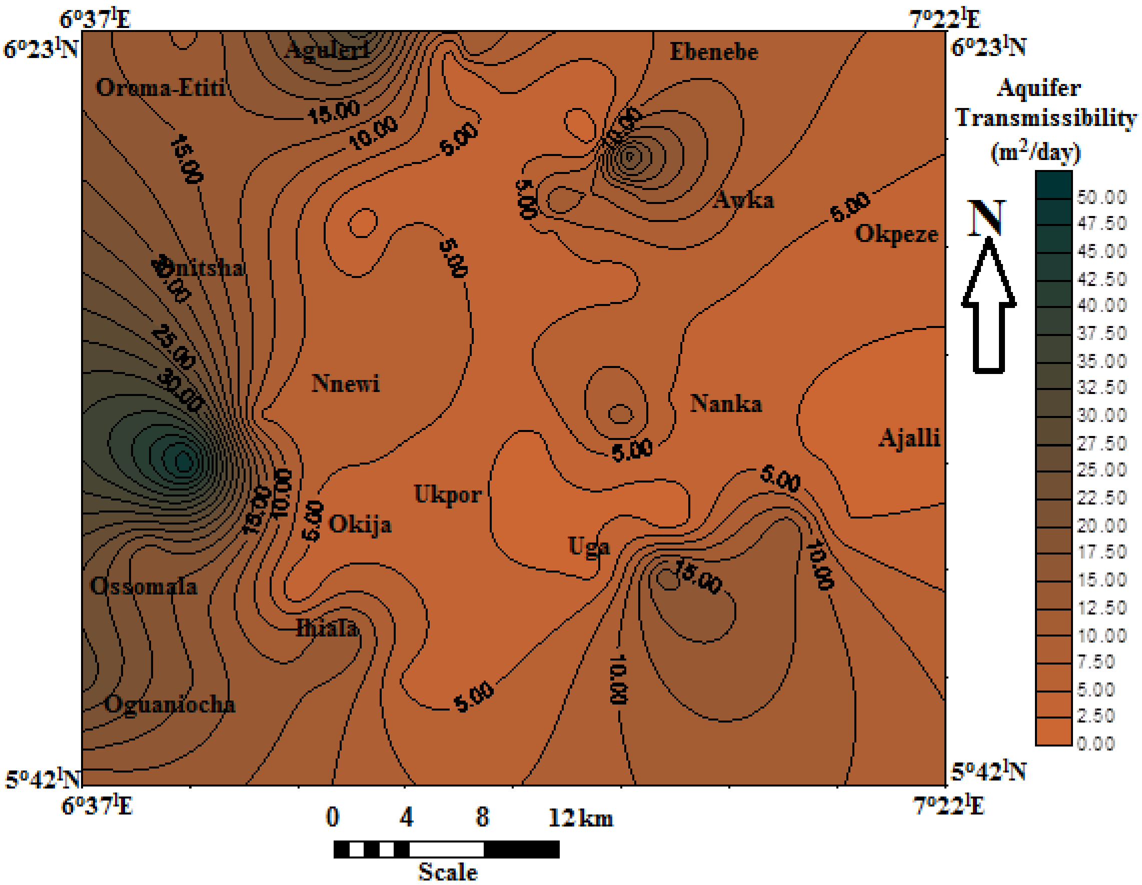


Figure 4.14: Aquifer Transmissibility within the study area (Contour Interval ~2.5m^2/day)

4.4.10 Erodibility of the Aquifer

The obtained results show that the value of erodibility within the area are between 0.004904 and 114.8572 m/day (Appendix III - IV). The aquifer erodibility distribution map was produced across the study area (Fig. 4.15). There are two distinct zones delineated within the area: a relatively high erodibility (> 2.40 m/day) and a relatively moderate erodibility (< 2.40 m/day). This map signifies that the study area has various erodibility of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. The Isothermal equation for the Overlying layer Erodibility contour map given as;

$$K_{Z\,(x,y)} = 1.9175 - 0.0556x + 0.0292y \qquad (4.10)$$

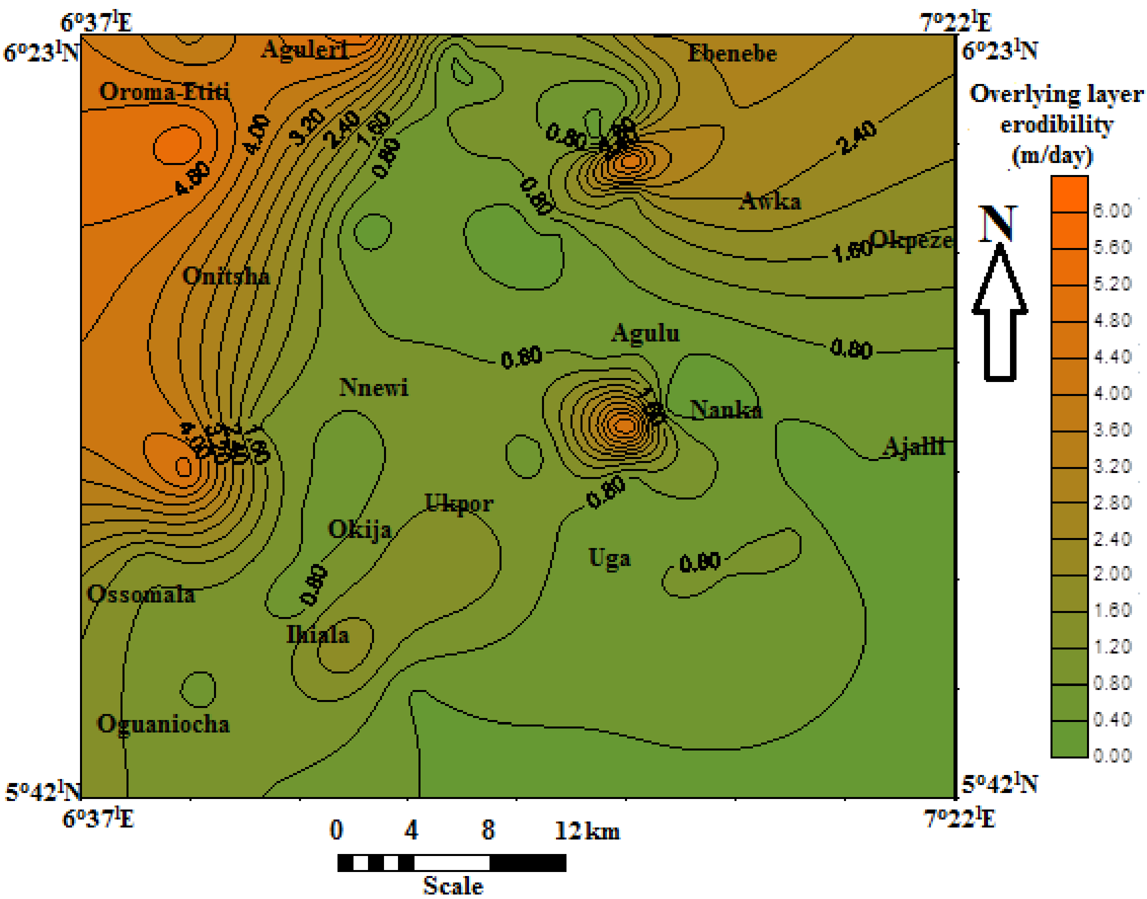


Figure 4.15: Overlying layer erodibility within the study area (Contour Interval ~0.4m/day)

4.4.11 Reflection Coefficient of the Aquifer

The results of the reflection coefficient of the aquifer obtained within the study area are presented in Appendix III - IV. The obtained results show that the value of reflection coefficient within the area is relatively low to high (-0.8632 to 0.9983) and the interpreted layer is water saturated unit. The map showing reflection coefficient distribution across the area with contour interval of 0.4 was produced (Fig. 4.16). This map signifies that the study area has various reflection coefficient of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. Fig. 4.16 depicts that the southwestern and northeastern parts of the area possess lower reflection coefficient (-0.8632 – 0.30) while at the other parts of the area, there are higher values of reflection coefficient (0.34 – 0.9983). The Isothermal equation for the Reflection Coefficient contour map given as;

$$\boldsymbol{R_{c\,(x,y)} = 0.464500 - 0.001759x - 0.001095y} \qquad \textbf{(4.11)}$$

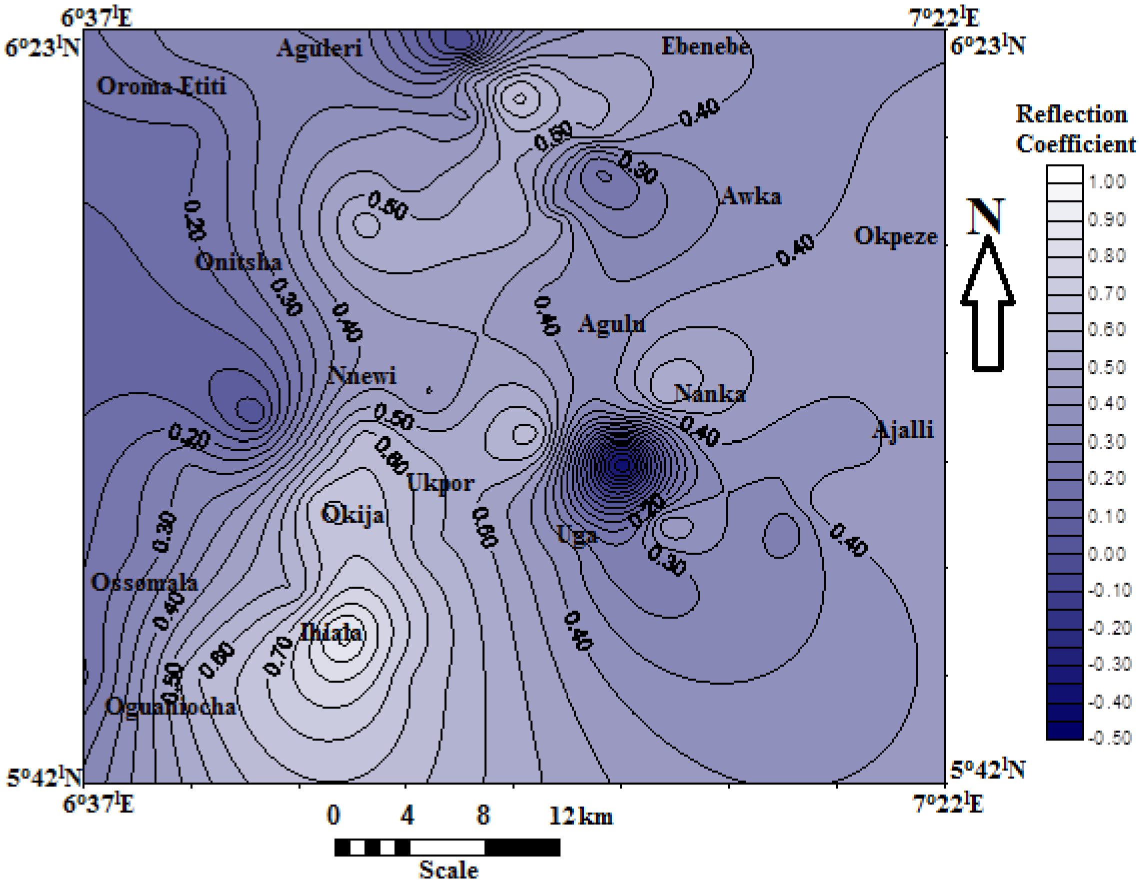


Figure 4.16: Aquifer Reflection Coefficient within the study area (Contour Interval ~ 0.4)

4.4.12 Fractured Contrast of the Aquifer

The results of the fractured contrast of the aquifer obtained within the study area are presented in Appendix III - IV. The obtained results show that the value of fractured contrast within the area is relatively low to high (0.000864 - 13.61448) and the interpreted layer is water saturated unit. The map showing fractured contrast distribution across the area with contour interval of 0.2 was produced (Fig. 4.17). This map signifies that the study area has various fractured contrast of the water saturated layer with its trend direction in northeast-southwest (NE-SW) path. Fig. 4.17 depicts lower fractured contrast 0.000864 – 0.8) southeastern and central parts of the area while at the other parts of the area, there are higher values of fractured contrast (0.90 – 13.61). The Isothermal equation for the Fractured Contrast contour map is given as:

$$\boldsymbol{F_{C\,(x,y)} = 0.003152x - 0.001312y + 0.430220} \qquad \textbf{(4.12)}$$

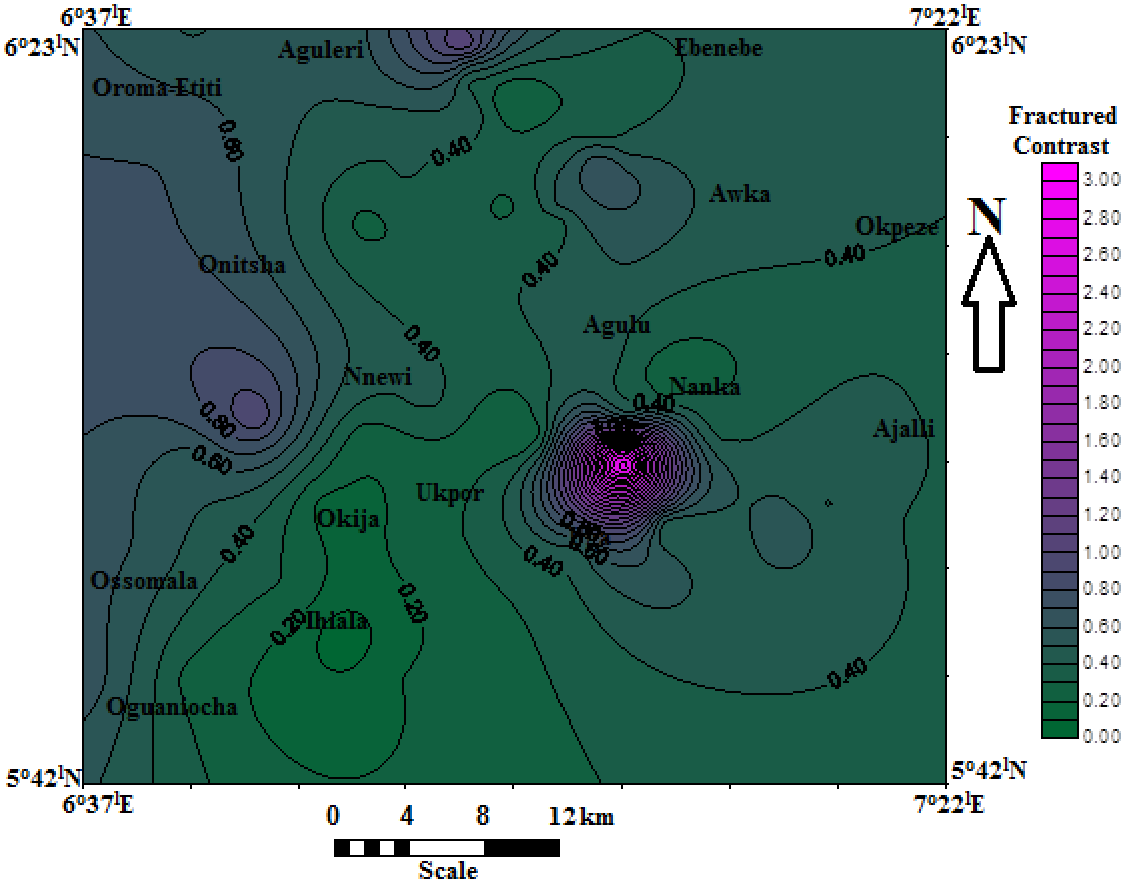


Figure 4.17: Fractured Contrast within the study area (Contour Interval ~ 0.2)

4.4.13 Elevation Map of the Study Area

The obtained results for elevation from the geophysical survey carried out within the study area are presented in Table 4.1. The obtained results show that the value of elevation within the area is relatively low to high (18 – 303m), meaning that the study area possess different topographical (elevation) values. The map showing elevation distribution across the area with contour interval of 15m was produced (Fig. 4.18). This map signifies that the study area has various elevation with its trend direction in northeast-southwest (NE-SW) path. Figure 4.18 depicts higher elevation (135 – 330m) central part of the area while at the other parts of the area, there are lower values of elevation (18 – 120m). The Isothermal equation for the elevation contour map is given as:

$$E_{(x,y)} = 4.1120x - 2.5996y + 107.4114 \quad (4.13)$$

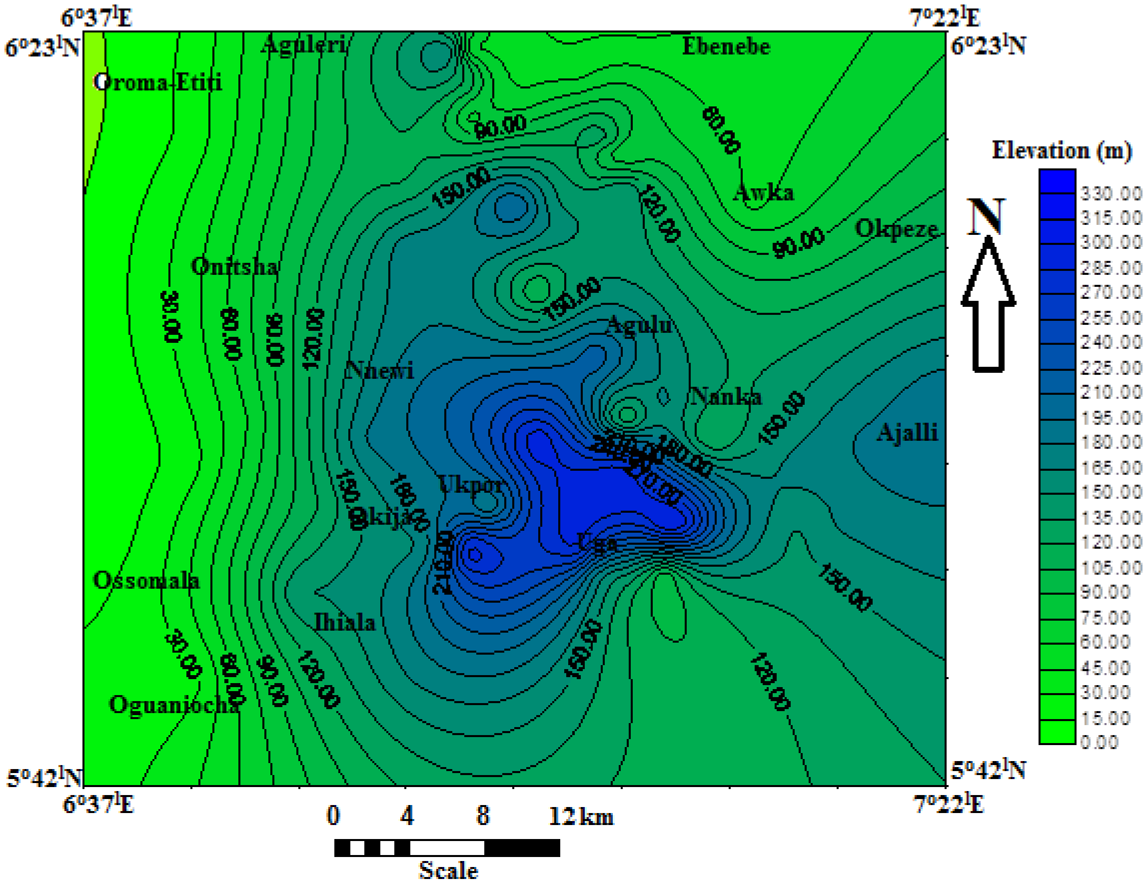


Figure 4.18: Elevation map within the study area (Contour Interval ~15m)

4.4.14 Deduction of Watertable With Respect to Mean Sea Level

The watertable is the plane which forms the upper surface of the zone of groundwater saturation in an unconfined aquifer. The level of the watertable is controlled partly by topography, the nature of the near surface rock and climatic condition. Thus, the depth to the top of the aquifer (watertable) deduced from the geoelectric sections were substracted from the topographic elevation measured from the mean sea level (Table 4.1). The differences showed areas with negative and positive values relative to the mean sea level. The obtained results show that the watertable level within the area is relatively low to high (-191.83 to 112.24m). The map showing watertable distribution across the area with contour interval of 20m was produced

(Figure 4.19). From the map, the groundwater flow direction is NE-SW within the study area. Figure 4.19 depicts lower watertable level (-191.83 to 8.08m) western and northern parts of the area while at the other parts of the area, there are higher values of watertable level (9.70 – 112.24). The Isothermal equation for the watertable contour map is given as;

$$\boldsymbol{S_{W\,(x,y)} = 4.4916x - 1.7890y - 42.2437} \qquad \textbf{(4.14)}$$

Table 4.1: Watertable relative to mean sea level

Town	VES No.	Elevation (m)	Depth to water (m)	Watertable w.r.t. MSL (m)
Oguaniocha	10	21	112.66	-91.66
Ossomala-1	8	23	115.12	-92.12
Ossomala-2	9	22	112.94	-90.94
Ihiala-3	37	142	162.53	-20.53
Isseke	40	164	115.18	48.82
Umunankwo	7	20	113.12	-93.12
Okija	29	150	163.25	-13.25
Ukpor	28	169	190.24	-21.24
Ezinifite	131	303	210.01	92.99
Umuchu	124	289	201.18	87.82
Ihite	155	166	67.83	98.17
Atani	5	23	115.06	-92.06
Ozubulu	22	120	110.3	9.7
Nnewi	19	180	168.19	11.81
Osumenyi	129	177	202.65	-25.65
Uga	133	288	189.25	98.75
Igbokwu	106	302	205.09	96.91
Aguluezechukwu	108	290	195.53	94.47
Achina	120	296	183.76	112.24
Umunze	152	161	48.89	112.11
Ezira	150	170	73.36	96.64
Umueje	205	182	96.09	85.91
Owerre-Ezukala	202	194	142.09	51.91
Nawfija	148	168	72.79	95.21
Ajalli	147	120	67.23	52.77
Ufuma	142	61	44.44	16.56
Nanka	139	217	107.05	109.95
Awgbu	136	160	83.08	76.92
Isiagu	196	89	201.76	-112.76
Okpeze	200	56	210.62	-154.62
Awka	179	152	75.88	76.12

Nibo	188	146	89.43	56.57
Ifite Awka	175	68	196.65	-128.65
Agulu	97	101	128.82	-27.82
Nnobi	92	202	168.02	33.98
Ogidi	77	175	99.02	75.98
Odekpe	11	65	110.88	-45.88
Onitsha	2	113	210.47	-97.47
Nkwelle-Ezunaka	55	97	49.88	47.12
Umukwu Anam	4	20	206.12	-186.12
Oroma-Etiti	1	18	209.83	-191.83
Umuleri	45	147	97.96	49.04
Aguleri	42	110	81.11	28.89
Nteje	49	120	50.07	69.93
Ogbunike	79	132	64.29	67.71
Nkpor	82	170	100.45	69.55
Ukpor	67	169	124.23	44.77
Nimo	73	224	123.07	100.93
Nawfia	186	151	56.92	94.08
Okpuno	172	138	52.38	85.62
Urum	166	70	186.11	-116.11
Umunya	58	118	76.76	41.24
Awkuzu	53	116	72.49	43.51
Mgbakwu	170	87	103.46	-16.46
Ebenebe	162	42	204.03	-162.03
Amanuke	157	54	90.24	-36.24
Igbariam	51	60	67.08	-7.08

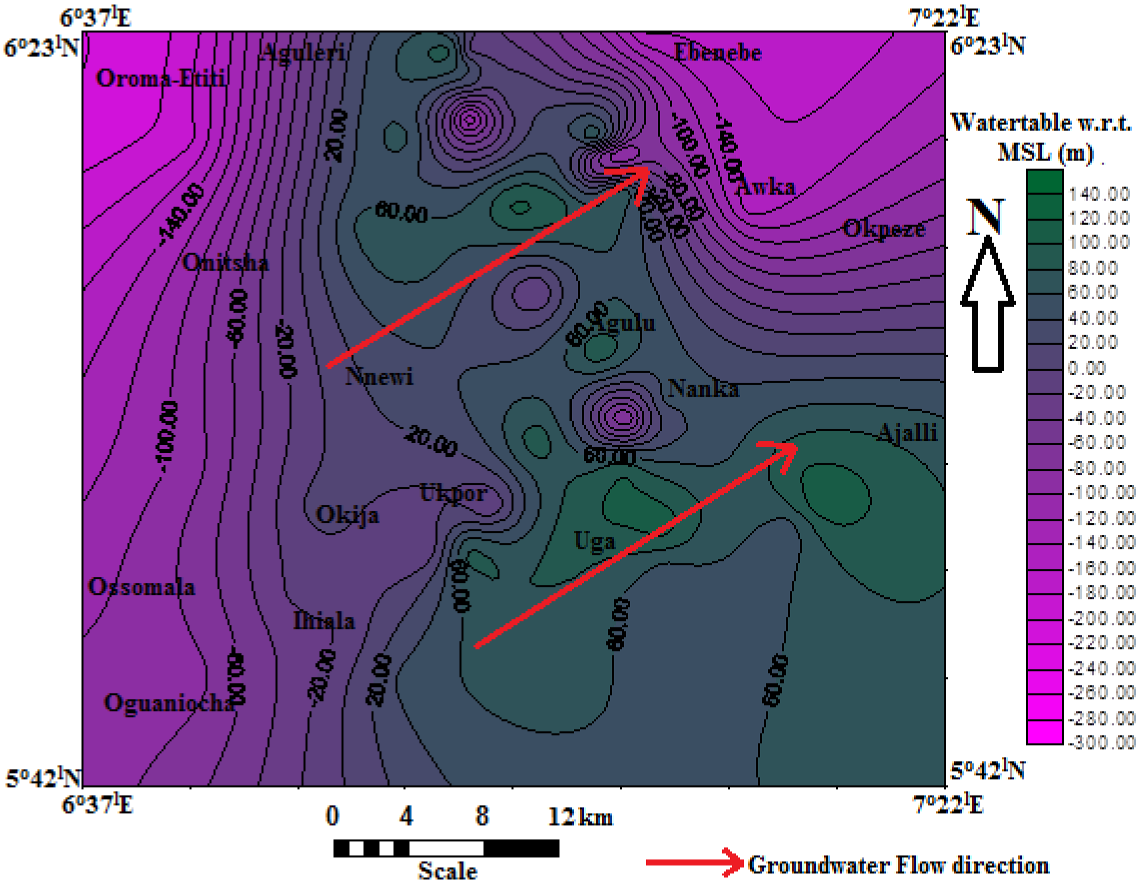


Figure 4.19: Watertable map within the study area (Contour Interval ~20m)

4.5 Water Analysis Results

The results of the water analysis of some selected boreholes from the study area are presented in Table 4.2. Based on these results, the following deductions were made:

4.5.1 Physical Parameters

Appendix I and Table 4.2 show that the five physical parameters namely; appearance which signifies clear quality; temperature shows ambient quality; colour, turbidity and odour result reveals nil (none) across the selected area. According to Nigerian Standard for Drinking Water Quality in 2015 (NSDWQ, 2015), Table 2.11, all the physical parameters are within the acceptable limit and therefore, they are satisfactory for human consumption. However, presence of turbidity has no direct health impact but it can entrap heavy metals and also harbour and protect microorganisms from disinfection. This can bring problem in water treatment process and can also be a potential risk of pathogen in treated water.

4.5.2 Chemical Parameters

A total of seventeen (17) chemical parameters (namely; pH, conductivity, total dissolved solid, salinity, chloride, carbonate, bicarbonate, total hardness, calcium, magnesium, potassium, sulphate, nitrite, nitrate, iron, manganese, copper, and residual chlorine) were tested and their results are presented in Table 4.2 and Appendix I. The pH values deduced range from 4.82 to 7.36 level across the area. Some areas like Abo-Nnokwa, Umuele Umudim Nnewi, Umunono Community-Igbokwu, Central School Echemnankwo-Nnobi, Ofolagbom Nnobi, Ugwuakwu-Umuchu, Ogunzele-Awka Etiti, Eziogwugwu Otolo-Nnewi, and others possess pH levels which are not within the acceptable limit but within the pH of underground water around the environment (NSDWQ, 2015). Other areas met the acceptable limit of the NSDWQ, 2015. Other parameters possess the following ranges: conductivity (16.8 – 45.1 uS/cm); TDS (8.4 – 22.6 mg/l); bicarbonate (6 – 117 mg/l); total hardness (1.7 – 29 mg/l); calcium (6 – 15 mg/l); potassium (0 – 1 mg/l); sulphate (1 – 4 mg/l); nitrite (0.01 – 0.04 mg/l); nitrate (1.8 – 3.42 mg/l); iron (0.01 – 0.35 mg/l); manganese (0.01 – 0.04 mg/l); copper (0 - 1 mg/l); residual chlorine (0.18 – 0.25 mg/l); salinity, chloride, and carbonate (Nil). All these results fall within the acceptable limit for drinking water according to Nigerian Standard for Drinking Water Quality in 2015 (NSDWQ, 2015) and therefore, they are satisfactory for human consumption.

4.5.3 Bacteriological Parameters

The result of the analyses (Table 4.2) shows that all samples except that of Nnobi and Igbokwu which have zero level of bacteriological pollution with Total Coliform and Faecal Coliform counts within acceptable limit of the NSDWQ (2015). However, there are high level of bacteriological pollution with Faecal Coliform (5 – 8 /100ml H_2O) and Total Coliform (13 –

16 /100ml H_2O) counts above acceptable limit of the NSDWQ, 2015, (Table 4.2). This is very harmful to health and therefore proper borehole treatment should be carried out to safeguard human health. Actually, disinfection treatments were carried out on these borehole water here in order to ensure no bacterial contamination**.** The most common and widespread health risk associated with drinking water is microbial contamination, the consequences of which mean that its control must always be of paramount importance (WHO, 2017). Diseases related to contamination of drinking water constitute a major burden on human health. Interventions to improve the quality of drinking water provide significant benefits to health (WHO, 2017).

Table 4.2: Results of Water Analysis around the Study area

	PHYSICAL PARAMETERS	**NIG STD**	Abo-Nnokwa TEST	(D.I.R)	Nnobi Test	D.I.R	Umudim Nnewi	D.I.R	Igbokwu	D.I.R	Umuchu	D.I.R	Awka-Etiti	D.I.R	Uruagu Nnewi	D.I.R
1	Appearance	Clear	Clear	-	Clear	-	Clear	-	Clear	-	Clear	-	Clear	-	Clear	-
2	Temperature ^{0}C	Ambient	Ambient	-	Ambient	-	Ambient	-	Ambient	-	Ambient	-	Ambient	-	Ambient	-
3	Colour (TCIJ)	15	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
4	Turbidity (NTU)	5	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
5	Odour	Nil	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
	CHEMICAL PARAMETERS															
1	pH	6.5-8.5	5.1	-	5.1		5.1	-	5.11	-	4.9	-	4.88	-	5.37	-
2	Conductivity uS/cm	1000	26.8	-	22.6		30.6	-	26.4	-	21.2	-	22	-	40.8	-
3	Total Dissolved solids mg/1	500	13.4	-	11.4		15.3	-	13.2	-	10.6	-	11	-	20.2	-
4	Salinity mg/1	500	Nil	-	Nil		Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
5	Chloride (C1$^-$) mg/1	250	Nil	-	Nil		Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
6	Carbonate (CO$^{2-}_3$)mg/l	500	Nil	-	Nil		Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
7	Bicarbonate (HCO$_3^-$) mg/1	500	14	-	13		11	-	11	-	8	-	10	-	38	-
8	Total hardness mg/1	500	39	-	23		19	-	17	-	18	-	41	-	18	-
9	Calcium (Ca^{2+}) mg/1	200	15	-	6		13	-	9	-	12	-	15	-	9	-
10	Magnesium (Mg^{2+}) mg/1	250	24	-	17		6	-	8	-	6	-	26	-	9	-
11	Potassium (K^+) mg/1	250	-	-	-		-	-	-	-	-	-	-	-	-	-
12	Sulphate (SO4^{2-}) mg/1	100	2	-	3		Nil	-	Nil	-	Nil	-	Nil	-	2	-
13	Nitrite (NO_2^-) mg/1	0.2	0.02	-	0.04		0.03	-	0.03	-	Nil	-	Nil	-	0.04	-

14	Nitrate (NO_3^{2-}) mg/1	50	3.1	-	3.42		2.2	-	2.2	-	1.8	-	1.8	-	3.2	-
15	Iron (Fe^{2+}) mg/1	0.3	0.25	-	0.2		0.2	-	0.1	-	0.01	-	0.12	-	0.15	-
16	Manganese (Mn^{2+}) mg/1	0.2	0.04	-	0.02		0.01	-	0.02	-	Nil	-	0.01	-	0.02	-
17	Copper (Cu^{2+}) mg/1	1	-	-			-	-	-	-	-	-	-	-	-	-
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.18		0.22	-	0.23	-	0.23	-	0.2	-	0.23	-	0.2
	BACTERIOLOGICAL PARAMETERS															
1	Total Coli form / 100 ml H_20	10	0	0	*13*	*0*	0	0	16	0		0	0	0	0	0
2	Feacal Coli form /100ml H_20	0	0	0	*8*	*0*	0	0	5	0		0	0	0	0	0
	PHYSICAL PARAMETERS	**NIG STD**	Eziama-Nnokwa TEST	D.I.R	Otolo Nnewi Test	D.I.R	Uga	D.I.R	Umumocha Awka-Etiti	D.I.R	Ofolagbom Nnobi	D.I.R	Ifite Aguleri	D.I.R	Ojoto	D.I.R
1	Appearance	Clear	Clear	-	Clear	-	Clear	-	Clear	-	Clear	-	Clear	-	Clear	-
2	Temperature ^0C	Ambient	Ambient	-	Ambient	-	Ambient	-	Ambient	-	Ambient	-	Ambient	-	Ambient	-
3	Colour (TCIJ)	15	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
4	Turbidity (NTU)	5	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
5	Odour	Nil	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
	CHEMICAL PARAMETERS															
1	pH	6.5-8.5	7.36	-	4.82	-	6.28	-	5.18	-	5.24	-	5.58	-	5.37	-
2	Conductivity uS/cm	1000	22.4	-	17.3	-	16.8	-	27	-	31.6	-	45.1	-	40.8	-
3	Total Dissolved solids mg/1	500	11.2	-	8.6	-	8.4	-	13.5	-	15.8	-	22.6	-	20.2	-
4	Salinity mg/1	500	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
5	Chloride ($C1^-$) mg/1	250	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
6	Carbonate (CO^{2-}_3)mg/l	500	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-	Nil	-
7	Bicarbonate (HCO_3^-) mg/1	500	117	-	6	-	9	-	11	-	15	-	18	-	38	-

8	Total hardness mg/1	500	29	-	27	-	30	-	17	-	23	-	27	-	18	-
9	Calcium (Ca^{2+}) mg/1	200	12	-	10	-	8	-	10	-	8	-	13	-	9	-
10	Magnesium (Mg^{2+}) mg/1	250	17	-	17	-	22	-	7	-	15	-	14	-	9	-
11	Potassium (K^{+}) mg/1	250	-	-	-	-	-	-	-	-	-	-	1	-	-	-
12	Sulphate ($SO4^{2-}$) mg/1	100	3	-	1	-	Nil	-	Nil	-	4	-	Nil	-	2	-
13	Nitrite (NO_2^{-}) mg/1	0.2	0.03	-	Nil	-	0.01	-	0.01	-	0.02	-	Nil	-	0.04	-
14	Nitrate (NO_3^{2-}) mg/1	50	1.9	-	1.8	-	1.48	-	1.8	-	3.2	-	2.2	-	3.2	-
15	Iron (Fe^{2+}) mg/1	0.3	0.05	-	0.04	-	0.01	-	0.07	-	0.28	-	0.35	-	0.15	-
16	Manganese (Mn^{2+}) mg/1	0.2	Nil	-	Nil	-	Nil	-	Nil	-	0.04	-	0.02	-	0.02	-
17	Copper (Cu^{2+}) mg/1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.25	-	0.24	-	0.2	-	0.2	-	0.2 1	-	0.19	-	0.2
	BACTERIOLOGICAL PARAMETERS															
1	Total Coli form / 100 ml H_20	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Feacal Coli form /100ml H_20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.6 Hydrological Implications

4.6.1 VES Curves and its Implications

The majority of VES curves generated across the study area are typically H and K-curves (Fig. 4.1 and Appendix II), which implies that the interpreted VES Curves are quite common in a sedimentary environment (including the study area) for multilayer structures of four or more layers. The interpreted VES in conjunction with the borehole data within the study area reveal the following layers: top soil/lateritic sand, shally-sand/clayey sand, dry sand, dry sandstone, water saturated sandstone and shale units. These are some characteristics of the Anambra and Niger-Delta Basins which are associated with the study area. The entire geoelectric sections shows lithology of varying composition based on their resistivity attributes. The study area falls within the sedimentary area of Nigeria, overlain by various geological formations in line with Anakwuba *et. al.*, 2014, Chinwuko *et al.*, 2016 and Anizoba *et al.*, 2018.

More so, the results of the VES interpretations within the study area (Table 4.2) reveal that In Alluvium terrain, the sixth layers are delineated as mainly water saturated dry sands (prospective aquifer units) with its thickness and resistivity values range from 22.29 – 28.71m and 600.07 – 886.43Ωm respectively. However, at the Benin Formation, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 276.08 - 1331.11Ωm and 30.45 - 64.75m respectively across the area. For Ogwashi Formation, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 23.09 - 4196.26Ωm and 21.77 - 58.38m respectively across the area. For Amerki Formation, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 1349.10 – 4620.14Ωm and 23.46 – 43.96m respectively across the area. For Imo Shale, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 139.14 – 3048.71Ωm and 21.81 – 42.13m respectively across the area. For Nsukka Formation, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 2470.51 – 5014Ωm and 23.02 – 35.42m respectively across the area.

4.6.2 Computed Aquifer Parameters and their Implications

The computed aquifer parameters for the overburden aquifer of the interpreted VES data (Appendix III - IV) show that the values of various parameters range from low to high across the area: overlying layer resistivity (490.92 to 30641.01 Ohm-m); aquifer resistivity (276.08 to 8207.54 Ohm-m); aquifer thickness (18.73 - 64.75 Ohm-m); depth to aquifer values (36.76 – 253.26 m); longitudinal conductance (0.0030289 to 1.0364 mhom); transverse resistance (552.54 to 14003090.56 Ohm-m^2); conductivity (0.0001218 to 0.0433088mho);hydraulic conductivity (0.04392 to 15.61045959 m/day); transmissivity (1.0918 to 373.5583 m^2/day); erodibility (0.004904 - 114.8572 m/day); reflection coefficient (-0.8632 to 0.9983) and fractured contrast (0.000864 - 13.61448).

Comparing the resistivity of the water saturate units (276.08 to 8207.54 Ohm-m) and the resistivity of the overlying layer (490.92 to 30641.01 Ohm-m); it means that the resistivity of the overlying layers is greater than that of the aquifer layers. This also implies that the conductivity of the aquifer layer is invariably high compared to that of the overlying layer which is relatively low. Hence, these resistivity values obtained in this study aligned with those obtained by Anakwuba *et al*., 2014, Chinwuko *et al.*, 2015, within Anambra Basin, Nigeria.

Generally, almost all the maps of the aquifer parameters generated across the study area, signified that the trend directions of all the contours occurs along northeast-southwest (NE-SW) path. This implies that all the subsurface water flow within the study area will possibly follow this trend.

4.6.3 Implications of Apparent Resistivity and Hydraulic Conductivity Relationship

The relationship between apparent resistivity and hydraulic conductivity across the geological formations within the study area established major statistical models as shown in Figures 4.20a-g. However, the correlation factors; 0.88, 0.86, 0.81, 0.87, 0.83, 0.73 and 0.85 respectively signified perfect correlations.

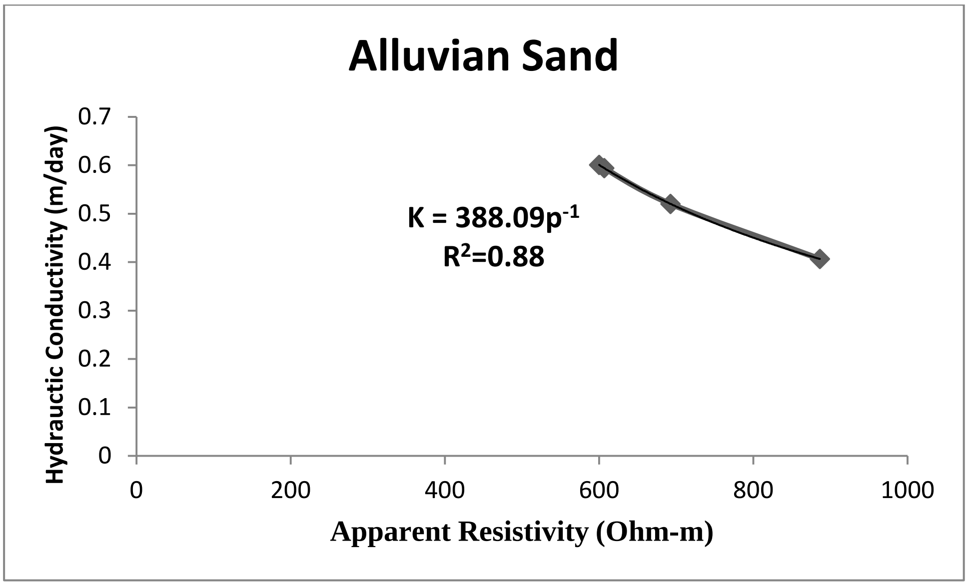


Figure 4.20a: Relationship between Apparent Resistivity and Hydraulic Conductivity within Alluvian Sand.

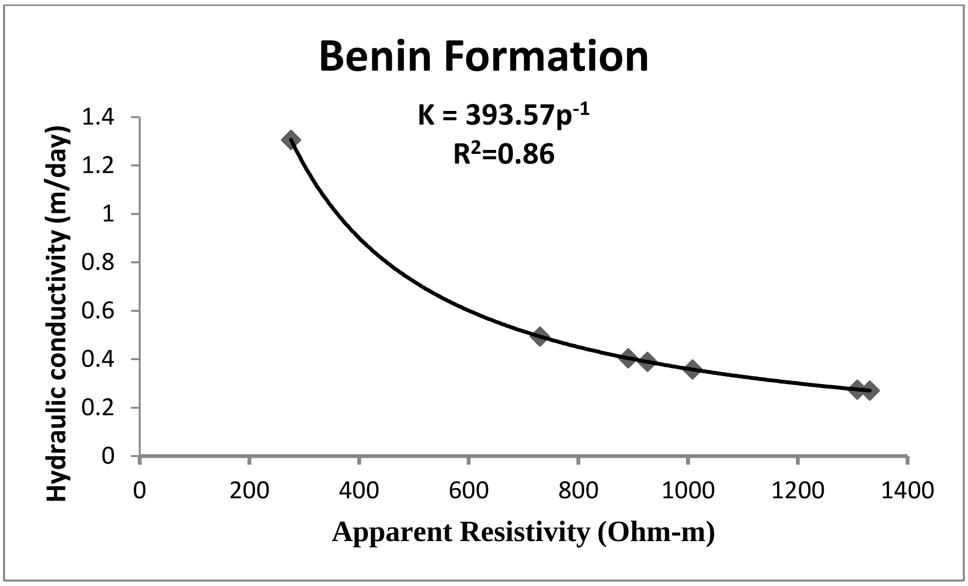


Figure 4.20b: Relationship between Apparent Resistivity and Hydraulic Conductivity within Benin Formation

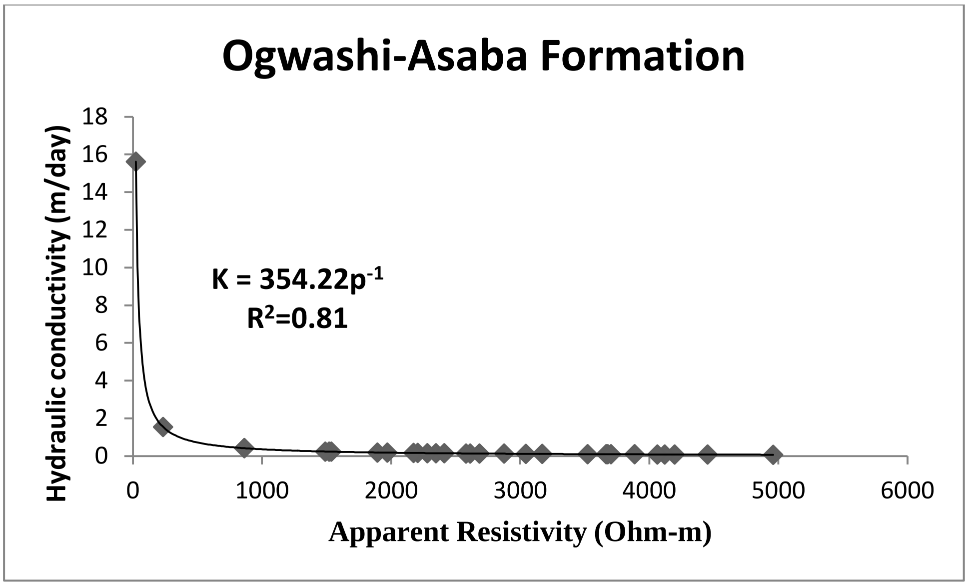


Figure 4.20c: Relationship between Apparent Resistivity and Hydraulic Conductivity within Ogwashi-Asaba Formation

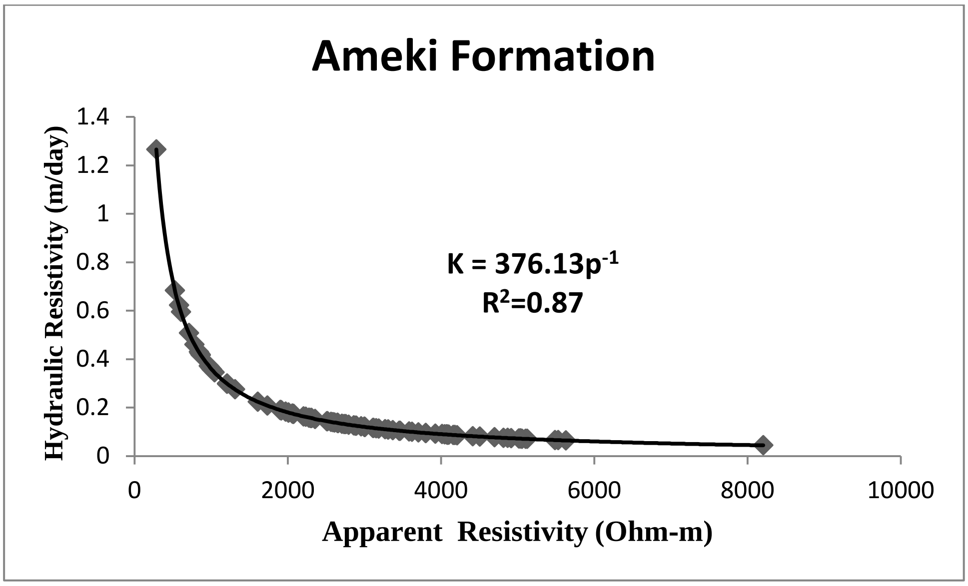


Figure 4.20d: Relationship between Apparent Resistivity and Hydraulic Conductivity within Ameki Formation

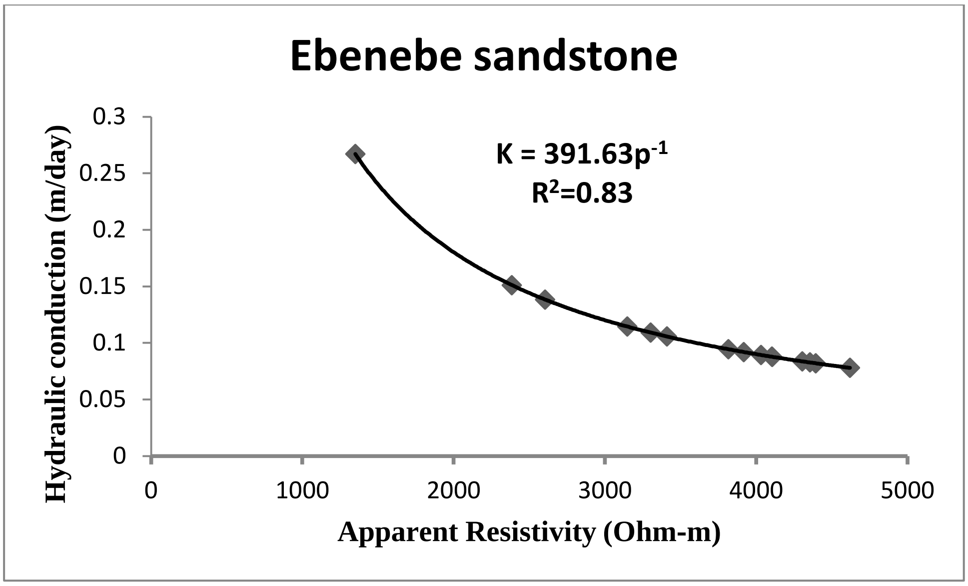


Figure 4.20e: Relationship between Apparent Resistivity and Hydraulic Conductivity within Ebenebe Sandstone.

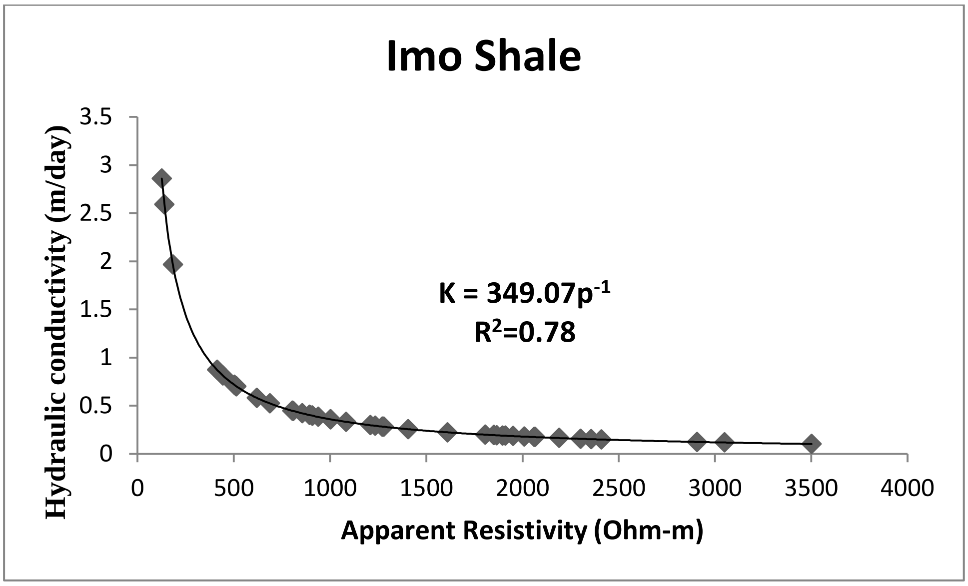


Figure 4.20f: Relationship between Apparent Resistivity and Hydraulic Conductivity within Imo Shale

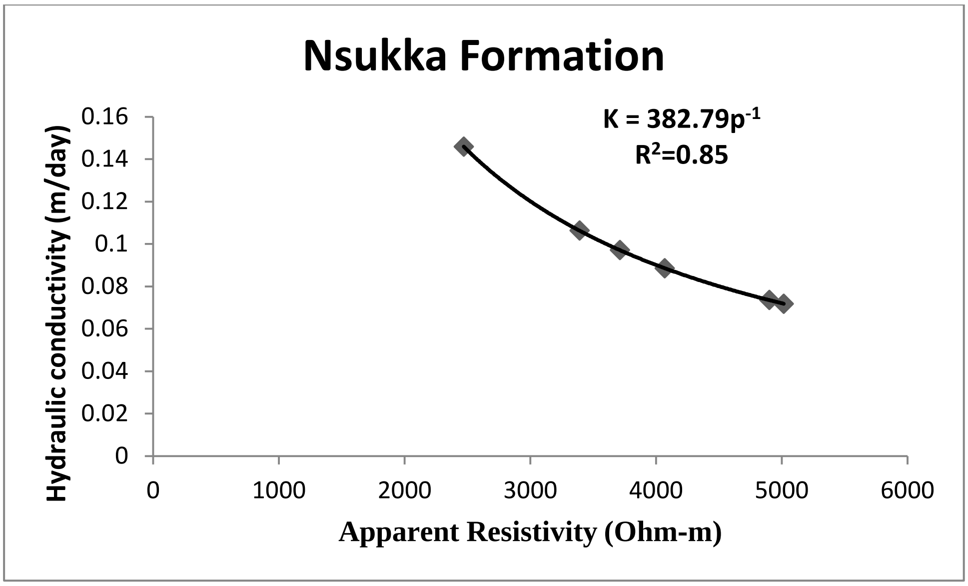


Figure 4.20g: Relationship between Apparent Resistivity and Hydraulic Conductivity within Nsukka Formation

However, the integration of all the values of Apparent resistivity and Hydraulic conductivity in the entire geological formations in the (see Figure 4.21) study area established equation 4.15:

$$K = 360.45\rho^{-1} \qquad (4.15)$$

Where, $\boldsymbol{K}$ = hydraulic conductivity of the aquifer (m/day)***;***

$\rho =$ Apparent resistivity of the aquifer (Ωm)

The above model (equation 4.15) implies that the relationship between hydraulic conductivity and apparent resistivity in any given area is an inverse relationship and increase in one will surely lead to decrease in the other. Also, the correlation factor (0.84) signifies a perfect correlation. This statistical model was validated (Appendix VI) and could be utilized in any sedimentary basin within and outside Nigeria. It is also good to note that the equation parameters for the model were established for the first time in Anambra State. Also, this model will assist in deducing some of the major aquifer parameters such as transmissivity, storability and yielding rate.

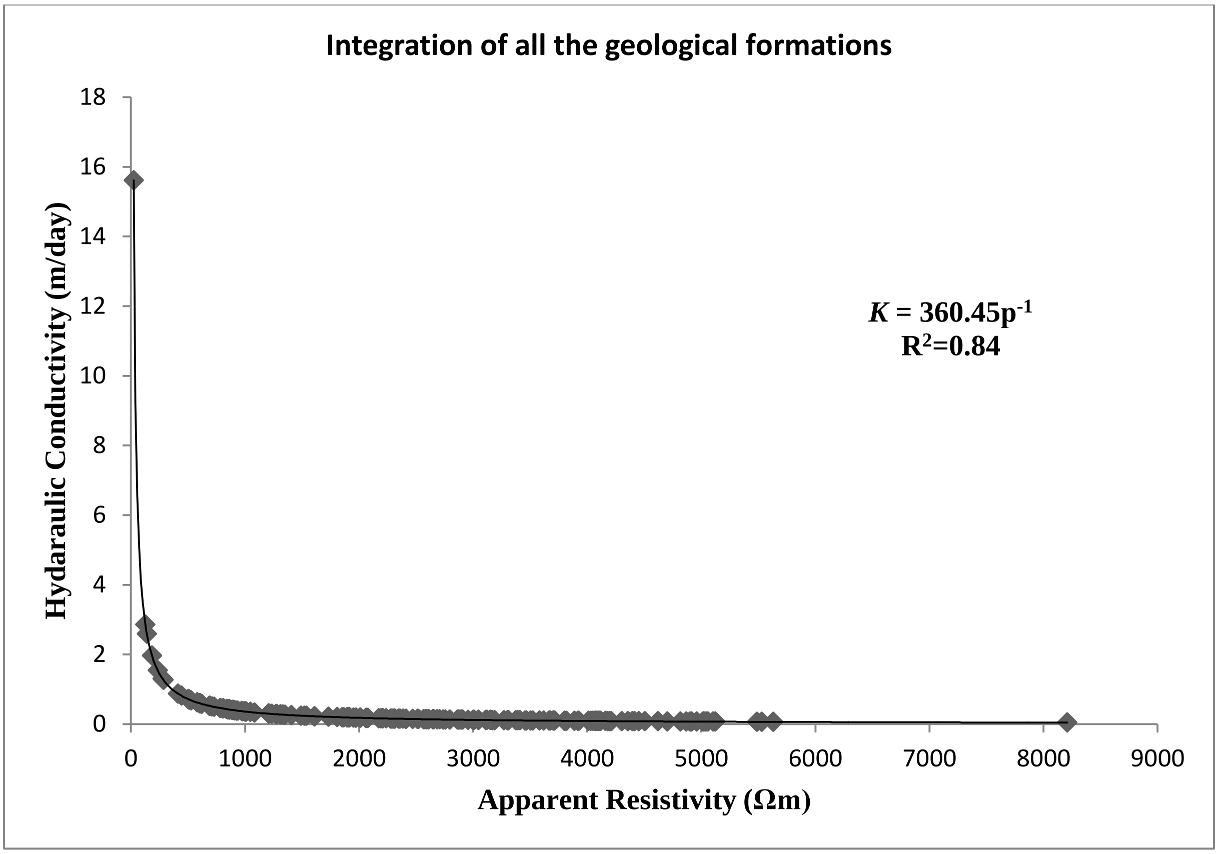
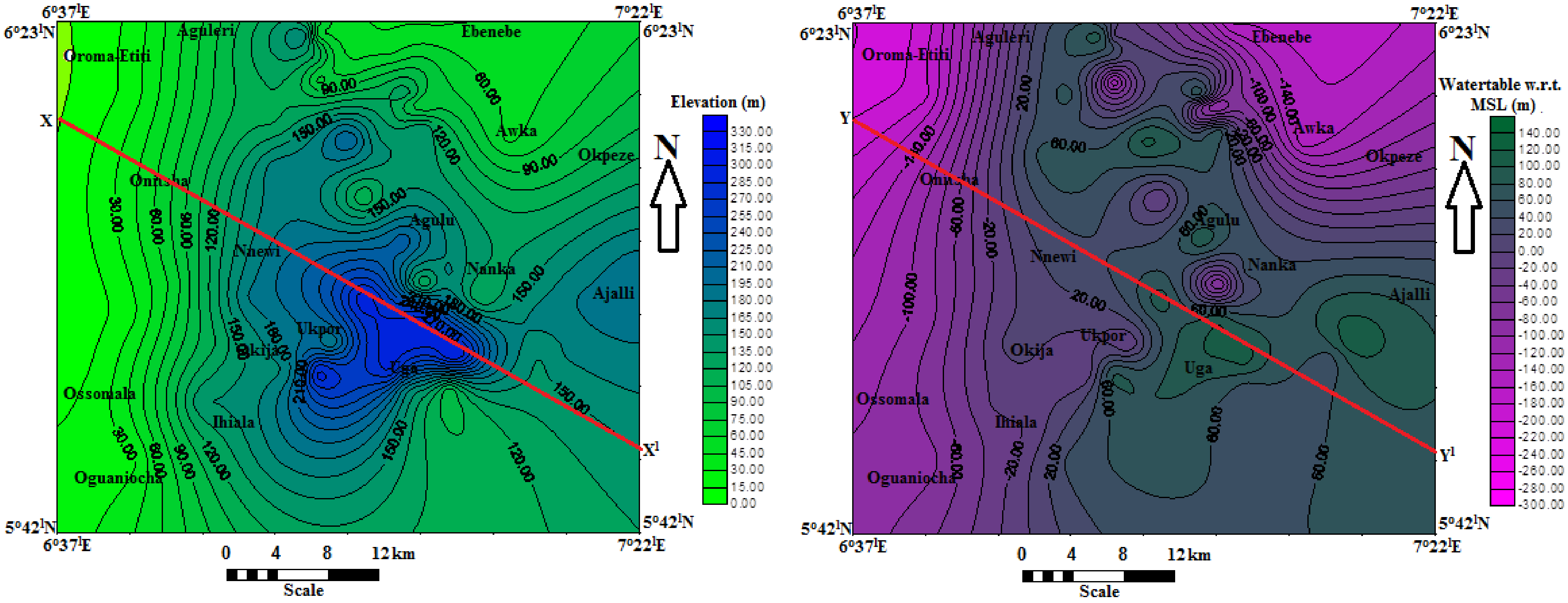


Figure 4.21: Relationship between Apparent Resistivity and Hydraulic Conductivity within the study area

4.6.4 Hydrogeological Implication associated with Watertable Level

Two cross sections were taken at both the elevation map (Figure 4.22a) and watertable level map (Figure 4.22b) at the study area respectively. The profiles running from X-X^l at Figure 4.21a and Y-Y^l at Figure 4.22b were superimposed in order to estimate the groundwater potential (Figure 4.23) obtainable in this area. Here, it was observed that the watertable level follows the topography which implies that the topography controls the configuration of the groundwater (Figure 4.23). Also, the gap between the peak of the watertable level and the average static water level in the area is 27m, since the depth of the peak watertable level and that of the static water level is 100m and 127m respectively (Figure 4.23). Also, considering the gap between the peak of topography and the average static water level in the area is 158m, since the depth of the peak elevation level and the static water level is 285m and 127m respectively (Figure 4.23). This implies that the vertical movement of any contaminant will be retarded by the earth materials thereby allowing physical (filtration), chemical and biochemical processes to remove contaminants before reaching the aquifer. This is confirmed by the water analysis results, where most of the parameters fall within the acceptable limit for drinking water according to Nigerian Standard for Drinking Water Quality in 2015 (NSDWQ, 2015) and therefore, they are satisfactory for human consumption..



(a)

(b)

Figure 4.22: Cross sections across elevation and watertable level maps in the area

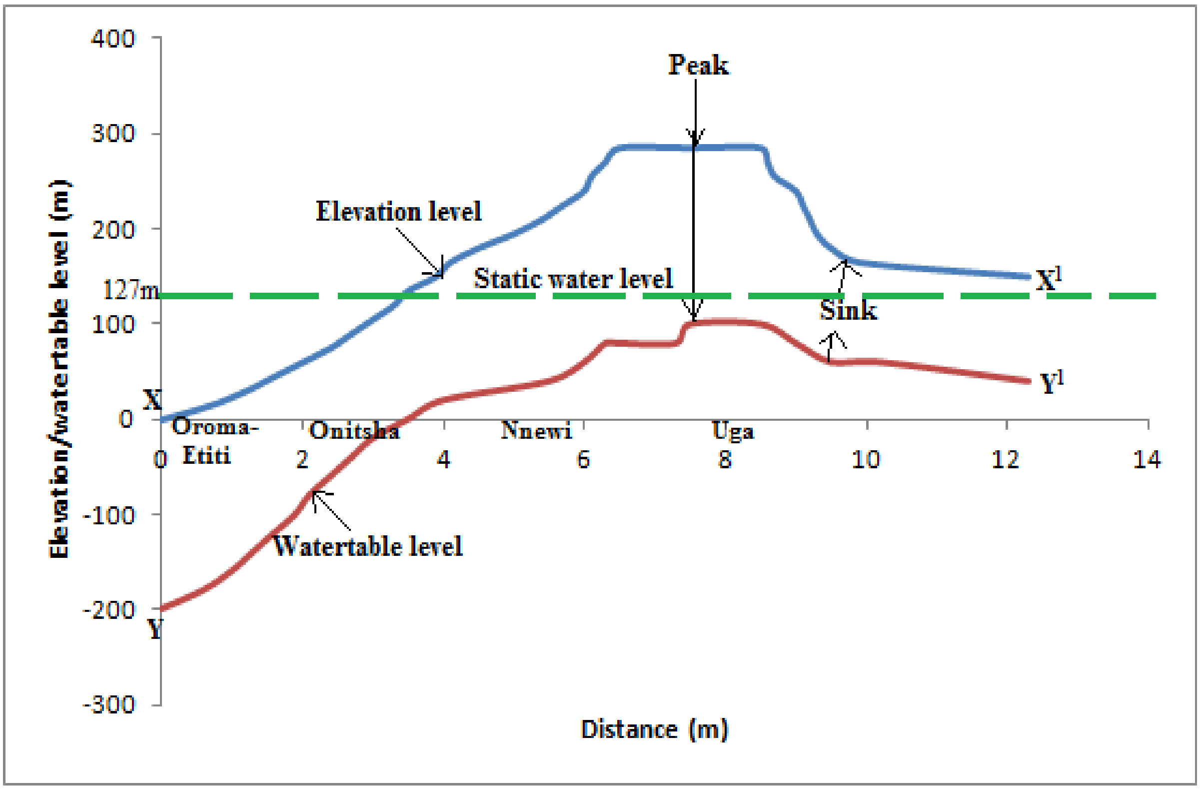


Figure 4.23: Groundwater Potential and Risk within the Study area

4.6.5 Groundwater Implication with respect to Agricultural Practice

The availability of good water supply (possibly for domestic, agricultural and industrial uses) in conjunction with access to food supply is some of the world greatest priority for man. As such, agriculture is a dominant component of the global economy. In Nigeria (including the study area), the quest to produce enough food through various agricultural practices has necessitated the search for a sustainable and reliable water supply source(s) which include groundwater exploitation and exploration. Hence, a groundwater model across the study area was generated (Fig. 4.24) in order to forecast the potential area for easy accessibility and drilling of subsurface water. Fig. 4.24 shows that the eastern and western parts of the study area which include Ebenebe, Okpeze, Oroma-Etiti, Ukpor, Ihiala, Okija, Oguaniocha, Ossomala and others possess deeper depth to the aquifer, as such, the cost of siting borehole there will be variably high, compared with other areas.

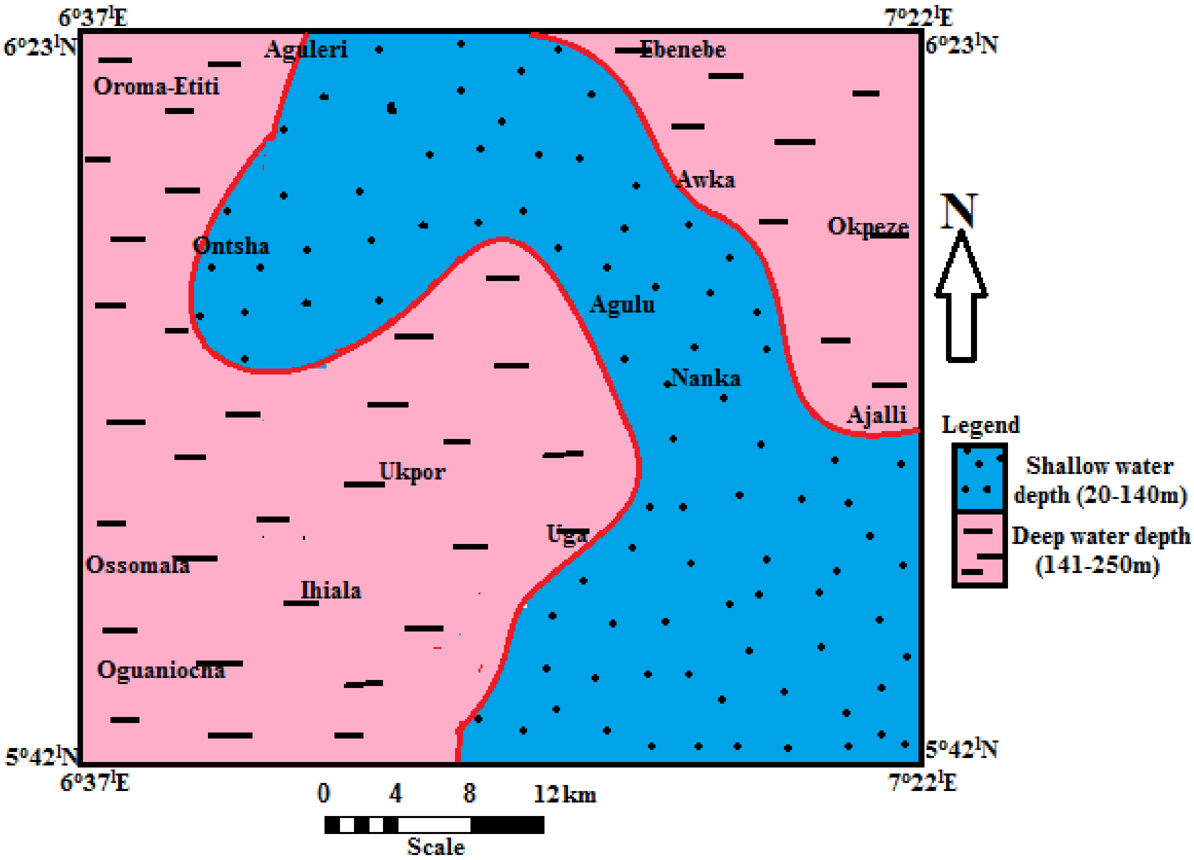


Figure 4.24: Groundwater Model for Siting Boreholes across the Study Area

Furthermore, agriculture happens to be the single major user of freshwater resources which include groundwater and surface water supplies. Except for water lost through evapotranspiration, agricultural water is recycled back to surface water and groundwater. Actually, according to Kuniansky et al. (2004), they proposed that the main effect of the changes in agricultural practices is the reduction in recharge to the aquifer and total irrigation withdrawals. Increases in groundwater withdrawals for public supply offset the reduction in groundwater withdrawals for irrigation purposes.

However, agriculture is both cause and victim of water pollution. It is a cause through its discharge of pollutants and sediment to surface and/or groundwater, through net loss of soil by poor agricultural practices, and through salinization and waterlogging of irrigated land. It is a victim through use of wastewater and polluted surface and groundwater which contaminates crops and transmit disease to consumers and farm workers. Agriculture exists within a symbiosis of land and water, thus, appropriate steps must be taken to ensure that agricultural activities do not adversely affect water quality so that subsequent uses of water for different purposes are not impaired. Although the effect of agricultural practice is not eminent within the study area.

CHAPTER FIVE

SUMMARY, CONCLUSION, RECOMMENDATION AND CONTRIBUTION TO KNOWLEDGE

5.1 Summary

This research work is summarized as follows:

The majority of VES curves generated across the study area are typically H and K-curves, which imply that the interpreted VES Curves are quite common in a sedimentary environment (including the study area) for multilayer structures of four or more layers. The interpreted VES in conjunction with the borehole data within the study area reveal the following layers: top soil/lateritic sand, shally-sand/clayey sand, dry sand, dry sandstone, water saturated sandstone and shale units. These are some characteristics of the Anambra and Niger-Delta Basins. The entire geoelectric sections show lithology of varying composition based on their resistivity attributes.

Furthermore, the results of the VES interpretations within the study area reveal that in Alluvium terrain, the sixth layers are delineated as mainly water saturated dry sands (prospective aquifer units) with its thickness and resistivity values range between 22.29 – 28.71m and 600.07 – 886.43Ωm respectively. However, at the Benin Formation, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 276.08 - 1331.11Ωm and 30.45 - 64.75m across the area. For Ogwashi Formation, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 23.09 - 4196.26Ωm and 21.77 - 58.38m across the area. For Amerki Formation), the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 1349.10 – 4620.14Ωm and 23.46 – 43.96m across the area. For Imo Shale, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 139.14 – 3048.71Ωm and 21.81 – 42.13m across the area.

For Nsukka Formation, the resistivity and thickness of the prospective aquifer layers (water saturated sand) range from 2470.51 – 5014Ωm and 23.02 – 35.42m across the area.

More so, the computed aquifer parameters for the overburden and aquifer of the interpreted VES data show that the values of various parameters range from low to high across the area: overlying layer resistivity (490.92 to 30641.01 Ohm-m); aquifer resistivity (276.08 to 8207.54 Ohm-m); aquifer thickness (18.73 - 64.75 Ohm-m); depth to aquifer values (36.76 – 253.26 m); longitudinal conductance (0.0030289 to 1.0364 mhom); transverse resistance (552.54 to 14003090.56 Ohm-m^2); conductivity (0.0001218 to 0.0433088mho);hydraulic conductivity (0.04392 to 15.61045959 m/day); transmissivity (1.0918 to 373.5583 m^2/day); erodibility (0.004904 - 114.8572 m/day); reflection coefficient (-0.8632 to 0.9983) and fractured contrast (0.000864 - 13.61448).

Two cross sections were taken at both the elevation and watertable level map at the study area namely: X-X^l and Y-Y^l profiles, which were superimposed in order to estimate the groundwater potential obtainable in the area. Here, it was observed that the watertable level follows the topography which implies that the topography controls the configuration of the groundwater. Also, the gap between the peak of topography and the average static water level in the area is 158m, while the depth of the peak elevation level and the static water level is 285m and 127m respectively. This implies that the vertical movement of any contaminant will be slowed by the earth materials thereby allowing physical (filtration), chemical and biochemical processes to remove contaminants before reaching the aquifer.

Finally, the availability of good water supply (possibly for domestic, agricultural and industrial uses) in conjunction with access to food supply is most of all the world greatest priority for man. As such, agriculture is a dominant component of the global economy.

5.2 Conclusions

This study reached the following conclusions:

1. The generated resistivity curve types show typical H-curves (namely; KH, HK, KHK, H and HKH) which are quite common in a sedimentary environment for multilayer structures.
    i. The results of the VES interpretations correlated well with nearby boreholes within the study area.
2. All the physical and chemical parameter results fall within the acceptable limit for drinking water and therefore, they are satisfactory for human consumption.
3. The result also shows that the watertable level follows the topography which implies that the topography controls the configuration of the groundwater.
4. The groundwater flow direction is NE-SW within the study area.
5. The groundwater model across the study area shows that the eastern and western parts of the study area which include Ebenebe, Okpeze, Oroma-Etiti, Ukpor, Ihiala, Okija, Oguaniocha, Ossomala and others possess deeper depth to the aquifer as such, the cost of siting borehole there will be variably high, compared with other areas.

5.3 Recommendations

1. It is recommended that continuous and regular monitoring of groundwater resources should be done and documented in the form of database for public use.

2. Groundwater protection policy and strategy should be emphasized through public awareness programs and training of water resources managers.

3. Further research on other parts of the State should be undertaken by relevant government agencies to provide holistic groundwater database

4. Caution should be applied in areas that have been classified as unsuitable for groundwater drilling, high erodibility index etc.

5.4 Contribution to Knowledge

1. The study provided detailed database of groundwater prospecting by using up to 207 VES points. The data base has the widest coverage of VES points for the State and will be veritable in decision making across the entire State.
2. The study successfully provided the soil erodibility map model based on the subsurface characteristics. This map will be essential in mapping erosion prone areas.
3. The relationship between apparent resistivity and hydraulic conductivity within the study area established statistical models. However, the model parameters were established for the first time in the study area.
4. A model map for siting of potential boreholes was generated for the study area.
5. This study was also able to develop a risk model map of groundwater resources for the study area.
6. This study will serve as a compendium on groundwater resources development in Anambra State.

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APPENDICES

Appendix **Page**

APPENDIX I

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled** ……………………
Location: Abo-Nnokwa **L.G.A** Idemili South **Riser Type** ……
Date of Sampling: 21/03/2018 **Date Tested:** 21/03/2018 **Date of Disinfection:** 06/06/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1^{ST} TEST**	**Disinfection Result**	**3^{RD} TEST**	**4^{TH} TEST**
1.	Appearance	Clear	Clear	-		
2.	Temperature ^{0}C	Ambient	Ambient	-		
3.	Colour (TCIJ)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	6.5-8.5	5.1	-		
2.	Conductivity uS/cm	1000	26.8	-		
3.	Total Dissolved solids mg/1	500	13.4	-		
4.	Salinity mg/1	500	Nil	-		
5	Chloride ($C1^-$) mg/1	250	Nil	-		
6	Carbonate ($CO^{2-}{}_3$)mg/l	500	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	500	14	-		
8	Total hardness mg/1	500	39	-		
9	Calcium (Ca^{2+}) mg/1	200	15	-		
10	Magnesium (Mg^{2+}) mg/1	250	24	-		
11	Potassium (K^+) mg/1	250	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	100	2.0	-		
13	Nitrite (NO_2^-) mg/1	0.2	0.02	-		
14	Nitrate (NO_3^{2-}) mg/1	50	3.1	-		
15	Iron (Fe^{2+}) mg/1	0.3	0.25	-		
16	Manganese (Mn^{2+}) mg/1	0.2	0.04	-		
17	Copper (Cu^{2+}) mg/1	1.0	-	-		
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.18		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	10	0	0		
2	Feacal Coli form /100ml H_20	0	0	0		

REMARKS

Disinfection result confirmed no coliform. pH is not within the acceptable limit but within the pH of underground water around the environment

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled …………………..**
Location: Central School Echemnankwo-Nnobi **L.G.A** Idemili South **Riser Type** ………
Date of Sampling: 12/02/2018 **Date Tested:** 12/02/2018 **Date of Disinfection:** 30/04/2018

	PHYSICAL. PARAMETERS	**NIG STD**	**1ST TEST**	**Disinfection Result**	**3RD TEST**	**4TH TEST**
1.	Appearance	Clear	Clear	-		
2.	Temperature ^{0}C	Ambient	Ambient	-		
3.	Colour (TCIJ)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS					
1.	pH	6.5-8.5	5.10			
2.	Conductivity uS/cm	1000	22.6	-		
3	Total Dissolved solids mg/1	500	11.4	-		
4.	Salinity mg/1	500	Nil	-		
5	Chloride ($C1^-$) mg/1	250	Nil	-		
6	Carbonate ($CO^{2-}{}_3$)mg/l	500	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	500	13	-		
8	Total hardness mg/1	500	23	-		
9	Calcium (Ca^{2+}) mg/1	200	6.0	-		
10	Magnesium (Mg^{2+}) mg/1	250	17	-		
11	Potassium (K^+) mg/1	250	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	100	3.0	-		
13	Nitrite (NO_2^-) mg/1	0.2	0.04	-		
14	Nitrate (NO_3^{2-}) mg/1	50	3.42	-		
15	Iron (Fe^{2+}) mg/1	0.3	0.20	-		
16	Manganese (Mn^{2+}) mg/1	0.2	0.02	-		
17	Copper (Cu^{2+}) mg/1	1.0	-	-		
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.22		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	**10**	13	0		
2	Feacal Coli form /100ml H_20	0	8	0		

REMARKS

Disinfection removed all coliforms and pH is not within the acceptable limit but within the pH of underground water in the environment

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled …………………..**

Location: Umuele Umudim Nnewi **L.G.A** Nnewi North **Riser Type ……………**

Date of Sampling: **Date Tested:** **Date of Disinfection:**

	PHYSICAL PARAMETERS	NIG STD	1^{ST} TEST	Disinfection Result	3^{RD} TEST	4^{TH} TEST
1.	Appearance	Clear	Clear	-		
2.	Temperature ^{0}C	Ambient	Ambient	-		
3.	Colour (TCIJ)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	6.5-8.5	5.1	-		
2.	Conductivity uS/cm	1000	30.6	-		
3.	Total Dissolved solids mg/1	500	15.3	-		
4.	Salinity mg/1	500	Nil	-		
5	Chloride ($C1^{-}$) mg/1	250	Nil	-		
6	Carbonate ($CO^{2-}{}_{3}$)mg/l	500	Nil	-		
7	Bicarbonate (HCO_3^{-}) mg/1	500	11	-		
8	Total hardness mg/1	500	19	-		
9	Calcium (Ca^{2+}) mg/1	200	13	-		
10	Magnesium (Mg^{2+}) mg/1	250	6.0	-		
11	Potassium (K^{+}) mg/1	250	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	100	Nil	-		
13	Nitrite (NO_2^{-}) mg/1	0.2	0.03	-		
14	Nitrate (NO_3^{2-}) mg/1	50	2.2	-		
15	Iron (Fe^{2+}) mg/1	0.3	0.2	-		
16	Manganese (Mn^{2+}) mg/1	0.2	0.01	-		
17	Copper (Cu^{2+}) mg/1	1.0	-	-		
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.23		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	10	0	0		
2	Feacal Coli form /100ml H_20	0	0	0		

REMARKS

Disinfection result confirmed no coliform. pH is not within the acceptable limit but within the pH of underground water around the environment

WATER ANALYSIS RESULT

Water Source: Borehole ____________________ *Date Drilled ……………………………*

Location: Umunono Community-Igboukwu L.G.A Aguata **Riser Type …………**

Date of Sampling: **27/02/2018** Date Tested: **27/02/2018** Date of Disinfection: **24/04/2018**

	PHYSICAL PARAMETERS	NIG STD	1^{ST} TEST	Disinfection Result	3^{RD} TEST	4^{TH} TEST
1.	Appearance	**Clear**	Clear	-		
2.	Temperature ^{0}C	**Ambient**	Ambient	-		
3.	Colour (TCIJ)	**15**	Nil	-		
4.	Turbidity (NTU)	**5**	Nil	-		
5	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	**6.5-8.5**	5.11	-		
2.	Conductivity uS/cm	**1000**	26.4	-		
3.	Total Dissolved solids mg/1	**500**	13.2	-		
4.	Salinity mg/1	**500**	Nil	-		
5	Chloride ($C1^{-}$) mg/1	**250**	Nil	-		
6	Carbonate ($CO^{2-}{}_{3}$)mg/l	**500**	Nil	-		
7	Bicarbonate (HCO_3^{-}) mg/1	**500**	11	-		
8	Total hardness mg/1	**500**	17	-		
9	Calcium (Ca^{2+}) mg/1	**200**	9.0	-		
10	Magnesium (Mg^{2+}) mg/1	**250**	8.0	-		
11	Potassium (K^{+}) mg/1	**250**	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	**100**	Nil	-		
13	Nitrite (NO_2^{-}) mg/1	**0.2**	0.03	-		
14	Nitrate (NO_3^{2-}) mg/1	**50**	2.2	-		
15	Iron (Fe^{2+}) mg/1	**0.3**	0.1	-		
16	Manganese (Mn^{2+}) mg/1	**0.2**	0.02	-		
17	Copper (Cu^{2+}) mg/1	**1.0**	-	-		
18	Residual Chlorine (CI_2) mg/1	**0.25**	-	0.23		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	**10**	16	0		
2	Feacal Coli form /100ml H_20	**0**	5	0		

REMARKS

Disinfection result shows no coliform. pH is not within the acceptable limit but within the pH common in the underground water around the environment

WATER ANALYSIS RESULT

Water Source: **Borehole** **Date Drilled…………………**
Location: Ugwuakwu-Umuchu L.G.A Aguata **Riser Type …………….**
Date of Sampling: 14/02/2018 **Date Tested:** 14/02/2018 **Date of Disinfection:** 23/05/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1^{ST} TEST**	**Disinfection Result**	**3^{RD} TEST**	**4^{TH} TEST**
1.	Appearance	**Clear**	Clear	-		
2.	Temperature ^{0}C	**Ambient**	Ambient	-		
3.	Colour (TCIJ)	**15**	Nil	-		
4.	Turbidity (NTU)	**5**	Nil	-		
5	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	**6.5-8.5**	4.9	-		
2.	Conductivity uS/cm	**1000**	21.2	-		
3.	Total Dissolved solids mg/1	**500**	10.6	-		
4.	Salinity mg/1	**500**	Nil	-		
5	Chloride ($C1^-$) mg/1	**250**	Nil	-		
6	Carbonate ($CO^{2-}{}_3$)mg/l	**500**	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	**500**	8.0	-		
8	Total hardness mg/1	**500**	18	-		
9	Calcium (Ca^{2+}) mg/1	**200**	12	-		
10	Magnesium (Mg^{2+}) mg/1	**250**	6.0	-		
11	Potassium (K^+) mg/1	**250**	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	**100**	Nil	-		
13	Nitrite (NO_2^-) mg/1	**0.2**	Nil	-		
14	Nitrate (NO_3^{2-}) mg/1	**50**	1.8	-		
15	Iron (Fe^{2+}) mg/1	**0.3**	0.01	-		
16	Manganese (Mn^{2+}) mg/1	**0.2**	Nil	-		
17	Copper (Cu^{2+}) mg/1	**1.0**	-	-		
18	Residual Chlorine (CI_2) mg/1	**0.25**	-	0.20		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	**10**		0		
2	Feacal Coli form /100ml H_20	**0**		0		

REMARKS

Water sample has acidic pH so not within the acceptable limit limit and disinfection ensured no bacterial contamination

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Eziama-Nnokwa **L.G.A** Idemili South **Riser Type …..…**
Date of Sampling: 03/03/2018 **Date Tested:** 03/05/2018 **Date of Disinfection:** 06/06/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1^{ST} TEST**	**Disinfection Result**	**3^{RD} TEST**	**4^{TH} TEST**
1.	Appearance	Clear	Clear	-		
2.	Temperature ^0C	Ambient	Ambient	-		
3.	Colour (TCIJ)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	6.5-8.5	7.36	-		
2.	Conductivity uS/cm	1000	22.4	-		
3.	Total Dissolved solids mg/1	500	11.2	-		
4.	Salinity mg/1	500	Nil	-		
5	Chloride ($C1^-$) mg/1	250	Nil	-		
6	Carbonate ($CO^{2-}{}_3$)mg/l	500	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	500	117	-		
8	Total hardness mg/1	500	29	-		
9	Calcium (Ca^{2+}) mg/1	200	12	-		
10	Magnesium (Mg^{2+}) mg/1	250	17	-		
11	Potassium (K^+) mg/1	250	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	100	3.0	-		
13	Nitrite (NO_2^-) mg/1	0.2	0.03	-		
14	Nitrate (NO_3^{2-}) mg/1	50	1.9	-		
15	Iron (Fe^{2+}) mg/1	0.3	0.05	-		
16	Manganese (Mn^{2+}) mg/1	0.2	Nil	-		
17	Copper (Cu^{2+}) mg/1	1.0	-	-		
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.25		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	10	0	0		
2	Feacal Coli form /100ml H_20	0	0	0		

REMARKS

Satisfactory analysis result and disinfection ensured no bacterial contamination.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Eziama-Nnokwa **L.G.A** Idemili South **Riser Type …..…**
Date of Sampling: 03/03/2018 **Date Tested:** 03/05/2018 **Date of Disinfection:** 06/06/2018

	PHYSICAL PARAMETERS	NIG STD	1^{ST} TEST	Disinfection Result	3^{RD} TEST	4^{TH} TEST
1.	Appearance	Clear	Clear	-		
2.	Temperature ^{0}C	Ambient	Ambient	-		
3.	Colour (TCIJ)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	6.5-8.5	7.36	-		
2.	Conductivity uS/cm	1000	22.4	-		
3.	Total Dissolved solids mg/1	500	11.2	-		
4.	Salinity mg/1	500	Nil	-		
5	Chloride ($C1^-$) mg/1	250	Nil	-		
6	Carbonate ($CO^{2-}{}_3$)mg/l	500	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	500	117	-		
8	Total hardness mg/1	500	29	-		
9	Calcium (Ca^{2+}) mg/1	200	12	-		
10	Magnesium (Mg^{2+}) mg/1	250	17	-		
11	Potassium (K^+) mg/1	250	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	100	3.0	-		
13	Nitrite (NO_2^-) mg/1	0.2	0.03	-		
14	Nitrate (NO_3^{2-}) mg/1	50	1.9	-		
15	Iron (Fe^{2+}) mg/1	0.3	0.05	-		
16	Manganese (Mn^{2+}) mg/1	0.2	Nil	-		
17	Copper (Cu^{2+}) mg/1	1.0	-	-		
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.25		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	10	0	0		
2	Feacal Coli form /100ml H_20	0	0	0		

REMARKS

Satisfactory analysis result and disinfection ensured no bacterial contamination.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Eziogwugwu Otolo **L.G.A** Nnewi North **Riser Type …..…**
Date of Sampling: 19/03/2018 **Date Tested:** 19/03/2018 **Date of Disinfection:** 11/07/2018

	PHYSICAL PARAMETERS	NIG STD	1^{ST} TEST	Disinfection Result	3^{RD} TEST	4^{TH} TEST
1.	Appearance	Clear	Clear	-		
2.	Temperature ^{0}C	Ambient	Ambient	-		
3.	Colour (TCIJ)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	6.5-8.5	4.82	-		
2.	Conductivity uS/cm	1000	17.3	-		
3.	Total Dissolved solids mg/1	500	8.6	-		
4.	Salinity mg/1	500	Nil	-		
5	Chloride ($C1^-$) mg/1	250	Nil	-		
6	Carbonate ($CO^{2-}{}_3$)mg/l	500	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	500	6.0	-		
8	Total hardness mg/1	500	27	-		
9	Calcium (Ca^{2+}) mg/1	200	10	-		
10	Magnesium (Mg^{2+}) mg/1	250	17	-		
11	Potassium (K^+) mg/1	250	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	100	1.0	-		
13	Nitrite (NO_2^-) mg/1	0.2	Nil	-		
14	Nitrate (NO_3^{2-}) mg/1	50	1.8	-		
15	Iron (Fe^{2+}) mg/1	0.3	0.04	-		
16	Manganese (Mn^{2+}) mg/1	0.2	Nil	-		
17	Copper (Cu^{2+}) mg/1	1.0	-	-		
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.24		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	10	0	0		
2	Feacal Coli form /100ml H_20	0	0	0		

REMARKS

Disinfection removed feacal coliform present. pH is not within the acceptable limit and outside that common in the underground water within the environment

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**

Location: Umueziama/Umucheke Oka-Uga **L.G.A** Aguata **Riser Type …..…**

Date of Sampling: 14/03/2018 **Date Tested:** 14/03/2018 **Date of Disinfection:** 30/04/2018

	PHYSICAL PARAMETERS	NIG STD	1^{ST} TEST	Disinfection Result	3^{RD} TEST	4^{TH} TEST
1.	Appearance	Clear	Clear	-		
2.	Temperature ^0C	Ambient	Ambient	-		
3.	Colour (TCIJ)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	6.5-8.5	6.28	-		
2.	Conductivity uS/cm	1000	16.8	-		
3.	Total Dissolved solids mg/1	500	8.4	-		
4.	Salinity mg/1	500	Nil	-		
5	Chloride ($C1^-$) mg/1	250	Nil	-		
6	Carbonate ($CO^{2-}{}_3$)mg/l	500	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	500	9.0	-		
8	Total hardness mg/1	500	30	-		
9	Calcium (Ca^{2+}) mg/1	200	8.0	-		
10	Magnesium (Mg^{2+}) mg/1	250	22	-		
11	Potassium (K^+) mg/1	250	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	100	Nil	-		
13	Nitrite (NO_2^-) mg/1	0.2	0.01	-		
14	Nitrate (NO_3^{2-}) mg/1	50	1.48	-		
15	Iron (Fe^{2+}) mg/1	0.3	0.01	-		
16	Manganese (Mn^{2+}) mg/1	0.2	Nil	-		
17	Copper (Cu^{2+}) mg/1	1.0	-	-		
18	Residual Chlorine (CI_2) mg/1	0.25	-	0.20		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	10	0	0		
2	Feacal Coli form /100ml H_20	0	0	0		

REMARKS

Satisfactory Result.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Umumocha Awka-Etiti **L.G.A** Idemili South **Riser Type …..…**
Date of Sampling: 02/03/2018 **Date Tested:** 02/03/2018 **Date of Disinfection:** 10/05/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1^{ST} TEST**	**Disinfection Result**	**3^{RD} TEST**	**4^{TH} TEST**
1.	Appearance	**Clear**	Clear	-		
2.	Temperature ^{0}C	**Ambient**	Ambient	-		
3.	Colour (TCIJ)	**15**	Nil	-		
4.	Turbidity (NTU)	**5**	Nil	-		
5	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	**6.5-8.5**	5.18	-		
2.	Conductivity uS/cm	**1000**	27	-		
3.	Total Dissolved solids mg/1	**500**	13.5	-		
4.	Salinity mg/1	**500**	Nil	-		
5	Chloride ($C1^{-}$) mg/1	**250**	Nil	-		
6	Carbonate (CO^{2-}_{3})mg/l	**500**	Nil	-		
7	Bicarbonate (HCO_3^{-}) mg/1	**500**	11	-		
8	Total hardness mg/1	**500**	17	-		
9	Calcium (Ca^{2+}) mg/1	**200**	10	-		
10	Magnesium (Mg^{2+}) mg/1	**250**	7.0	-		
11	Potassium (K^{+}) mg/1	**250**	-	-		
12	Sulphate ($SO4^{2-}$) mg/1	**100**	Nil	-		
13	Nitrite (NO_2^{-}) mg/1	**0.2**	0.01	-		
14	Nitrate (NO_3^{2-}) mg/1	**50**	1.8	-		
15	Iron (Fe^{2+}) mg/1	**0.3**	0.07	-		
16	Manganese (Mn^{2+}) mg/1	**0.2**	Nil	-		
17	Copper (Cu^{2+}) mg/1	**1.0**	-	-		
18	Residual Chlorine (CI_2) mg/1	**0.25**	-	0.20		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	**10**	0	0		
2	Feacal Coli form /100ml H_20	**0**	0	0		

REMARKS

Disinfection result confirmed no coliform. pH is not within the acceptable limit but within the pH of underground water around the environment.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Nnaku Community-Nnokwa **L.G.A** Idemili South **Riser Type …..…**
Date of Sampling: 07/02/2018 **Date Tested:** 07/02/2018 **Date of Disinfection:** 28/03/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1^{ST} TEST**	**Disinfection Result**	**3^{RD} TEST**	**4^{TH} TEST**
1.	Appearance	**Clear**	Clear	-		
2.	Temperature ^0C	**Ambient**	Ambient	-		
3.	Colour (TCIJ)	**15**	Nil	-		
4.	Turbidity (NTU)	**5**	Nil	-		
5	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS		.			
1.	pH	**6.5-8.5**	5.07	-		
2.	Conductivity uS/cm	**1000**	25.2	-		
3.	Total Dissolved solids mg/1	**500**	12.6	-		
4.	Salinity mg/1	**500**	Nil	-		
5	Chloride ($C1^-$) mg/1	**250**	Nil	-		
6	Carbonate (CO^{2-}_3)mg/l	**500**	Nil	-		
7	Bicarbonate (HCO_3^-) mg/1	**500**	10	-		
8	Total hardness mg/1	**500**	25	-		
9	Calcium (Ca^{2+}) mg/1	**200**	9.0	-		
10	Magnesium (Mg^{2+}) mg/1	**250**	16	-		
11	Potassium (K^+) mg/1	**250**	Nil	-		
12	Sulphate ($SO4^{2-}$) mg/1	**100**	Nil	-		
13	Nitrite (NO_2^-) mg/1	**0.2**	Nil	-		
14	Nitrate (NO_3^{2-}) mg/1	**50**	1.2	-		
15	Iron (Fe^{2+}) mg/1	**0.3**	0.02	-		
16	Manganese (Mn^{2+}) mg/1	**0.2**	Nil	-		
17	Copper (Cu^{2+}) mg/1	**1.0**	-	-		
18	Residual Chlorine (CI_2) mg/1	**0.25**	-	0.20		
	BACTERIOLOGICAL PARAMETERS					
1	Total Coli form / 100 ml H_20	**10**	0	0		
2	Feacal Coli form /100ml H_20	**0**	0	0		

REMARKS

Disinfection shows no coliform. pH is not within the acceptable limit but within the pH of underground water around the environment.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Umudunu Awka-Etiti **L.G.A** Idemili South **Riser Type ……..…**
Date of Sampling: 22/02/2018 **Date Tested:** 22/02/2018 **Date of Disinfection:** 09/05/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1ST TEST**	**Disinfection Result**	**3RD TEST**	**4TH TEST**
1.	Appearance	Clear	Clear	-		
2.	Temperature ^0C	Ambient	Ambient	-		
3.	Colour (TCU)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5.	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS					
1.	pH	6.5-8.5	5.09	-		
2.	Conductivity uS/cm	1000	26.2	-		
3.	Total Dissolved solids mg/l	500	13.1	-		
4.	Salinity mg/l	500	Nil	-		
5.	Chloride (CT) mg/l	250	Nil	-		
6.	Carbonate ($CO^{2-}{}_3$) mg/l	500	Nil	-		
7.	Bicarbonate (HCO_3^-)mg/l	500	13	-		
8.	Total hardness mg/l	500	20	-		
9.	Calcium (Ca^{2+})mg/l	200	10	-		
10.	Magnesium (Mg^{2+})mg/l	250	10	-		
11.	Potassium (K^+)mg/l	250	-	-		
12.	Sulphate (SO_4^{2-})mg/l	100	3.0	-		
13.	Nitrite (NO_2^-)mg/l	0.2	0.03	-		
14.	Nitrate (NO_3^{2-})mg/l	50	2.4	-		
15.	Iron (Fe^{2+})mg/l	0.3	0.08	-		
16.	Manganese (Mn^{2+})mg/l	0.2	0.01	-		
17.	Copper (Cu^{2+})mg/l	1.0	-	-		
18.	Residual Chlorine (CI_2)mg/l	0.25	-	0.19		
	BACTERIOLOGICAL PARAMETERS					
1.	Total Coli form/100ml H_20	10	0	0		
2.	Feacal Coli form/100ml H_20	0	0	0		

REMARKS

Disinfection result confirmed no coliform. pH is not within the acceptable limit but within the pH of underground water around the environment.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Ofolagbom Nnobi **L.G.A** Idemili South **Riser Type ……..…**
Date of Sampling: 08/02/2018 **Date Tested:** 08/02/2018 **Date of Disinfection:** 09/05/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1ST TEST**	**Disinfection Result**	**3RD TEST**	**4TH TEST**
1.	Appearance	Clear	Clear	-		
2.	Temperature ^{0}C	Ambient	Ambient	-		
3.	Colour (TCU)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5.	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS					
1.	pH	6.5-8.5	5.24	-		
2.	Conductivity uS/cm	1000	31.6	-		
3.	Total Dissolved solids mg/l	500	15.8	-		
4.	Salinity mg/l	500	Nil	-		
5.	Chloride (CT) mg/l	250	Nil	-		
6.	Carbonate ($CO^{2-}{}_3$) mg/l	500	Nil	-		
7.	Bicarbonate (HCO_3^-)mg/l	500	15	-		
8.	Total hardness mg/l	500	23	-		
9.	Calcium (Ca^{2+})mg/l	200	8	-		
10.	Magnesium (Mg^{2+})mg/l	250	15	-		
11.	Potassium (K^+)mg/l	250	-	-		
12.	Sulphate (SO_4^{2-})mg/l	100	4	-		
13.	Nitrite (NO_2^-)mg/l	0.2	0.02	-		
14.	Nitrate (NO_3^{2-})mg/l	50	3.2	-		
15.	Iron (Fe^{2+})mg/l	0.3	0.28	-		
16.	Manganese (Mn^{2+})mg/l	0.2	0.04	-		
17.	Copper (Cu^{2+})mg/l	1.0	-	-		
18.	Residual Chlorine (CI_2)mg/l	0.25	-	0.2 1		
	BACTERIOLOGICAL PARAMETERS					
1.	Total Coli form/100ml H_20	10	0	0		
2.	Feacal Coli form/100ml H_20	0	0	0		

REMARKS

Disinfection result confirmed no coliform. pH is not within the acceptable limit but within the pH of underground water around the environment.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Ofolagbom Nnobi **L.G.A** Idemili South **Riser Type ……..…**
Date of Sampling: 08/02/2018 **Date Tested:** 08/02/2018 **Date of Disinfection:** 09/05/2018

	PHYSICAL PARAMETERS	**NIG STD**	**1ST TEST**	**Disinfection Result**	**3RD TEST**	**4TH TEST**
1.	Appearance	Clear	Clear	-		
2.	Temperature ^{0}C	Ambient	Ambient	-		
3.	Colour (TCU)	15	Nil	-		
4.	Turbidity (NTU)	5	Nil	-		
5.	Odour	Nil	Nil	-		
	CHEMICAL PARAMETERS					
1.	pH	6.5-8.5	6.05	-		
2.	Conductivity uS/cm	1000	61.3	-		
3.	Total Dissolved solids mg/l	500	15.8	-		
4.	Salinity mg/l	500	Nil	-		
5.	Chloride (CT) mg/l	250	Nil	-		
6.	Carbonate ($CO^{2-}{}_3$) mg/l	500	Nil	-		
7.	Bicarbonate (HCO_3^-)mg/l	500	30	-		
8.	Total hardness mg/l	500	26	-		
9.	Calcium (Ca^{2+})mg/l	200	10	-		
10.	Magnesium (Mg^{2+})mg/l	250	16	-		
11.	Potassium (K^+)mg/l	250	-	-		
12.	Sulphate (SO_4^{2-})mg/l	100	7.0	-		
13.	Nitrite (NO_2^-)mg/l	0.2	0.02	-		
14.	Nitrate (NO_3^{2-})mg/l	50	1.34	-		
15.	Iron (Fe^{2+})mg/l	0.3	0.22	-		
16.	Manganese (Mn^{2+})mg/l	0.2	0.01	-		
17.	Copper (Cu^{2+})mg/l	1.0	-	-		
18.	Residual Chlorine (CI_2)mg/l	0.25	-	0.23		
	BACTERIOLOGICAL PARAMETERS					
1.	Total Coli form/100ml H_20	10	0	0		
2.	Feacal Coli form/100ml H_20	0	0	0		

REMARKS

Disinfection removed feacal coliform present. pH is not within the acceptable limit but within the pH of underground water around the environment.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**

Location: **Okpodo-Ifite Aguleri** L.G.A **Anambra East** Riser Type ……..…

Date of Sampling: **27/01/2018** Date Tested: **27/01/2018** Date of Disinfection: **23/05/2018**

	PHYSICAL PARAMETERS	**NIG STD**	**1ST TEST**	**Disinfection Result**	**3RD TEST**	**4TH TEST**
1.	Appearance	**Clear**	Clear	-		
2.	Temperature ^{0}C	**Ambient**	Ambient	-		
3.	Colour (TCU)	**15**	Nil	-		
4.	Turbidity (NTU)	**5**	Nil	-		
5.	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS					
1.	pH	**6.5-8.5**	5.58	-		
2.	Conductivity uS/cm	**1000**	45.1	-		
3.	Total Dissolved solids mg/l	**500**	22.6	-		
4.	Salinity mg/l	**500**	Nil	-		
5.	Chloride (CT) mg/l	**250**	Nil	-		
6.	Carbonate ($CO^{2-}{}_3$) mg/l	**500**	Nil	-		
7.	Bicarbonate (HCO_3^-)mg/l	**500**	18	-		
8.	Total hardness mg/l	**500**	27	-		
9.	Calcium (Ca^{2+})mg/l	**200**	13	-		
10.	Magnesium (Mg^{2+})mg/l	**250**	14	-		
11.	Potassium (K^+)mg/l	**250**	1.0	-		
12.	Sulphate (SO_4^{2-})mg/l	**100**	Nil	-		
13.	Nitrite (NO_2^-)mg/l	**0.2**	Nil	-		
14.	Nitrate (NO_3^{2-})mg/l	**50**	2.2	-		
15.	Iron (Fe^{2+})mg/l	**0.3**	0.35	-		
16.	Manganese (Mn^{2+})mg/l	**0.2**	0.02	-		
17.	Copper (Cu^{2+})mg/l	**1.0**	-	-		
18.	Residual Chlorine (CI_2)mg/l	**0.25**	-	0.19		
	BACTERIOLOGICAL PARAMETERS					
1.	Total Coli form/100ml H_20	**10**	0	0		
2.	Feacal Coli form/100ml H_20	**0**	0	0		

REMARKS

Water sample has colour and this might be as a result of the iron content above the acceptable limit. The pH is also above the acceptable limit but within the range common in the environment.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: Ngogwugwu Ojoto **L.G.A** Idemili South **Riser Type** ……..…
Date of Sampling: **27/01/2018** Date Tested: **27/01/2018** Date of Disinfection: **23/05/2018**

	PHYSICAL PARAMETERS	**NIG STD**	**1ST TEST**	**Disinfection Result**	**3RD TEST**	**4TH TEST**
1.	Appearance	**Clear**	Clear	-		
2.	Temperature ^{0}C	**Ambient**	Ambient	-		
3.	Colour (TCU)	**15**	Nil	-		
4.	Turbidity (NTU)	**5**	Nil	-		
5.	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS					
1.	pH	**6.5-8.5**	5.37	-		
2.	Conductivity uS/cm	**1000**	40.8	-		
3.	Total Dissolved solids mg/l	**500**	20.2	-		
4.	Salinity mg/l	**500**	Nil	-		
5.	Chloride (CT) mg/l	**250**	Nil	-		
6.	Carbonate ($CO^{2-}{}_3$) mg/l	**500**	Nil	-		
7.	Bicarbonate (HCO_3^-)mg/l	**500**	38	-		
8.	Total hardness mg/l	**500**	18	-		
9.	Calcium (Ca^{2+})mg/l	**200**	9.0	-		
10.	Magnesium (Mg^{2+})mg/l	**250**	9.0	-		
11.	Potassium (K^+)mg/l	**250**	-	-		
12.	Sulphate (SO_4^{2-})mg/l	**100**	2.0	-		
13.	Nitrite (NO_2^-)mg/l	**0.2**	0.04	-		
14.	Nitrate (NO_3^{2-})mg/l	**50**	3.2	-		
15.	Iron (Fe^{2+})mg/l	**0.3**	0.15	-		
16.	Manganese (Mn^{2+})mg/l	**0.2**	0.02	-		
17.	Copper (Cu^{2+})mg/l	**1.0**	-	-		
18.	Residual Chlorine (CI_2)mg/l	**0.25**	-	0.20		
	BACTERIOLOGICAL PARAMETERS					
1.	Total Coli form/100ml H_20	**10**	0	0		
2.	Feacal Coli form/100ml H_20	**0**	0	0		

REMARKS

Disinfection result confirmed no coliform. pH is not within the acceptable limit but within the pH of underground water around the environment.

WATER ANALYSIS RESULT

Water Source: Borehole **Date Drilled ……………………**
Location: **Okpunoeze 1 Uruagu** L.G.A: **Nnewi North** Riser Type ……..…
Date of Sampling: **15/03/2018** Date Tested: **15/03/2018** Date of Disinfection: **04/07/2018**

	PHYSICAL PARAMETERS	**NIG STD**	**1ST TEST**	**Disinfection Result**	**3RD TEST**	**4TH TEST**
1.	Appearance	**Clear**	Clear	-		
2.	Temperature ^{0}C	**Ambient**	Ambient	-		
3.	Colour (TCU)	**15**	Nil	-		
4.	Turbidity (NTU)	**5**	Nil	-		
5.	Odour	**Nil**	Nil	-		
	CHEMICAL PARAMETERS					
1.	pH	**6.5-8.5**	5.37	**-**		
2.	Conductivity uS/cm	**1000**	40.8	**-**		
3.	Total Dissolved solids mg/l	**500**	20.2	**-**		
4.	Salinity mg/l	**500**	Nil	**-**		
5.	Chloride (CT) mg/l	**250**	Nil	**-**		
6.	Carbonate ($CO^{2-}{}_3$) mg/l	**500**	Nil	**-**		
7.	Bicarbonate (HCO_3^-)mg/l	**500**	38	**-**		
8.	Total hardness mg/l	**500**	18	**-**		
9.	Calcium (Ca^{2+})mg/l	**200**	9.0	**-**		
10.	Magnesium (Mg^{2+})mg/l	**250**	9.0	**-**		
11.	Potassium (K^+)mg/l	**250**	-	**-**		
12.	Sulphate (SO_4^{2-})mg/l	**100**	2.0	**-**		
13.	Nitrite (NO_2^-)mg/l	**0.2**	0.04	**-**		
14.	Nitrate (NO_3^{2-})mg/l	**50**	3.2	**-**		
15.	Iron (Fe^{2+})mg/l	**0.3**	0.15	**-**		
16.	Manganese (Mn^{2+})mg/l	**0.2**	0.02	**-**		
17.	Copper (Cu^{2+})mg/l	**1.0**	-	**-**		
18.	Residual Chlorine (CI_2)mg/l	**0.25**	-	0.20		
	BACTERIOLOGICAL PARAMETERS					
1.	Total Coli form/100ml H_20	**10**	0	0		
2.	Feacal Coli form/100ml H_20	**0**	0	0		

REMARKS

Disinfection result confirmed no coliform. pH is not within the acceptable limit **and outside that common in the** underground water around the environment.

APPENDIX II

Identified curve types within the study area

Curve Types	No of curve types	Percentage (%)
KH	27	13
HK	71	34.3
KHK	43	20.8
K	24	11.6
A	5	2.4
HK	2	1
HKH	3	1.4
Q	3	1.4
KA	8	3.9
QK	5	2.4
AK	16	7.8
	207	100

APPENDIX III

Detailed Baseline geo-electric Model Parameters for Different geological Formations

A. Detailed Baseline geo-electric model parameters for Alluvium Deposit

VES No. & Name	Layer	App. Res. (Ohm-m)	Thickness (m)	Depth (m)	Description
	1	222.09	2.01	2.01	Top soil
VES 1	2	508.11	12.11	14.12	Shally-sand
KH-Curve Type	3	1127.25	20.45	34.57	Sand
Oroma-Etiti-1	4	20.71	106.19	140.76	Shale
	5	1824.09	69.07	209.83	Dry sand
	6	886.43	28.7	238.53	Water saturated sand
	7	16.27	Base not reached		Shale
	1	197.32	4.77	4.77	Top soil
VES 2	2	356.47	15.88	20.65	Shally-sand
KH-Curve Type	3	982.05	25.31	45.96	Sand
Oroma-Etiti-2	4	17.71	105.07	151.03	Shale
	5	1336.08	59.44	210.47	Dry sand
	6	692.43	22.29	232.76	Water saturated sand
	7	10.11	Base not reached		Shale
	1	90.14	1.76	1.76	Top soil
VES 3	2	478.16	7	8.76	Shally-sand
KH-Curve Type	3	821.09	14.32	23.08	Sand

Umudora-Anam	4	29.19	115.84	138.92	Shale
	5	909.58	67.96	206.88	Dry sand
	6	600.07	28.71	235.59	Water saturated sand
	7	18.82	Base not reached		Shale
	1	89.91	1.91	1.91	Top soil
	2	453.06	6.32	8.23	Shally-sand
VES 4	3	927.07	10.8	19.03	Dry sand
KH-Curve Type	4	31.08	99.73	118.76	Shale
Umuikwu-Anam	5	882.08	87.36	206.12	Dry sand
	6	606.81	24.96	231.08	Water saturated sand
	7	18.91	Base not reached		Shale

B. Detailed Baseline geo-electric model parameters for Benin Formation

VES No. & Name	Layer	App. Res. (Ohm-m)	Thickness (m)	Depth (m)	Description
	1	287.32	1.86	1.86	Top soil
VES 5	2	134.07	20.2	22.06	Shally sand
HK-Curve Type	3	463.17	27.08	49.14	Sand
Atani	4	20.34	33.93	83.07	Shale
	5	518.976	31.99	115.06	Sand
	6	276.08	39.3	154.36	Water saturated sand
	7	39.25	Base not reached		Shale
	1	86.18	1.67	1.67	Top soil
VES 6	2	308.26	3.94	5.61	Shally-sand
KHK-Curve Type	3	50.77	13.14	18.75	Shale
Ogbakuba	4	386.04	29.93	48.68	Shally-sand
	5	1558.37	68.17	116.85	Dry sandstone
	6	890.66	48.22	165.07	Water saturated sand
	7	25.69	Base not reached		Shale
	1	79.06	1.79	1.79	Top soil
VES 7	2	377.08	3.76	5.55	Shally-sand
KHK-Curve Type	3	61.34	9.51	15.06	Shale
Umunakwo	4	449.11	30	45.06	Shally-sand
	5	1599.32	68.17	113.23	Dry sandstone
	6	926.11	46.54	159.77	Water saturated sand
	7	27.55	Base not reached		Shale
	1	44.76	1.85	1.85	Top soil/laterite
VES 8	2	301.42	4.03	5.88	Shally-sand
KHK-Curve Type	3	30.63	3.15	9.03	Shale
Osu-Akwa	4	1058.32	106.09	115.12	Dry sandstone
	5	729.73	54.21	169.33	Water saturated sand

	6	15.98	Base not reached		Shale
	1	99.05	1.74	1.74	Top soil
VES 9	2	498.11	15.14	16.88	Shally-sand
K-Curve Type	3	5066.21	96.06	112.94	Dry sandstone
Ossomala	4	1308.77	64.75	177.69	Water saturated sand
	5	28.57	Base not reached		Shale
	1	889.26	2.02	2.02	Top soil
VES 10	2	376.04	2.53	4.55	Shally-sand
HK-Curve Type	3	1600.01	4.99	9.54	Sand
Oguaniocha	4	33.29	9.37	18.91	Shale
	5	1913.07	93.75	112.66	Dry sand
	6	1008.01	36.45	149.11	Water saturated sand
	7	19.21	Base not reached		Shale
	1	699.07	2.22	2.22	Top soil
VES 11	2	266.12	2.85	5.07	Shally-sand
HK-Curve Type	3	2001.11	7.15	12.22	Sand
Okoti-Odekpe	4	40.24	10.96	23.18	Shale
	5	2187.06	87.7	110.88	Dry sand
	6	1331.11	30.45	141.33	Water saturated sand
	7	23.08	Base not reached		Shale

C. Detailed Baseline geo-electric model parameters for Ogwashi-Asaba Formation

VES No. & Name	Layer	App. Res. (Ohm-m)	Thickness (m)	Depth (m)	Description
	1	182.77	1.78	1.78	Top soil/laterite
VES 12	2	741.25	46.15	47.93	Clayey sand
K-Curve Type	3	2637.71	53.66	101.59	Dry sandstone
Onitsha-1	4	1519.45	46.84	148.43	Water saturated sand
	5	89.667	Base not reached		Shale
	1	191.08	2.53	2.53	Top soil/laterite
VES 13	2	988.12	47.5	50.03	Clayey sand
K-Curve Type	3	5016.37	41.52	91.55	Dry sandstone
Onitsha-2	4	2205.19	40.49	132.04	Water saturated sand
	5	49.03	Base not reached		Shale
	1	105.1	0.89	0.89	Top soil (Laterite)
VES 14	2	821.1	4.22	5.11	Dry Sandstone
A-Curve Type	3	329.9	7.56	12.67	Clayey sand
Ezele- Oba	4	10856	101.53	114.74	Dry Sandstone
	5	3666.01	36.14	150.88	Water saturated sandstone
	6	29.12	Base not reached		Shale
	1	480.7	0.8	0.8	Top soil (Laterite)
VES 15	2	226.1	2.31	3.11	Clayey sand
H-Curve Type	3	19830	85.29	88.4	Dry Sandstone

Ogwugwu-Oba	4	1538	32.9	121.3	Water saturated sandstone
	5	34980	Base not reached		Lignite
	1	362.5	0.78	0.78	Top soil (Laterite)
VES 16	2	525.7	4.02	4.8	Sandstone
K-Curve Type	3	409	5.94	10.74	Clayey sand
Okuzu-Oba	4	4256	42.86	53.6	Sandstone
	5	233.6	36.3	89.9	Water saturated sandstone
	6	149	Base not reached		Clayey sand
	1	45.2	1.56	1.56	Top soil (Laterite)
VES 17	2	15995	46.8	48.36	Sandstone
A-Curve Type	3	3887	42.76	91.12	Water saturated sandstone
Oraifite-1	4	36393	Base not reached		Lignite
	1	643.1	1.12	1.12	Top soil (Laterite)
VES 18	2	103.5	2.18	2.18	Clayey sand
H-Curve Type	3	9187	63	65.18	Dry Sandstone
Oraifite-2	4	3678	45.02	110.2	Water saturated sandstone
	5	22219	Base not reached		Lignite
	1	424.3	1.83	1.83	Top soil/laterite
VES 19	2	19.472	11.43	13.26	Shale
HK-Curve Type	3	11687	154.93	168.19	Dry sandstone
Nnewi Catholic Cath.	4	2611.3	43.89	212.08	Water saturated sand
	5	12.126	Base not reached		Shale
	1	700.12	3.22	3.22	Top soil/laterite
VES 20	2	31.01	14.84	18.06	Shale
HK-Curve Type	3	5077.89	98.13	116.19	Dry sandstone
Otolo-Nnewi	4	1893.41	35.92	152.11	Water saturated sand
	5	10.17	Base not reached		Shale
	1	1200.1	2.19	2.19	Top soil/laterite
VES 21	2	50.23	15.88	18.07	Shale
HK-Curve Type	3	20776.12	154.98	173.05	Dry sandstone
Oba-Nnewi	4	4196.26	38.31	211.36	Water saturated sand
	5	20.68	Base not reached		Shale
	1	1107.22	4.12	4.12	Top soil/laterite
S22	2	48.81	10.97	15.09	Shale
HKH-Curve Type	3	467.11	11.92	27.01	Sandy-clay
Ozubulu-1	4	17894.27	83.29	110.3	Dry sandstone
	5	3044.23	33.71	144.01	Water saturated sand
	6	588.93	13.76	157.77	Sandy-clay
	7	50366.12	Base not reached		Dry sandstone
	1	1566.07	5.54	5.54	Top soil/laterite
S23	2	37.98	16.87	22.41	Shale
HKH-Curve Type	3	708.11	13.35	35.76	Sandy-clay
Ozubulu-2	4	14769.27	73.22	108.98	Dry sandstone
	5	4118.16	32.1	141.08	Water saturated sand

	6	604.43	20.8	161.88	Sandy-clay
	7	29785.04	Base not reached		Dry sandstone
	1	100.23	4.08	4.08	Top soil
VES 24	2	298.66	9.14	13.22	Shally-sand
KH-Curve Type	3	32.19	12.5	25.72	Shale
Utuh-1	4	384.09	10.75	36.47	Shally-sand
	5	6832.12	147.65	184.12	Dry sandstone
	6	1907.68	30.05	214.17	Water saturated sand
	7	33.06	Base not reached		Shale
	1	169.4	3.89	3.89	Top soil/laterite
VES 25	2	420.81	12.32	16.21	Shally-sand
KH-Curve Type	3	33.22	14.32	30.53	Shale
Utuh-2	4	4530	152.44	182.97	Dry sandstone
	5	1490.8	28.66	211.63	Water saturated sand
	6	19.73	Base not reached		Shale
	1	219.441	4.23	4.23	Top soil/laterite
VES 26	2	181.1	9.64	13.87	Shally-sand/Clayey-sand
HK-Curve Type	3	14.51	13.9	27.77	Shale
Ihembosi	4	315.59	23.06	50.83	Shally-sand/Clayey-sand
	5	25523	105.29	156.12	Dry sandstone
	6	3169.9	22.92	179.04	Water saturated sand
	7	12.579	Base not reached		Shale
	1	265.08	3.88	3.88	Top soil/laterite
VES 27	2	26.49	11.16	15.04	Shale
HK-Curve Type	3	384.32	13.72	28.76	Shally-sand/Clayey-sand
Ukpor-1	4	26.09	10.42	39.18	Shale
	5	9171.32	146.88	186.06	Dry sandstone
	6	2347.01	31.44	217.5	Water saturated sand
	7	19.23	Base not reached		Shale
	1	401.31	5.26	5.26	Top soil/laterite
VES 28	2	31.04	12.85	18.11	Shale
HK-Curve Type	3	306.07	12.97	31.08	Shally-sand/Clayey-sand
Ukpor-2	4	21.36	9.6	40.68	Shale
	5	7666.11	149.56	190.24	Dry sandstone
	6	2173.08	21.77	212.01	Water saturated sand
	7	26.05	Base not reached		Shale
	1	3221	4.22	4.22	Top soil (Latrite)
VES 29	2	66.01	13.9	18.12	Shale
KH-Curve Type	3	467.84	9.62	27.74	Clayey Sand
Okija-1	4	14271.32	135.51	163.25	Dry sandstone
	5	4063.06	30.82	194.07	Water saturated sandstone
	6	15.07	Base not reached		Shale
	1	4658	5.67	5.67	Top soil (Laterite)
VES 30	2	63.5	18.16	23.83	Shale
HK-Curve Type	3	437.08	5.1	28.93	Clayey Sand
Okija-2	4	9486.04	138.51	167.44	Dry sandstone

	5	2280.81	22.19	189.63	Water saturated sandstone
	6	23.05	Base not reached		Shale
	1	998.68	5.54	5.54	Top soil/laterite
VES 31	2	19.07	16.87	22.41	Shale
HKH-Curve Type	3	358.02	13.35	35.76	Clayey Sand
Azia-1	4	8341.02	105.32	141.08	Dry sandstone
	5	2580.06	30.8	171.88	Water saturated sand
	6	550.06	Base not reached		Shale
	1	1007.23	4.08	4.08	Top soil
VES 32	2	158.08	9.14	13.22	Shally-sand
HK-Curve Type	3	22.33	12.5	25.72	Shale
Azia-2	4	266.65	10.75	36.47	Shally-sand
	5	9206.08	107.65	144.12	Dry sandstone
	6	2683.68	42.05	186.17	Water saturated sand
	7	23.72	Base not reached		Shale
	1	18552	4.93	4.93	Top soil (Laterite)
VES 33	2	566.7	13.9	18.83	Clayey Sand
HK-Curve Type	3	3876.9	14.66	33.49	Sandstone
Orsumoghu-1	4	1099.2	6.65	40.14	Clayey Sand
	5	30403	118.92	159.06	Dry sandstone
	6	863.8	34.48	193.54	Water saturated sand
	7	13.78	Base not reached		Shale
	1	205.8	3.95	3.95	Top soil (Laterite)
VES 34	2	39139	11.06	15.01	Sandstone
KH-Curve Type	3	3477.5	19.72	34.73	Clayey Sand
Orsumoghu-2	4	24777	122.68	157.41	Dry sandstone
	5	4451.8	28.68	186.09	Water saturated sand
	6	42.69	Base not reached		Shale
	1	1116	3.97	3.97	Top soil (Laterite)
VES 35	2	4389	16.06	20.03	Sandstone
KH-Curve Type	3	126.8	8.91	28.94	Clayey Sand
Ihite-Ihiala	4	2868	139.3	168.24	Dry sandstone
	5	2411	34.83	203.07	Water saturated sandstone
	6	39.81	Base not reached		Shale
	1	410.3	5.11	5.11	Top soil (Laterite)
VES 36	2	14117	18.02	23.13	Sandstone
KH-Curve Type	3	1744.5	12.26	35.39	Clayey Sand
Ihiala-2	4	14330	124.25	159.64	Dry sandstone
	5	3523.7	29.43	189.07	Water saturated sandstone
	6	20.89	Base not reached		Shale
	1	18552	4.42	4.42	Top soil (Laterite)
VES 37	2	566.7	7.34	11.76	Clayey Sand
KH-Curve Type	3	3876.9	15.06	26.82	Sandstone
Ihiala-3	4	1099.2	10.35	37.17	Clayey Sand
	5	30403	125.36	162.53	Dry sandstone
	6	863.8	38.68	201.21	Water saturated sandstone

	7	13.86	Base not reached		Shale
	1	6130.8	3.76	3.76	Top soil (Laterite)
VES 38	2	607.94	18.58	22.34	Clayey Sand
KH-Curve Type	3	34783.08	95.89	118.23	Dry sandstone
Ubuluisizor-1	4	4960.07	58.38	176.61	Water saturated sandstone
	5	39.77	Base not reached		Shale
	1	1056.04	5.03	5.03	Top soil (Laterite)
VES 39	2	827.89	21.05	26.08	Clayey Sand
KH-Curve Type	3	26738.21	93.97	120.05	Dry Sandstone
Ubuluisizor-2	4	5082.08	56.02	176.07	Clayey Sand
	5	23.09	Base not reached		Water saturated sandstone
	1	1030.84	4.11	4.11	Top soil (Laterite)
VES 40	2	609.12	17.98	22.09	Clayey Sand
KH-Curve Type	3	17742.38	93.09	115.18	Dry Sandstone
Iseke-1	4	3703.06	42.88	158.06	Water saturated sandstone
	5	18.84	Base not reached		Shale
	1	1377.09	4.64	4.64	Top soil (Laterite)
VES 41	2	701.11	19.69	24.33	Clayey Sand
KH-Curve Type	3	16233.07	92.6	116.93	Dry Sandstone
Iseke-2	4	2874.22	31.88	148.81	Water saturated sandstone
	5	30.16	Base not reached		Shale

D. Detailed Baseline geo-electric model parameters for Ameki Formation (Nanka Sandstone)

VES No. & Name	Layer	App. Res. (Ohm-m)	Thickness (m)	Depth (m)	Description
	1	1036.15	4.62	4.62	Top soil (Laterite)
VES 42	2	57.12	29.47	34.09	Shale
HK-Curve Type	3	139.18	36.95	71.04	Clayey Sand
Umuekete-	4	490.92	10.07	81.11	Dry sandstone
Aguleri-1	5	284.8	25.51	106.62	Water saturated sandstone
	6	30.27	Base not reached		Shale
	1	124.53	3.79	3.79	Top soil (Laterite)
VES 43	2	3.84	15.76	19.55	Shale
KH-Curve Type	3	301.81	17.57	37.12	Clayey Sand
Umuawunu-	4	669.26	37.86	74.98	Dry sandstone
Aguleri-2	5	527.88	21.87	96.85	Water saturated sandstone
	6	41.65	Base not reached		Shale
	1	462.72	2.99	2.99	Top soil
VES 44	2	788.62	10.65	13.64	Clayey sand
K-Curve Type	3	1907.04	80.78	94.42	Dry sandstone
Umuleri-1	4	1311.08	55.12	149.54	Water saturated sand
	5	42.22	Base not reached		Shale

	1	399.11	3.72	3.72	Top soil
VES 45	2	815.52	11.05	14.77	Clayey sand
K-Curve Type	3	2076.07	83.19	97.96	Dry sandstone
Umuleri-2	4	1208.11	49.67	147.63	Water saturated sand
	5	36.24	Base not reached		Shale
	1	7420.46	3.55	3.55	Top soil/laterite
VES 46	2	3007.21	31.51	35.06	Dry sandstone
Q-Curve Type	3	208.01	35.05	70.11	Clayey sand
Nsugbe-1	4	3226.87	25.97	96.08	Dry sandstone
	5	980.11	34.48	130.56	Water saturated sand
	6	26.43	Base not reached		Shale
	1	10912.7	4.07	4.07	Top soil/laterite
VES 47	2	5208.44	36.06	40.13	Dry sandstone
Q-Curve Type	3	479.11	32.9	73.03	Clayey sand
Nsugbe-2	4	2980.87	28.02	101.05	Dry sandstone
	5	1044.9	40.51	141.56	Water saturated sand
	6	33.05	Base not reached		Shale
	1	8769.52	3.65	3.65	Top soil/laterite
VES 48	2	4893.08	33.64	37.29	Dry sandstone
Q-Curve Type	3	706.64	29.2	66.49	Clayey sand
Nsugbe-3	4	5011.83	30.38	96.87	Dry sandstone
	5	2356.73	28.18	125.05	Water saturated sand
	6	41.47	Base not reached		Shale
	1	802.11	3.06	3.06	Top soil/laterite
VES 49	2	1419.06	8.95	12.01	Dry sandstone
KH-Curve Type	3	509.06	11.87	23.88	Clayey sand
Nteje-1	4	5166.08	26.19	50.07	Dry sandstone
	5	2077.05	46.87	96.94	Water saturated sand
	6	19.76	Base not reached		Shale
	1	583.17	4.11	4.11	Top soil/laterite
VES 50	2	2085.06	10.32	14.43	Dry sandstone
KHK-Curve Type	3	600.11	6.66	21.09	Clayey sand
Nteje-2	4	4871.93	28.65	49.74	Dry sandstone
	5	1900.35	50.37	100.11	Water saturated sand
	6	28.08	Base not reached		Shale
	1	1500.11	4.13	4.13	Top soil/laterite
VES 51	2	48.64	46.05	50.18	Shale
KH-Curve Type	3	2156.77	16.9	67.08	Dry sandstone
Igbariam-1	4	1009.01	33.72	100.8	Water saturated sand
	5	26.66	Base not reached		Shale
	1	2020.79	5.21	5.21	Top soil/laterite
VES 52	2	34.17	35.86	41.07	Shale
KH-Curve Type	3	1900.61	27.69	68.76	Dry sandstone
Igbariam-2	4	970.41	26.43	95.19	Water saturated sand
	5	29.09	Base not reached		Shale
	1	1001.51	4.44	4.44	Top soil/laterite

VES 53	2	2331.09	11.77	16.21	Dry sandstone
KH-Curve Type	3	791.11	17.85	34.06	Clayey sand
Akwuzu-1	4	4476.3	38.43	72.49	Dry sandstone
	5	1912.6	21.45	93.94	Water saturated sand
	6	30.77	Base not reached		Shale
	1	811.23	3.93	3.93	Top soil/laterite
VES 54	2	3100.28	15.13	19.06	Dry sandstone
KHK-Curve Type	3	509.13	9.5	28.56	Clayey sand
Akwuzu-2	4	5008.8	50.65	79.21	Dry sandstone
	5	2311.03	22.82	102.03	Water saturated sand
	6	22.86	Base not reached		Shale
	1	501.76	3.76	3.76	Top soil/laterite
VES 55	2	709.03	26.32	30.08	Clayey sand
K-Curve Type	3	1429.11	19.8	49.88	Dry sandstone
Nkwelle-Ezunaka-1	4	864.26	46.25	96.13	Water saturated sand
	5	36.09	Base not reached		Shale
	1	491.08	4.03	4.03	Top soil/laterite
VES 56	2	594.36	22.82	26.85	Clayey sand
K-Curve Type	3	1882.34	31.06	57.91	Dry sandstone
Nkwelle-Ezunaka-2	4	995.11	45.31	103.22	Water saturated sand
	5	19.46	Base not reached		Shale
	1	498.76	3.26	3.26	Top soil/laterite
VES57	2	599.36	25.17	28.43	Clayey sand
K-Curve Type	3	1602.12	24.89	53.32	Dry sandstone
Nkwelle-Ezunaka-3	4	860.15	44.82	98.14	Water saturated sand
	5	35.01	Base not reached		Shale
	1	2306.07	3.09	3.09	Top soil/laterite
VES 58	2	4071.43	16.92	20.01	Dry sandstone
KH-Curve Type	3	885.08	17.33	37.34	Clayey sand
Umunya-1	4	6078.44	39.42	76.76	Dry sandstone
	5	2511.03	23.26	100.02	Water saturated sand
	6	23.86	Base not reached		Shale
	1	1869.03	4.11	4.11	Top soil/laterite
VES 59	2	3831.99	19.36	23.47	Dry sandstone
KH-Curve Type	3	809.84	17.12	40.59	Clayey sand
Umunya-2	4	5018.44	40.45	81.04	Dry sandstone
	5	2296.7	26.9	107.94	Water saturated sand
	6	27.06	Base not reached		Shale
	1	36.06	2.87	2.87	Top soil/laterite
VES 60	2	873.76	15.17	18.04	Sand
KH-Curve Type	3	28.05	23.71	41.75	Shale
Enugwu-Agidi-1	4	1176.38	79.51	121.26	Dry sandstone
	5	606.23	38.83	160.09	Water saturated sand

	6	19.15	Base not reached		Shale
	1	48.92	3.98	3.98	Top soil/laterite
VES 61	2	900.06	12.08	16.06	Sand
KH-Curve Type	3	40.22	23.55	39.61	Shale
Enugwu-Agidi-2	4	987.96	86.51	126.12	Dry sandstone
	5	579.42	33.42	159.54	Water saturated sand
	6	17.09	Base not reached		Shale
	1	29.76	2.88	2.88	Top soil/laterite
VES 62	2	893.76	11.16	14.04	Sand
KH-Curve Type	3	41.08	28.49	42.53	Shale
Enugwu-Agidi-3	4	997.66	95.62	138.15	Dry sandstone
	5	710.23	29.94	168.09	Water saturated sand
	6	16.08	Base not reached		Shale
	1	206.86	3.56	3.56	Top soil/laterite
VES 63	2	1200.93	10.35	13.91	Sand
KH-Curve Type	3	201.33	35.16	49.07	Clayey sand
Nawgu-1	4	2010.07	90.04	139.11	Dry sandstone
	5	782.33	36.98	176.09	Water saturated sand
	6	30.45	Base not reached		Shale
	1	279.61	4.06	4.06	Top soil/laterite
VES 64	2	1193.48	15.59	19.65	Sand
KH-Curve Type	3	253.35	25.4	45.05	Shale
Nawgu-2	4	1607.63	92.94	137.99	Dry sandstone
	5	848.23	30.46	168.45	Water saturated sand
	6	26.46	Base not reached		Shale
	1	860.22	4.23	4.23	Top soil/laterite
VES 65	2	1704.03	5.03	9.26	Dry sandstone
HK-Curve Type	3	248.11	8.81	18.07	Clayey sand
Nawfia-1	4	1970.41	73.76	91.83	Dry sandstone
	5	839.08	56.35	148.18	Water saturated sand
	6	25.21	Base not reached		Shale
	1	660.65	3.61	3.61	Top soil/laterite
VES 66	2	1467.22	7.01	10.62	Dry sandstone
HK-Curve Type	3	227.46	9.91	20.53	Clayey sand
Nawfia-2	4	2869.71	67.28	87.81	Dry sandstone
	5	1206.19	51.8	139.61	Water saturated sand
	6	31.08	Base not reached		Shale
	1	1706.31	4.05	4.05	Top soil/laterite
VES 67	2	43.65	7.03	11.08	Shale
HK-Curve Type	3	605.32	14.96	26.04	Clayey sand
Ukpo-1	4	8759.53	98.19	124.23	Dry sandstone
	5	2519.08	35.63	159.86	Water saturated sand
	6	27.21	Base not reached		Shale
	1	1609.11	3.72	3.72	Top soil/laterite
VES 68	2	31.08	10.49	14.21	Shale

HK-Curve Type	3	703.36	10.57	24.78	Clayey sand
Ukpo-2	4	9415.09	102.31	127.09	Dry sandstone
	5	3110.89	34.93	162.02	Water saturated sand
	6	28.92	Base not reached		Shale
	1	1078.62	3.06	3.06	Top soil/laterite
VES 69	2	1911.42	10.03	13.09	Dry sandstone
KHK-Curve Type	3	409.48	13.19	26.28	Clayey sand
Enugwu Ukwu-1	4	4319.78	81.94	108.22	Dry sandstone
	5	1608.49	37.82	146.04	Water saturated sand
	6	33.07	Base not reached		Shale
	1	2498.67	3.92	3.92	Top soil/laterite
VES 70	2	4001.47	6.7	10.62	Dry sandstone
KHK-Curve Type	3	628.25	17.66	28.28	Clayey sand
Enugwu Ukwu-2	4	6024.08	86.79	115.07	Dry sandstone
	5	2275.06	34.84	149.91	Water saturated sand
	6	50.32	Base not reached		Shale
	1	1359.86	4.44	4.44	Top soil/laterite
VES 71	2	3066.74	9.58	14.02	Dry sandstone
KHK-Curve Type	3	572.49	12.1	26.12	Clayey sand
Enugwu Ukwu-3	4	4489.87	85.63	111.75	Dry sandstone
	5	1732.06	41.26	153.01	Water saturated sand
	6	33.56	Base not reached		Shale
	1	1269.04	5.46	5.46	Top soil/laterite
VES 72	2	2289.06	9.62	15.08	Dry sandstone
KHK-Curve Type	3	502.76	13	28.08	Clayey sand
Nimo-1	4	5011.83	92.85	120.93	Dry sandstone
	5	1972.08	47.44	168.37	Water saturated sand
	6	27.16	Base not reached		Shale
	1	1611.38	4.48	4.48	Top soil/laterite
VES 73	2	3861.48	13.63	18.11	Dry sandstone
HK-Curve Type	3	601.74	11.9	30.01	Clayey sand
Nimo-2	4	4086.87	93.06	123.07	Dry sandstone
	5	2011.06	38.96	162.03	Water saturated sand
	6	28.52	Base not reached		Shale
	1	2002.69	6.04	6.04	Top soil/laterite
VES 74	2	5120.89	21.13	27.17	Dry sandstone
KHK-Curve Type	3	830.72	15.76	42.93	Clayey sand
Neni-1	4	7180.7	165.14	208.07	Dry sandstone
	5	2609.42	28.96	237.03	Water saturated sand
	6	39.08	Base not reached		Shale
	1	1871.11	5.48	5.48	Top soil/laterite
VES 75	2	2918.46	30.61	36.09	Dry sandstone
KHK-Curve Type	3	710.06	5.26	41.35	Clayey sand
Neni-2	4	6641.83	172.29	213.64	Dry sandstone

	5	3155.21	26.47	240.11	Water saturated sand
	6	33.81	Base not reached		Shale
	1	1062.34	3.06	3.06	Top soil/laterite
VES 76	2	40.82	9.85	12.91	Shale
K-Curve Type	3	784.62	9.94	22.85	Clayey sand
Ogidi-1	4	5583.97	82.01	104.86	Dry sandstone
	5	2059.44	46.15	151.01	Water saturated sand
	6	35.61	Base not reached		Shale
	1	2013.01	4.03	4.03	Top soil/laterite
VES 77	2	42.71	11.79	15.82	Shale
K-Curve Type	3	711.81	8.26	24.08	Clayey sand
Ogidi-2	4	6091.66	74.94	99.02	Dry sandstone
	5	1908.62	39.07	138.09	Water saturated sand
	6	36.07	Base not reached		Shale
	1	1523.02	3.87	3.87	Top soil/laterite
VES 78	2	29.07	7.85	11.72	Shale
K-Curve Type	3	800.31	10.36	22.08	Clayey sand
Ogidi-3	4	5976.33	79.78	101.86	Dry sandstone
	5	2705.37	34.8	136.66	Water saturated sand
	6	19.05	Base not reached		Shale
	1	87.28	4.22	4.22	Top soil/laterite
VES 79	2	724.12	8.46	12.68	Sand
A-Curve Type	3	239.96	2.59	15.27	Clayey sand
Azu-Ogbunike	4	30641.01	49.02	64.29	Dry sandstone
	5	8207.54	24.86	89.15	Water saturated sand
	6	49.17	4.07	93.22	Shale
	7	50261.21	Base not reached		Dry sandstone
	1	606.79	3.96	3.96	Top soil/laterite
VES 80	2	437.98	18.3	22.26	Clayey sand
HK-Curve Type	3	11708.11	47.58	69.84	Dry sandstone
Ogbunike-1	4	4079.43	28.23	98.07	Water saturated sand
	5	18.08	Base not reached		Shale
	1	108.28	5.01	5.01	Top soil/laterite
VES 81	2	900.27	8.75	13.76	Sand
A-Curve Type	3	308.37	13.07	26.83	Clayey sand
Ogbunike-2	4	24181.42	39.92	66.75	Dry sandstone
	5	5122.07	29.24	95.99	Water saturated sand
	6	53.33	2.1	98.09	Shale
	7	32819.01	Base not reached		Dry sandstone
	1	278.1	3.88	3.88	Top soil/laterite
VES 82	2	7639.7	50.21	54.09	Dry sandstone
KA-Curve Type	3	832.31	29.17	83.26	Clayey sand
Nkpor-1	4	9049.81	17.19	100.45	Dry sandstone
	5	4868.24	22.21	122.66	Water saturated sand
	6	40613.01	Base not reached		Dry sandstone
	1	388.02	5.32	5.32	Top soil/laterite

VES 83	2	4761.33	43.73	49.05	Dry sandstone
KA-Curve Type	3	692.14	27.43	76.48	Clayey sand
Nkpor-2	4	11053.01	26.61	103.09	Dry sandstone
	5	3883.38	20.72	123.81	Water saturated sand
	6	27765.11	Base not reached		Dry sandstone
	1	300.7	4.63	4.63	Top soil/laterite
VES 84	2	6019.33	46.25	50.88	Dry sandstone
KA-Curve Type	3	508.26	26.44	77.32	Clayey sand
Nkpor-3	4	90116.27	21.44	98.76	Dry sandstone
	5	4089.02	21.22	119.98	Water saturated sand
	6	19077.06	Base not reached		Dry sandstone
	1	449.18	3.96	3.96	Top soil/laterite
VES 85	2	808.26	24.63	28.59	Clayey sand
K-Curve Type	3	9623.08	69.59	98.18	Dry sandstone
Obosi-1	4	3800.94	23.86	122.04	Water saturated sand
	5	60.28	Base not reached		Shale
	1	359.11	5.41	5.41	Top soil/laterite
VES 86	2	763.02	15.47	20.88	Clayey sand
KA-Curve Type	3	10248.04	71.19	92.07	Dry sandstone
Obosi-2	4	5630.9	24.76	116.83	Water saturated sand
	5	66.07	Base not reached		Shale
	1	518.01	4.18	4.18	Top soil/laterite
VES 87	2	800.43	18.24	22.42	Clayey sand
KA-Curve Type	3	14180.35	67.49	89.91	Dry sandstone
Obosi-3	4	4505.05	21.24	111.15	Water saturated sand
	5	77.23	Base not reached		Shale
	1	607.11	2.67	2.67	Top soil/laterite
VES 88	2	6111.63	45.44	48.11	Dry sandstone
KA-Curve Type	3	702.45	22.91	71.02	Clayey sand
Umuoji-1	4	14001.19	23.54	94.56	Dry sandstone
	5	5039.75	21.47	116.03	Water saturated sand
	6	27096.13	Base not reached		Dry sandstone
	1	409.13	3.81	3.81	Top soil/laterite
VES 89	2	7322.71	39.46	43.27	Dry sandstone
KA-Curve Type	3	564.09	24.79	68.06	Clayey sand
Umuoji-2	4	9918.15	33.37	101.43	Dry sandstone
	5	4816.75	19.22	120.65	Water saturated sand
	6	31022.27	Base not reached		Dry sandstone
	1	443.01	4.04	4.04	Top soil/laterite
VES 90	2	10382.25	47.02	51.06	Dry sandstone
KA-Curve Type	3	777.18	22.05	73.11	Clayey sand
Umuoji-3	4	17959.38	24.75	97.86	Dry sandstone
	5	5529.16	20.19	118.05	Water saturated sand
	6	46191.02	Base not reached		Dry sandstone

	1	33.67	3.09	3.09	Top soil/laterite
VES 91	2	659.55	17.14	20.23	Shally-sand/Clayey-sand
KHK-Curve Type	3	19.87	27.82	48.05	Shale
Nnobi-1	4	6113.07	123.67	171.72	Dry sandstone
	5	2068.26	37.44	209.16	Water saturated sand
	6	56.17	Base not reached		Shale
	1	97.34	2.51	2.51	Top soil/laterite
VES 92	2	704.64	22.56	25.07	Shally-sand/Clayey-sand
KHK-Curve Type	3	41.48	18.04	43.11	Shale
Nnobi-2	4	4310.71	124.91	168.02	Dry sandstone
	5	1916.11	31.61	199.63	Water saturated sand
	6	48.61	Base not reached		Shale
	1	51.04	2.48	2.48	Top soil/laterite
VES 93	2	515.22	20.79	23.27	Shally-sand/Clayey-sand
KHK-Curve Type	3	37.08	26.86	50.13	Shale
Nnokwa-1	4	5328.11	108.88	159.01	Dry sandstone
	5	2736.77	32.11	191.12	Water saturated sand
	6	29.06	Base not reached		Shale
	1	115.05	1.99	1.99	Top soil/laterite
VES 94	2	611.06	17.69	19.68	Shally-sand/Clayey-sand
KHK-Curve Type	3	38.99	27.16	46.84	Shale
Nnokwa-2	4	5521.38	113.32	160.16	Dry sandstone
	5	2008.91	27.92	188.08	Water saturated sand
	6	27.08	Base not reached		Shale
	1	2500.12	2.67	2.67	Top soil/laterite
VES 95	2	34.99	5.11	7.78	Shale
HK-Curve Type	3	714.11	18.73	26.51	Clayey sand
Adazi-Nnukwu-1	4	5250.7	70.55	97.06	Dry sandstone
	5	2309.05	24.6	121.66	Water saturated sandstone.
	6	20.08	Base not reached		Shale
	1	1972.54	3.07	3.07	Top soil/laterite
VES 96	2	27.03	7.05	10.12	Shale
HK-Curve Type	3	583.64	17.94	28.06	Clayey sand
Adazi-Nnukwu-2	4	6011.57	71.95	100.01	Dry sandstone
	5	3120.9	32.26	132.27	Water saturated sandstone.
	6	34.28	Base not reached		Shale
	1	224.08	3.81	3.81	Top soil/laterite
VES 97	2	894.28	19.25	23.06	Clayey sand
AK-Curve Type	3	8101.23	105.76	128.82	Dry sandstone
Agulu-1	4	3466.01	41.17	169.99	Water saturated sandstone
	3	38.74	Base not reached		Shale
	1	5021.24	2.88	2.88	Top soil
	2	840.81	16.27	19.15	Shaly sandstone

VES 98	3	3911.35	12.89	32.04	Dry sandstone
QK-Curve Type	4	27.34	59.18	91.22	shale
Agulu-2	5	2501.06	29.87	121.09	Dry sandstone
	6	1009.13	30.93	152.02	Water saturated sandstone
	6	14.93	Base not reached		shale
	1	3026.43	3.35	3.35	Top soil/laterite
VES 99	2	800.32	25.31	28.66	Clayey sand
HK-Curve Type	3	5417.01	38.9	67.56	Dry sandstone
Agulu-3	4	2755.08	33.86	101.42	Water saturated sandstone
	5	41.23	Base not reached		Shale
	1	372.27	2.89	2.89	Top soil/laterite
VES 100	2	739.06	22.42	25.31	Clayey sand
AK-Curve Type	3	5022.62	92.74	118.05	Dry sandstone
Agulu-4	4	2566.18	28.36	146.41	Water saturated sandstone
	3	26.13	Base not reached		Shale
	1	33.147	4.62	4.62	Top soil/laterite
VES 101	2	8169.28	21.86	26.48	Dry sandstone
KHK-Curve Type	3	756.48	19.94	46.42	Clayey sand
Awka-Etiti-1	4	17811.97	114.32	160.74	Dry sandstone
	5	3619.14	36.37	197.11	Water saturated sand
	6	30.08	Base not reached		Shale
	1	87.04	4.71	4.71	Top soil/laterite
VES 102	2	2861.11	23.51	28.22	Dry sandstone
KHK-Curve Type	3	882.06	13.82	42.04	Clayey sand
Awka-Etiti-2	4	12008.15	121.97	164.01	Dry sandstone
	5	4100.04	29.54	193.55	Water saturated sand
	6	41.44	Base not reached		Shale
	1	116.02	3.64	3.64	Top soil/laterite
VES 103	2	6615.54	21.19	24.83	Dry sandstone
KHK-Curve Type	3	655.09	14.66	39.49	Clayey sand
Awka-Etiti-3	4	20176.88	123.34	162.83	Dry sandstone
	5	5058.92	27.68	190.51	Water saturated sand
	6	52.65	Base not reached		Shale
	1	1623.65	3.52	3.52	Top soil/laterite
VES 104	2	2996.52	11.35	14.87	Sand
HK-Curve Type	3	588.71	31.28	46.15	Shally-sand/Clayey-sand
Aguluzigbo-1	4	10791.74	152.66	198.81	Dry sandstone
	5	2647.62	20.21	219.02	Water saturated sand
	6	22.146	Base not reached		Shale
	1	1317.08	2.26	2.26	Top soil/laterite
VES 105	2	3482.22	1.49	3.75	Sand
HK-Curve Type	3	708.12	40.33	44.08	Shally-sand/Clayey-sand
Aguluzigbo-2	4	8673.14	156.8	200.88	Dry sandstone

	5	5488.71	27.18	228.06	Water saturated sand
	6	30.059	Base not reached		Shale
	1	2068.09	4.08	4.08	Top soil/laterite
VES 106	2	4157.96	13.98	18.06	Sand
HK-Curve Type	3	875.21	25.32	43.38	Shally-sand/Clayey-sand
Igbokwu-1	4	23024.07	161.71	205.09	Dry sandstone
	5	5016.11	25.09	230.18	Water saturated sand
	6	50.05	Base not reached		Shale
	1	1841.56	3.99	3.99	Top soil/laterite
VES 107	2	4466.58	18.02	22.01	Sand
HK-Curve Type	3	723.01	25.28	47.29	Shally-sand/Clayey-sand
Igbokwu-2	4	16199.06	156.17	203.46	Dry sandstone
	5	4914.06	27.77	231.23	Water saturated sand
	6	43.28	Base not reached		Shale
	1	518.02	5.21	5.21	Top soil/laterite
VES 108	2	3095.24	25.42	30.63	Dry sandstone
KHK-Curve Type	3	765.01	15.78	46.41	Clayey sand
Aguluezechukwu-1	4	1056.32	149.12	195.53	Dry sandstone
	5	3305.77	33.09	228.62	Water saturated sand
	6	37.08	Base not reached		Shale
	1	409.11	4.74	4.74	Top soil/laterite
VES 109	2	1985.53	20.35	25.09	Dry sandstone
KHK-Curve Type	3	809.11	13.5	38.59	Clayey sand
Aguluezechukwu-2	4	12259.82	154.48	193.07	Dry sandstone
	5	4179.55	33.24	226.31	Water saturated sand
	6	60.91	Base not reached		Shale
	1	363.66	3.95	3.95	Top soil/laterite
VES 110	2	2900.07	24.27	28.22	Dry sandstone
KHK-Curve Type	3	789.51	13.84	42.06	Clayey sand
Aguluezechukwu-3	4	9681.12	154.42	196.48	Dry sandstone
	5	3455.84	27.04	223.52	Water saturated sand
	6	57.04	Base not reached		Shale
	1	301.33	3.66	3.66	Top soil/laterite
VES 111	2	3048.66	14.96	18.62	Dry sandstone
KHK-Curve Type	3	700.28	9.88	28.5	Clayey sand
Ekwulobia-1	4	7715.13	178.58	207.08	Dry sandstone
	5	2207.18	22.01	229.09	Water saturated sand
	6	83.04	Base not reached		Shale
	1	442.13	2.75	2.75	Top soil/laterite
VES 112	2	2346.07	17.29	20.04	Dry sandstone
KHK-Curve Type	3	743.19	4.99	25.03	Clayey sand
Ekwulobia-2	4	8469.82	180.69	205.72	Dry sandstone
	5	2955.67	25.29	231.01	Water saturated sand

	6	47.04	Base not reached		Shale
	1	351.09	2.06	2.06	Top soil/laterite
VES 113	2	2746.05	16.96	19.02	Dry sandstone
KHK-Curve Type	3	881.33	11.73	30.75	Clayey sand
Ekwulobia-3	4	11091.17	174.16	204.91	Dry sandstone
	5	4071.42	23.1	228.01	Water saturated sand
	6	57.04	Base not reached		Shale
	1	477.04	5.01	5.01	Top soil
VES 114	2	791.34	13.2	18.21	Clayey sand
AK-Curve Type	3	16321.24	187.01	205.22	Dry sandstone
Oko-1	4	4058.11	22.9	228.12	Water Saturated sandstone
	5	42.58	Base not reached		Shale
	1	380.22	3.64	3.64	Top soil
VES 115	2	838.62	19.41	23.05	Clayey sand
AK-Curve Type	3	9539.38	180.3	203.35	Dry sandstone
Oko-2	4	5104.05	24.43	227.78	Water Saturated sandstone
	5	67.29	Base not reached		Shale
	1	405.83	4.26	4.26	Top soil
VES 116	2	663.23	15.83	20.09	Clayey sand
AK-Curve Type	3	13074.52	180.46	200.55	Dry sandstone
Oko-3	4	3925.79	23.06	223.61	Water Saturated sandstone
	5	51.67	Base not reached		Shale
	1	346.27	3.56	3.56	Top soil
VES 117	2	806.91	18.5	22.06	Clayey sand
AK-Curve Type	3	8934.83	173.99	196.05	Dry sandstone
Ndiokpalaeze-1	4	2895.58	24.38	220.43	Water Saturated sandstone
	5	51.06	Base not reached		Shale
	1	411.83	3.09	3.09	Top soil
VES 118	2	901.37	22.39	25.48	Clayey sand
AK-Curve Type	3	7618.95	167.55	193.03	Dry sandstone
Ndiokpalaeze-2	4	3008.14	29.11	222.14	Water Saturated sandstone
	5	63.06	Base not reached		Shale
	1	510.66	4.71	4.71	Top soil
VES 119	2	876.02	19.62	24.33	Clayey sand
AK-Curve Type	3	11137.75	171.53	195.86	Dry sandstone
Ndiokpalaeze-3	4	4209.29	24.06	219.92	Water Saturated sandstone
	5	46.05	Base not reached		Shale
	1	300.08	2.86	2.86	Top soil/Laterite
VES 120	2	1601.46	9.67	12.53	Sand
HK-Curve Type	3	446.28	12.56	25.09	Clayey-sand
Achina-1	4	12381.63	158.67	183.76	Dry sandstone

	5	4700.03	22.79	206.55	Water saturated sandstone
	6	69.11	Base not reached		Shale
	1	238.55	4.11	4.11	Top soil/Laterite
VES 121	2	1439.73	10.98	15.09	Sand
HK-Curve Type	3	621.06	11.36	26.45	Clayey-sand
Achina-2	4	10842.35	153.51	179.96	Dry sandstone
	5	5031.76	20.85	200.81	Water saturated sandstone
	6	53.08	Base not reached		Shale
	1	907.46	5.09	5.09	Top soil/Laterite
VES 122	2	565.72	15.47	20.56	Clayey-sand
HK-Curve Type	3	8399.63	167.55	188.11	Dry sandstone
Ibughubu Umuchu-1	4	2235.81	29.37	217.48	Water saturated sandstone
	5	43.05	Base not reached		Shale
	1	1034.66	4.88	4.88	Top soil/Laterite
VES 123	2	486.02	12.19	17.07	Clayey-sand
HK-Curve Type	3	10495.63	176.54	193.61	Dry sandstone
Ibughubu Umuchu-2	4	3702.85	24.66	218.27	Water saturated sandstone
	5	39.26	Base not reached		Shale
	1	204.19	3.59	3.59	Top soil/Laterite
VES 124	2	1506.23	19.46	23.05	Sand
HK-Curve Type	3	415.08	10.02	33.07	Clayey-sand
Umuchu-1	4	9811.05	168.11	201.18	Dry sandstone
	5	4011.67	28.06	229.24	Water saturated sandstone
	6	65.03	Base not reached		Shale
	1	364.89	4.71	4.71	Top soil/Laterite
VES 125	2	989.33	16.22	20.93	Sand
HK-Curve Type	3	340.21	9.73	30.66	Clayey-sand
Umuchu-2	4	7977.35	174.11	204.77	Dry sandstone
	5	2654.31	26.05	230.82	Water saturated sandstone
	6	71.05	Base not reached		Shale
	1	1294.66	3.55	3.55	Top soil/Laterite
VES 126	2	306.02	14.52	18.07	Clayey-sand
HK-Curve Type	3	9083.71	166.85	184.92	Dry sandstone
Amaeshi-1	4	3802.22	25.15	210.07	Water saturated sandstone
	5	33.55	Base not reached		Shale
	1	1511.29	4.14	4.14	Top soil/Laterite
VES 127	2	403.17	15.87	20.01	Clayey-sand
HK-Curve Type	3	8079.63	168.06	188.07	Dry sandstone
Amaeshi-2	4	3001.11	23.54	211.61	Water saturated sandstone

	5	30.79	Base not reached		Shale
	1	374.01	3.87	3.87	Top soil/Laterite
VES 128	2	1177.08	17.96	21.83	Sand
HK-Curve Type	3	505.61	8.61	30.44	Clayey-sand
Osumenyi-1	4	8891.77	169.89	200.33	Dry sandstone
	5	2861.94	24.72	225.05	Water saturated sandstone
	6	51.46	Base not reached		Shale
	1	611.64	3.77	3.77	Top soil/Laterite
VES 129	2	1196.89	18.32	22.09	Sand
HK-Curve Type	3	484.02	5.57	27.66	Clayey-sand
Osumenyi-2	4	9017.06	174.99	202.65	Dry sandstone
	5	3269.55	22.74	225.39	Water saturated sandstone
	6	57.38	Base not reached		Shale
	1	1106.12	4.27	4.27	Top soil/Laterite
VES 130	2	2325.22	18.82	23.09	Dry sandstone
KHK-Curve Type	3	719.03	8.06	31.15	Clayey sand
Ezinifite-1	4	9082.14	175.33	206.48	Dry sandstone
	5	3372.13	22.01	228.49	Saturated sandstone
	6	73.04	Base not reached		Shale
	1	1351.19	3.81	3.81	Top soil/Laterite
VES 131	2	2811.51	18.08	21.89	Dry sandstone
KHK-Curve Type	3	860.83	12.17	34.06	Clayey sand
Ezinifite-2	4	8816.56	175.95	210.01	Dry sandstone
	5	2649.08	21.1	231.11	Saturated sandstone
	6	55.27	Base not reached		Shale
	1	1221.09	5.01	5.01	Top soil/Laterite
VES 132	2	3200.28	18.98	23.99	Dry sandstone
KHK-Curve Type	3	631.45	6.09	30.08	Clayey sand
Ezinifite-3	4	8275.01	173.15	203.23	Dry sandstone
	5	3001.44	27.22	230.45	Saturated sandstone
	6	42.29	Base not reached		Shale
	1	611.52	2.77	2.77	Top soil/laterite
VES 133	2	2007.11	19.64	22.41	Dry sandtone
KHK-Curve Type	3	701.81	7.68	30.09	Clayey sand
Uga-1	4	8652.26	159.16	189.25	Dry sandtone
	5	4158.79	28.84	218.09	Water saturated sand
	6	98.61	Base not reached		Shale
	1	555.73	3.69	3.69	Top soil/laterite
VES 134	2	3100.52	16.06	19.75	Dry sandstone
KHK-Curve Type	3	660.61	9.09	28.84	Clayey sand
Uga-2	4	9081.22	158.34	187.18	Dry sandstone
	5	3581.57	27.99	215.17	Water saturated sand
	6	85.42	Base not reached		Shale
	1	719.33	3.56	3.56	Top soil/laterite

VES 135	2	2811.27	17.32	20.88	Dry sandstone
KHK-Curve Type	3	812.46	10.17	31.05	Clayey sand
Uga-3	4	8560.15	167.31	198.36	Dry sandstone
	5	4415.07	22.2	220.56	Water saturated sand
	6	63.47	Base not reached		Shale
	1	238.53	2.96	2.96	Top soil/laterite
VES 136	2	793.15	15.73	18.69	Shally-sand/Clayey-sand
KHK-Curve Type	3	7217.48	64.39	83.08	Dry sandstone
Awgbu-1	4	2589.24	39.06	122.14	Water saturated sand
	5	63.82	Base not reached		Shale
	1	269.58	3.47	3.47	Top soil/laterite
VES 137	2	656.37	17.18	20.65	Shally-sand/Clayey-sand
KHK-Curve Type	3	8147.81	54.24	74.89	Dry sandstone
Awgbu-2	4	3310.25	37.37	112.26	Water saturated sand
	5	47.23	Base not reached		Shale
	1	401.65	4.04	4.04	Top soil/laterite
VES 138	2	800.01	11.27	15.31	Shally-sand/Clayey-sand
KHK-Curve Type	3	6803.69	76.87	92.18	Dry sandstone
Awgbu-3	4	2794.08	30.83	123.01	Water saturated sand
	5	59.27	Base not reached		Shale
	1	8021.16	4.53	4.53	Top soil
VES 139	2	918.87	20.34	24.87	Clayey sand
HK-Curve Type	3	14262.43	82.18	107.05	Dry sandstone
Nanka-1	4	4086.71	35.58	142.63	Water saturated sandstone
	5	72.11	Base not reached		Shale
	1	7829.14	5.05	5.05	Top soil
VES 140	2	872.63	17.13	22.18	Clayey sand
HK-Curve Type	3	9872.88	75.93	98.11	Dry sandstone
Nanka-2	4	2998.81	38.01	136.12	Water saturated sandstone
	5	87.26	Base not reached		Shale
	1	7500.67	3.75	3.75	Top soil
VES 141	2	806.68	16.9	20.65	Clayey sand
HK-Curve Type	3	8692.73	82.68	103.33	Dry sandstone
Nanka-3	4	3188.41	32.48	135.81	Water saturated sandstone
	5	90.82	Base not reached		Shale

E. Detailed Baseline geo-electric model parameters for Imo Formation (Ebenebe Sandstone)

VES No. & Name	Layer	App. Res. (Ohm-m)	Thickness (m)	Depth (m)	Description
	1	1629.6	3.78	3.78	Top soil/laterite
VES 142	2	435.85	14.13	17.91	Clayey sand
HK-Curve Type	3	7548.4	26.53	44.44	Dry sandstone
Ufuma-1	4	1349.1	18.73	63.17	Water saturated sand
	5	29.663	Base not reached		Shale
	1	1700.86	4.04	4.04	Top soil/laterite
VES 143	2	566.72	17.79	21.83	Clayey sand
HK-Curve Type	3	9104.64	29.95	51.78	Dry sandstone
Ufuma-2	4	3301.49	28.83	80.61	Water saturated sand
	5	50.19	Base not reached		Shale
	1	1607.87	3.85	3.85	Top soil/laterite
VES 144	2	608.24	15.98	19.83	Clayey sand
AK-Curve Type	3	8772.72	68.89	88.72	Dry sandstone
Enugwu-Abo Ufuma-1	4	2605.08	36.28	125	Water saturated sand
	5	60.41	Base not reached		Shale
	1	1959.96	5.21	5.21	Top soil/laterite
VES 145	2	785.71	17.85	23.06	Sandy-clay
AK-Curve Type	3	9012.28	60.85	83.91	Dry sandstone
Enugwu-Abo Ufuma-1	4	4102.83	26.31	110.22	Water saturated sand
	5	49.63	Base not reached		Shale
	1	1388.4	3.98	3.98	Top soil/Laterite
VES 146	2	672.26	14.7	18.68	Clayey-sand
HK-Curve Type	3	9623.4	51.35	70.03	Dry sandstone
Ajalli-1	4	2385.3	39.35	109.38	Water saturated sandstone
	5	26.138	Base not reached		Shale
	1	1601.52	4.79	4.79	Top soil/Laterite
VES 147	2	582.08	17.73	22.52	Clayey-sand
HK-Curve Type	3	10041.23	44.71	67.23	Dry sandstone
Ajalli-2	4	4031.85	37.38	104.61	Water saturated sandstone
	5	43.67	Base not reached		Shale
	1	320.15	2.94	2.94	Top soil/Laterite
VES 148	2	700.11	17.09	20.03	Clayey sand
K-Curve Type	3	14026.15	52.76	72.79	Dry sandstone
Nawfija-1	4	4394.27	37.28	110.07	Water saturated sandstone
	5	50.69	Base not reached		Shale
	1	483.05	3.64	3.64	Top soil/Laterite

VES 149	2	878.76	14.23	17.87	Clayey sand
K-Curve Type	3	12062.15	56.14	74.01	Dry sandstone
Nawfija-2	4	3816.48	38.43	112.44	Water saturated sandstone
	5	46.27	Base not reached		Shale
	1	981.79	3.88	3.88	Top soil/Laterite
VES 150	2	420.74	15.17	19.05	Clayey-sand
HK-Curve Type	3	9063.51	54.31	73.36	Dry sandstone
Ezira-1	4	4355.68	36.72	110.08	Water saturated sandstone
	5	45.81	Base not reached		Shale
	1	831.07	4.13	4.13	Top soil/Laterite
VES 151	2	502.03	13.38	17.51	Clayey-sand
HK-Curve Type	3	10602.66	57.58	75.09	Dry sandstone
Ezira-2	4	3917.04	33.47	108.56	Water saturated sandstone
	5	49.85	Base not reached		Shale
	1	882.79	3.47	3.47	Top soil/Laterite
VES 152	2	304.12	18.15	21.62	Clayey-sand
HK-Curve Type	3	7890.65	27.27	48.89	Dry sandstone
Umunze-1	4	3148.35	43.96	92.85	Water saturated sandstone
	5	30.71	Base not reached		Shale
	1	308.2	3.71	3.71	Top soil/Laterite
VES 153	2	705.16	14.35	18.06	Clayey-sand
K-Curve Type	3	9410.62	35.52	53.58	Dry sandstone
Umunze-2	4	4303.91	38.55	92.13	Water saturated sandstone
	5	38.16	Base not reached		Shale
	1	278.63	4.06	4.06	Top soil/Laterite
VES 154	2	789.52	16.83	20.89	Clayey-sand
K-Curve Type	3	11356.04	50.02	70.91	Dry sandstone
Umunze-3	4	4620.14	36.65	107.56	Water saturated sandstone
	5	53.07	Base not reached		Shale
	1	680.91	3.88	3.88	Top soil/Laterite
VES 155	2	909.7	16.16	20.04	Clayey-sand
AK-Curve Type	3	9897.58	47.79	67.83	Dry sandstone
Ihite-1	4	4106.74	36.23	104.06	Water saturated sandstone
	5	56.02	Base not reached		Shale
	1	702.52	4.17	4.17	Top soil/Laterite
VES 156	2	891.81	23.66	27.83	Clayey-sand
AK-Curve Type	3	10976.18	42.86	70.69	Dry sandstone
Ihite-2	4	3410.32	28.96	99.65	Water saturated sandstone
	5	44.95	Base not reached		Shale

F. Detailed Baseline geo-electric model parameters for Imo Formation (Imo shale)

VES No. & Name	Layer	App. Res. (Ohm-m)	Thickness (m)	Depth (m)	Description
	1	448.72	1.34	1.34	Top soil
	2	144.26	3.11	4.45	Clayey sand
VES 157 HK-Curve	3	1218.7	9.64	14.09	Sandstone
Type	4	23.85	14.27	28.36	Clayey sand
Amanuke-1	5	5747.12	61.88	90.24	Dry sandstone
	6	2065.26	23.46	113.7	Water Saturated Sandstone
	7	20.74	Base not Reached		Shale
	1	59.13	1.29	1.29	Top soil
VES 158	2	499.47	2.79	4.08	Sand
AK-Curve Type	3	66.11	5.63	9.71	Clayey sand
Amanuke-2	4	4149	82.08	91.79	Dry sandstone
	5	1895.24	27.49	119.28	Water saturated sandstone
	6	25.24	Base not Reached		Shale
	1	1.933	1.161	1.161	Top soil
	2	9.519	2.131	3.292	Shale
VES 159	3	2508.8	15.448	18.74	Dry sandstone
AK-Curve Type	4	41.176	50.45	69.19	Shale
Amanuke-3	5	1405.7	12.942	82.132	Dry sandstone
	6	906.59	25.558	107.69	Water saturated sandstone
	7	87.13	Base not Reached		Shale
	1	34.012	3.26	3.26	Top soil
	2	1592.3	11.21	14.47	Sand
VES 160	3	246.212	32.05	46.52	Shaly-sand
KHK-Curve Type	4	2235	56.29	102.81	Dry sandstone
Ebenebe-1	5	803.23	27.71	130.52	Water saturated sandstone
	6	14.246	Base not Reached		Shale
	1	6993.96	1.532	1.532	Top soil
	2	231.39	7.379	8.911	Shale
VES 161	3	3492.8	38.246	47.157	Dry sand
KHK-Curve Type	4	70.187	23.133	70.29	Shale
Ebenebe-2	5	8167.6	31.05	101.34	Dry sandstone
	6	1911.36	26.84	128.18	Water saturated sandstone
	7	41.03	Base not Reached		Shale

	1	4894.03	1.532	1.532	Top soil
	2	370.14	17.379	18.911	Clayey sand
VES 162 KHK-Curve	3	5041.92	8.246	27.157	Dry sandstone
Type	4	58.09	120.273	147.43	Shale
Ebenebe-3	5	3016.88	56.6	204.03	Dry sandstone
	6	1209.45	24.15	228.18	Water saturated sandstone
	7	37.84	Base not Reached		Shale
	1	252.16	2.18	2.18	Top soil
	2	7.89	34.46	36.64	Clayey sand
VES 163 QK-Curve	3	301.3	8.37	45.01	Dry sandstone
Type	4	4.29	173.04	218.05	Shale
Amansea-1	5	280.25	8.06	226.11	Dry sandstone
	6	126.08	32.15	258.26	Water saturated sandstone
	7	1.02	Base not Reached		Shale
	1	406.31	3.02	3.02	Top soil
	2	137.83	7.82	10.84	Clayey sand
VES 164 QK-Curve	3	711.36	8.02	18.86	Dry sandstone
Type	4	21.08	201.76	220.62	Shale
Amansea-2	5	901.33	7.46	228.08	Dry sandstone
	6	442.38	27.68	255.76	Water saturated sandstone
	7	19.56	Base not Reached		Shale
	1	307.07	2.77	2.77	Top soil
	2	230.57	11.85	14.62	Clayey sand
VES 165 HK-Curve	3	620.59	5.92	20.54	Dry sandstone
Type	4	27.06	200.34	220.88	Shale
Amansea-3	5	893.02	4.13	225.01	Dry sandstone
	6	511.26	28.25	253.26	Water saturated sandstone
	7	9.69	Base not Reached		Shale
	1	80.59	3.11	3.11	Top soil
VES 166 AK-Curve	2	183.11	1.27	4.38	Shaly-sand
Type	3	6.049	14.06	18.44	Shale
Urum-1	4	123.49	118.63	137.07	Shaly-sand
	5	4256.41	49.04	186.11	Dry sandstone
	6	2061.26	30.94	217.05	Water saturated sandstone
	7	59.46	Base not Reached		Shale
	1	116.89	2.06	2.06	Top soil
VES 167	2	248.47	3.76	5.82	Shaly-sand

AK-Curve Type	3	20.58	14.34	20.16	Shale
Urum-2	4	201.04	154.25	174.41	Shaly-sand
	5	3874.26	33.44	207.85	Dry sandstone
	6	1850.61	21.97	229.82	Water saturated sandstone
	7	31.73	Base not Reached		Shale
	1	228.29	2.35	2.35	Top soil
VES 168	2	403.52	8.6	10.95	Shaly-sand
KHK-Curve Type	3	5365.31	71.28	82.23	Dry sandstone
Isuaniocha-1	4	1270.4	31.75	113.98	Water saturated sandstone
	5	2.7499	Base not Reached		Shale
	1	938.07	1.89	1.89	Top soil
	2	537.76	7.44	9.33	Shally sand
VES 169	3	2669.22	67.66	76.99	Dry sandstone
KHK-Curve Type	4	1001.08	28.07	105.06	Water saturated sandstone
Isuanioha-2	5	8.79	Base not Reached		Shale
	1	2739.12	1.46	1.46	Top soil
	2	5321.96	3.95	5.41	Sand
VES 170	3	882.99	31.12	36.53	Sandy-Shale
KHK-Curve Type	4	101.29	41.6	78.13	Shale
Mgbakwu-1	5	6850.11	25.33	103.46	Dry sandstone
	6	2356.3	35.36	138.82	Water saturated Sandstone
	7	8.99	Base not Reached		Shale
	1	74.62	2.81	2.81	Top soil
	2	549.12	1.91	4.72	Sandy-shale
VES 171	3	1073.71	47.81	52.53	Sand
KHK-Curve Type	4	245.87	25.29	77.82	Shally sand
Mgbakwu-2	5	9733.8	24.93	102.75	Dry sandstone
	6	1865.59	33.52	136.27	Water saturated sandstone
	7	18.95	Base not Reached		Shale
	1	365.08	2.14	2.14	Top soil/Laterite
	2	1763.01	4.89	7.03	Dry sand
VES 172	3	650.27	2.98	10.01	Clayey sand
KHK-Curve Type	4	10246.62	42.37	52.38	Dry sandstone
Okpuno-1	5	3502.01	21.81	74.19	Water saturated sandstone
	6	45.26	Base not Reached		Shale
	1	119.22	3.95	3.95	Top soil/Laterite

	2	1456.57	6.73	10.68	Dry sand
VES 173	3	220.32	10.37	21.05	Clayey sand
KHK-Curve Type	4	6869.56	28.66	49.71	Dry sandstone
Okpuno-2	5	2906.18	29.3	79.01	Water saturated sandstone
	6	22.05	Base not Reached		Shale
	1	201.28	4.07	4.07	Top soil/Laterite
VES 174	2	738.51	3.98	8.05	Clayey sand
K-Curve Type	3	5530.21	31.8	39.85	Dry sandstone
Okpuno-3	4	2302.09	34.16	74.01	Water saturated sandstone
	5	61.48	Base not Reached		Shale
	1	182.7	2.87	2.87	Top soil
VES 175	2	219	9.21	12.08	Sand
HK-Curve Type	3	13.74	168.64	180.72	Shale
Ifite-Awka-1	4	795.48	15.93	196.65	Dry sandstone
	5	412.76	34.83	231.48	Water saturated sand
	6	14.32	Base not Reached		Shale
	1	144.18	3.08	3.08	Top soil
VES 176	2	483.91	7.56	10.64	Sand
HK-Curve Type	3	20.62	166.19	176.83	Shale
Ifite-Awka-2	4	900.95	13.22	190.05	Dry sandstone
	5	502.88	32.28	222.33	Water saturated sand
	6	18.53	Base not Reached		Shale
	1	167.82	3.11	3.11	Top soil
VES 177	2	630.75	8.02	11.13	Sand
HK-Curve Type	3	9.07	171.93	183.06	Shale
Ifite-Awka-3	4	882.04	6.87	189.93	Dry sandstone
	5	513.65	30.11	220.04	Water saturated sand
	6	16.65	Base not Reached		Shale
VES 178	1	235.21	2.86	2.86	Top soil
HK-Curve Type	2	42.54	2.38	5.24	Shale
Real Estate	3	1986.1	98.06	103.3	Sand
Awka-1	4	893.2	32.9	136.2	Water saturated sand
	5	107.04	Base not Reached		Shale
VES 179	1	399.18	3.32	3.32	Top soil
HK-Curve Type	2	151.05	5.29	8.61	Shaly sand
Udoka Housing	3	1035.23	19.31	27.92	Sand
Awka-2	4	8.19	47.96	75.88	Shale
	5	687.03	Base not Reached		Water saturated sand
VES 180	1	910.05	3.27	3.27	Top soil

HK-Curve Type	2	47.81	11.36	14.63	Shale
Ifite-Road	3	6080.11	85.94	100.57	Sand
Awka-3	4	1274.08	24.64	125.21	Water saturated sand
	5	34.87	Base not Reached		Shale
VES 181	1	232.92	2.94	2.94	Top soil
HK-Curve Type	2	875.54	9.1	12.04	Shaly-sand
Unizik Temp. Site	3	4090.16	22.89	34.93	Sand
Awka-4	4	1004.04	30.35	65.28	Water saturated sand
	5	106.52	Base not Reached		Shale
	1	720.91	3.64	3.64	Top soil
VES 182	2	329.05	6.89	10.53	Shaly sand
HK-Curve Type	3	1528.58	26.23	36.76	Sand
Umudioka	4	893.21	34.09	70.85	Water saturated sand
Awka-5	5	8.11	Base not Reached		Shale
	1	425.23	2.95	2.95	Top soil
VES 183	2	3.41	15.52	18.47	Shale
QK-Curve Type	3	38.14	19.59	38.06	Shaly-sand
Amawbia-1	4	532.52	4.89	42.95	Sand
	5	183.21	34.13	77.08	Water saturated sand
	6	10.12	Base not Reached		Shale
VES 184	1	597.02	2.56	2.56	Top soil
QK-Curve Type	2	858.21	8.52	11.08	Sand
Amawbia-2	3	10.22	27.65	38.73	Shale
	4	139.14	42.13	80.86	Water saturated sand
	5	1221.09	Base not Reached		Sand
	1	300.22	2.1	2.1	Top soil
VES 185	2	704.03	10.92	13.02	Sand
KHK-Curve Type	3	78.11	8.72	21.74	Shale
Amawbia-3	4	970.41	28.32	50.06	Sand
	5	619.08	31.91	81.97	Water saturated sand
	6	85.21	Base not Reached		Shale
	1	606.17	3.03	3.03	Top soil
VES 186	2	18.64	9.04	12.07	Shale
HK-Curve Type	3	100.06	11.33	23.4	Shaly-sand
Nawfia-1	4	1550.03	33.52	56.92	Sand
	5	809.18	28.73	85.65	Water saturated sand
	6	22.75	Base not Reached		Shale
	1	562.02	2.81	2.81	Top soil
VES 187	2	41.06	12.3	15.11	Shale
HK-Curve Type	3	123.01	11.43	26.54	Shaly-sand
Nawfia-2	4	1805.84	20.18	46.72	Sand

	5	938.08	37.31	84.03	Water saturated sand
	6	35.7612	Base not Reached		Shale
	1	433.07	2.74	2.74	Top soil/laterite
VES 188	2	134.13	7.31	10.05	Shally-sand/Clayey-sand
HK-Curve Type	3	34.36	6.17	16.22	Shale
Nibo-1	4	4019.07	73.21	89.43	Dry sandstone
	5	2201.74	24.66	114.09	Water saturated sand
	6	22.02	Base not reached		Shale
	1	391.16	2.69	2.69	Top soil/laterite
VES 189	2	206.05	6.26	8.95	Shally-sand/Clayey-sand
HK-Curve Type	3	28.07	4.71	13.66	Shale
Nibo-2	4	3614.04	78.52	92.18	Dry sandstone
	5	1950.06	30.54	122.72	Water saturated sand
	6	30.28	Base not reached		Shale
	1	510.33	2.07	2.07	Top soil/laterite
VES 190	2	229.06	7.8	9.87	Shally-sand/Clayey-sand
HK-Curve Type	3	18.08	5.24	15.11	Shale
Nibo-3	4	3669.39	82.38	97.49	Dry sandstone
	5	1806.43	23.1	120.59	Water saturated sand
	6	25.07	Base not reached		Shale
	1	609.07	3.01	3.01	Top soil/laterite
VES 191	2	184.11	7.37	10.38	Shally-sand/Clayey-sand
HK-Curve Type	3	46.55	5.44	15.82	Shale
Mbakwu-1	4	5406.31	85.71	101.53	Dry sandstone
	5	2190.32	32.53	134.06	Water saturated sand
	6	24.62	Base not reached		Shale
	1	459.63	2.58	2.58	Top soil/laterite
VES 192	2	157.44	10.15	12.73	Shally-sand/Clayey-sand
HK-Curve Type	3	31.52	4.33	17.06	Shale
Mbakwu-2	4	4611.03	82.4	99.46	Dry sandstone
	5	1850.64	34.62	134.08	Water saturated sand
	6	19.18	Base not reached		Shale
	1	394.61	3.39	3.39	Top soil/laterite
VES 193	2	27.94	10.45	13.84	Shale
HK-Curve Type	3	640.07	34.25	48.09	Clayey-sand
Umuawulu-1	4	7038.84	54.53	102.62	Dry sandstone
	5	3048.71	27.94	130.56	Water saturated sand
	6	21.09			Shale
	1	231.5	2.87	2.87	Top soil/laterite
VES 194	2	773.15	20.89	23.76	Shally-sand/Clayey-sand
K-Curve Type	3	5017.4	74.12	97.88	Dry sandstone
Umuawulu-2	4	1083.2	34.13	132.01	Water saturated sand
	5	24.06	Base not reached		Shale
	1	26.09	2.82	2.82	Top soil/laterite
VES 195	2	709.58	16.26	19.08	Shally-sand/Clayey-sand

KHK-Curve Type	3	1283.17	18.59	37.67	Dry sandstone
Isiagu-1	4	51.44	105.57	143.24	Shale
	5	1490.89	55.38	198.62	Dry sand
	6	854.83	27.85	226.47	Water saturated sand
	7	28.13	Base not reached		Shale
	1	40.28	2.77	2.77	Top soil/laterite
VES 196	2	681.05	19.06	21.83	Shally-sand/Clayey-sand
KHK-Curve Type	3	1042.08	19.22	41.05	Dry sandstone
Isiagu-2	4	28.92	109.03	150.08	Shale
	5	1301.84	51.68	201.76	Dry sand
	6	909.08	22.25	224.01	Water saturated sand
	7	30.56	Base not reached		Shale
	1	504.69	2.59	2.59	Top soil/laterite
VES 197	2	151.6	8.04	10.63	Shally-sand/Clayey-sand
HK-Curve Type	3	17.01	7.42	18.05	Shale
Nise-1	4	2800.68	55.52	73.57	Dry sandstone
	5	1279.45	28.76	102.33	Water saturated sand
	6	30.65	Base not reached		Shale
	1	355.09	3.04	3.04	Top soil/laterite
VES 198	2	172.11	9.21	12.25	Shally-sand/Clayey-sand
HK-Curve Type	3	43.66	3.43	15.68	Shale
Nibo-2	4	3049.47	70.33	86.01	Dry sandstone
	5	1610.34	23.4	109.41	Water saturated sand
	6	27.86	Base not reached		Shale
	1	488.23	2.05	2.05	Top soil/laterite
VES 199	2	172.36	9.03	11.08	Shally-sand/Clayey-sand
HK-Curve Type	3	50.21	5.39	16.47	Shale
Nibo-3	4	4277.14	68.34	84.81	Dry sandstone
	5	2409.88	28.27	113.08	Water saturated sand
	6	38.62	Base not reached		Shale
	1	178.88	3.44	3.44	Top soil/laterite
VES 200	2	26.08	5.52	8.96	Shale
HK-Curve Type	3	581.56	9.79	18.75	Shally-sand/Clayey-sand
Okpeze-1	4	1550.39	41.33	60.08	Dry sandstone
	5	283.01	79.19	139.27	Shally-sand/Clayey-sand
	6	3025.84	71.35	210.62	Dry sandstone
	7	1405.36	26.16	236.78	Water saturated sand
	8	50.87	Base not reached		Shale
	1	206.05	3.06	3.06	Top soil/laterite
VES 201	2	41.11	7.25	10.31	Shale
HK-Curve Type	3	475.63	10.18	20.49	Shally-sand/Clayey-sand
Okpeze-2	4	2300.81	43.15	63.64	Dry sandstone
	5	357.62	77.38	141.02	Shally-sand/Clayey-sand
	6	2809.02	67.29	208.31	Dry sandstone

	7	1233.72	25.64	233.95	Water saturated sand
	8	47.087	Base not reached		Shale

G. Detailed Baseline geo-electric model parameters for Nsukka Formation

VES No. & Name	Layer	App. Res. (Ohm-m)	Thickness (m)	Depth (m)	Description
	1	3175.71	3.59	3.59	Top soil/Laterite
VES 202	2	801.11	12.25	15.84	Clayey-sand
K-Curve Type	3	13091.21	126.25	142.09	Dry sandstone
Owerre-Ezukala-1	4	5014.74	26.07	168.16	Water saturated sandstone
	5	52.56	Base not reached		Shale
	1	2805.79	2.98	2.98	Top soil/Laterite
VES 203	2	791.82	14.83	17.81	Clayey-sand
K-Curve Type	3	10014.82	119.21	137.02	Dry sandstone
Owerre-Ezukala-2	4	4900.08	24.03	161.05	Water saturated sandstone
	5	41.75	Base not reached		Shale
	1	2057.53	2.71	2.71	Top soil
VES 204	2	630.17	12.32	15.03	Clayey-sand
K-Curve Type	3	13455.01	58.29	73.32	Dry Sandstone
Umueje-1	4	3711.9	35.42	108.74	Saturated Sandstone
	5	37.06	Base not reached		Shale
	1	1820.08	2.83	2.83	Top soil
VES 205	2	844.11	12.66	15.49	Clayey-sand
K-Curve Type	3	9038.05	80.6	96.09	Dry Sandstone
Umueje-2	4	4069.11	23.02	119.11	Water Saturated Sandstone
	5	46.18	Base not reached		Shale
	1	2880.17	4.02	4.02	Top soil/Laterite
VES 206	2	730.86	6.04	10.06	Clayey-sand
K-Curve Type	3	8642.39	126.8	136.86	Dry sandstone
Umuchukwu-1	4	2470.51	23.23	160.09	Water saturated sandstone
	5	46.08	Base not reached		Shale
	1	2258.08	3.76	3.76	Top soil/Laterite
VES 207	2	683.16	10.05	13.81	Clayey-sand
K-Curve Type	3	9389.07	124.72	138.53	Dry sandstone
Umuchukwu-2	4	3390.65	25.9	164.43	Water saturated sandstone
	5	32.69	Base not reached		Shale

APPENDIX IV

Estimated Aquifer Parameters for the Study Area

VES Point	Aquifer Resistivity (Ohm-m)	Aquifer thickness (m)	Depth to Aquifer Z(m)	S (mhom)	TR(Ohm-m^2)	Conductivity (mho)	K (m/day)	T (m2/day)	Kz (m/day)	RC	FC
1	886.43	28.7	209.83	0.032377063	25440.541	0.001128121	0.40662603	11.6701671	3.379529858	0.3459336	0.48595738
2	692.43	22.29	210.47	0.03219098	15434.2647	0.001444189	0.520551553	11.6030941	5.435781942	0.3173019	0.51825489
3	600.07	28.71	206.88	0.047844418	17228.0097	0.001666472	0.600672442	17.2453058	4.929028931	0.205021	0.65972207
4	606.81	24.96	206.12	0.041133139	15145.9776	0.001647962	0.594000613	14.8262553	5.499265291	0.1848827	0.6879308
5	276.08	39.3	115.06	0.142350043	10849.944	0.003622139	1.30558357	51.3094343	5.127986765	0.305508	0.53197065
6	890.66	48.22	116.85	0.054139627	42947.6252	0.001122763	0.404694847	19.5143855	1.385379063	0.2726426	0.57153308
7	926.11	46.54	113.12	0.05025321	43101.1594	0.001079785	0.389203779	18.1135439	1.336121353	0.2665724	0.57906485
8	729.73	54.21	115.12	0.07428775	39558.6633	0.00137037	0.493943667	26.7766862	1.542879194	0.18377	0.68951735
9	1308.77	64.75	112.94	0.049473934	84742.8575	0.000764076	0.275407835	17.8326573	0.755787154	0.5894042	0.25833315
10	1008.01	36.45	112.66	0.036160356	36741.9645	0.000992054	0.357581286	13.0338379	1.46279686	0.3098375	0.52690701
11	1331.11	30.45	110.88	0.022875645	40532.2995	0.000751253	0.270785669	8.24542362	1.256819002	0.2432941	0.60862985
12	1519.45	46.84	101.59	0.030826944	71171.038	0.000658133	0.237221042	11.1114336	0.751723298	0.2689961	0.57604892
13	2205.19	40.49	91.55	0.01836123	89288.1431	0.000453476	0.163453268	6.61822282	0.533029625	0.389276	0.43959875
14	3666.01	36.88	114.74	0.010059983	135202.4488	0.000272776	0.09832093	3.62607589	0.402241375	0.4951098	0.33769436
15	1538	32.9	88.4	0.021391417	50600.2	0.000650195	0.234359891	7.71044041	0.864068534	0.8560464	0.07755925
16	233.6	36.3	53.6	0.155393836	8479.68	0.004280822	1.543003048	56.0110106	3.821376695	0.8959373	0.05488722
17	3887	42.76	48.36	0.011000772	166208.12	0.000257268	0.09273103	3.96517883	0.197606442	0.6089931	0.24301344
18	3678	45.02	65.18	0.012240348	165583.56	0.000271887	0.098000411	4.41197851	0.239885502	0.4282161	0.40034832
19	2611.3	43.89	168.19	0.01680772	114609.957	0.000382951	0.138032977	6.05826735	0.666986415	0.6347398	0.2234363
20	1893.41	35.92	116.19	0.018971063	68011.2872	0.000528148	0.190368442	6.83803444	0.806150994	0.4567986	0.37287338
21	4196.26	38.31	173.05	0.009129558	160758.7206	0.000238307	0.085896849	3.29070829	0.413651356	0.6639279	0.20197515

22	3044.23	33.71	110.3	0.011073408	102620.9933	0.00032849	0.118402851	3.99136012	0.554150632	0.7092218	0.17012317
23	4118.16	32.1	108.98	0.007794743	132192.936	0.000242827	0.087525864	2.80958023	0.384677536	0.5639258	0.27883301
24	1970.68	30.05	184.12	0.015248544	59218.934	0.000507439	0.182904131	5.49626912	1.303579958	0.5522606	0.28844341
25	1490.8	28.66	182.97	0.019224577	42726.328	0.000670781	0.241779925	6.92941265	1.785341435	0.5047834	0.32909492
26	3169.9	22.92	156.12	0.007230512	72654.108	0.000315467	0.113708796	2.6062056	0.888238344	0.7790464	0.12419778
27	2347.01	31.44	186.06	0.013395767	73789.9944	0.000426074	0.15357647	4.82844423	1.062432641	0.5924739	0.25590755
28	2173.08	21.77	190.24	0.010018039	47307.9516	0.000460176	0.165868496	3.61095717	1.615332101	0.5582807	0.2834658
29	4063.06	30.82	163.25	0.007585416	125223.5092	0.00024612	0.08871282	2.73412912	0.558614438	0.5567824	0.28470106
30	2280.81	22.19	167.44	0.009729	50611.1739	0.000438441	0.158033993	3.50677431	1.350517625	0.612333	0.24043858
31	2580.06	30.8	141.08	0.011937707	79465.848	0.000387588	0.139704314	4.30289287	0.779622646	0.5275083	0.30932188
32	2683.68	42.05	144.12	0.015668783	112848.744	0.000372623	0.134310168	5.64774257	0.594637907	0.5485729	0.2915117
33	863.8	34.48	159.06	0.039916647	29783.824	0.001157675	0.417278898	14.3877764	2.342231958	0.9447465	0.02841167
34	4451.8	28.68	186.09	0.006442338	127677.624	0.000224628	0.080966241	2.32211179	0.525348947	0.6953826	0.1796747
35	2411	28.68	168.24	0.011895479	69147.48	0.000414766	0.14950042	4.28767204	1.058544292	0.0865694	0.84065551
36	3523	29.43	159.64	0.008353676	103681.89	0.000283849	0.102312095	3.01104497	0.657293503	0.6053324	0.24584787
37	863.8	38.68	162.53	0.044778884	33411.784	0.001157675	0.417278898	16.1403478	2.17064858	0.9447465	0.02841167
38	4960.07	58.38	178.23	0.011769995	289568.8866	0.00020161	0.072669441	4.24244194	0.219838129	0.7503937	0.14260008
39	23.09	23.93	176.07	1.036379385	552.5437	0.043308792	15.61045959	373.558298	114.8572344	0.9982744	0.00086356
40	3703.06	42.88	115.18	0.011579613	158787.2128	0.000270047	0.097337205	4.17381937	0.358794744	0.6546529	0.2087127
41	2874.22	31.88	116.93	0.011091705	91630.1336	0.00034792	0.125406375	3.99795524	0.585373986	0.6991494	0.17705955
42	284.8	25.51	81.11	0.089571629	7265.248	0.003511236	1.265609242	32.2856918	5.289661207	0.2657144	0.58013526
43	527.88	21.87	74.98	0.04142987	11544.7356	0.00189437	0.68281714	14.9332109	3.023815272	0.1180981	0.78875176
44	1311.08	55.12	149.54	0.042041676	72266.7296	0.00076273	0.274922592	15.1537333	0.745862199	0.1851889	0.68749476
45	1208.11	49.67	97.96	0.041113806	60006.8237	0.000827739	0.298354878	14.8192868	0.88677533	0.2642851	0.58192161
46	980.11	34.48	96.08	0.035179725	33794.1928	0.001020294	0.367760264	12.6803739	1.392540025	0.5340553	0.30373396
47	1044.9	40.51	101.05	0.03876926	42328.899	0.000957029	0.344956945	13.9742058	1.205433353	0.4808943	0.35053525
48	2356.73	28.18	96.87	0.011957246	66412.6514	0.000424317	0.152943066	4.3099356	0.67869164	0.3603282	0.47023343

49	2077.03	46.87	50.07	0.022565875	97350.3961	0.000481457	0.173538905	8.13376848	0.358925996	0.4264812	0.40205146
50	1900.35	50.37	49.74	0.026505644	95720.6295	0.000526219	0.189673224	9.55384031	0.376974121	0.4387858	0.39006102
51	1009.01	33.72	67.08	0.033418896	34023.8172	0.00099107	0.357226898	12.045691	1.067866884	0.362552	0.46783384
52	970.41	26.43	68.76	0.027235911	25647.9363	0.001030492	0.371436312	9.81706174	1.337760974	0.3239963	0.51057818
53	1912.6	21.45	72.49	0.0112151	41025.27	0.000522848	0.188458388	4.04243241	0.825351094	0.4012741	0.42727252
54	2311.03	22.82	79.21	0.009874385	52737.7046	0.000432707	0.155967474	3.55917776	0.697342742	0.3685564	0.46139395
55	864.26	46.25	49.88	0.053513989	39972.025	0.001157059	0.417056802	19.2888771	0.866846927	0.2462969	0.60475401
56	995.11	43.31	57.91	0.043522827	43098.2141	0.001004914	0.362216752	15.6876075	0.863265138	0.308339	0.52865582
57	860.15	44.82	53.32	0.052107191	38551.923	0.001162588	0.419049598	18.781803	0.917570896	0.3013358	0.53688238
58	2511.03	23.26	76.76	0.009263131	58406.5578	0.000398243	0.143544885	3.33885402	0.617255348	0.4153236	0.41310435
59	2296.7	26.9	81.04	0.011712457	61781.23	0.000435407	0.156940616	4.22170256	0.6297461	0.3720694	0.45765218
60	606.23	38.83	121.26	0.064051598	23539.9109	0.001649539	0.594568913	23.0871109	2.451314378	0.31984	0.51533518
61	579.42	33.42	126.12	0.057678368	19364.2164	0.001725864	0.622079859	20.7899089	2.96967746	0.2606515	0.58648123
62	710.23	29.94	138.15	0.042155358	21264.2862	0.001407995	0.507505332	15.1947096	2.849250877	0.1682954	0.71189584
63	782.33	36.98	139.11	0.047269055	28930.5634	0.001278233	0.460733338	17.0379188	2.193903015	0.439672	0.38920535
64	848.23	30.46	137.99	0.035910072	25837.0858	0.001178926	0.424938415	12.9436241	2.349995929	0.3092196	0.52762763
65	839.08	56.35	91.83	0.067156886	47282.158	0.001191781	0.429572284	24.2063982	1.12961883	0.4026816	0.42584031
66	1206.19	51.8	87.81	0.042945141	62480.642	0.000829057	0.298829796	15.4793834	0.80539822	0.4081356	0.42031773
67	2519.08	35.63	124.23	0.014144053	89754.8204	0.00039697	0.143086171	5.09816028	0.042704395	0.5532996	0.28758164
68	3110.89	34.93	127.09	0.011228298	108663.3877	0.000321451	0.115865721	4.04718963	0.537433842	0.50329	0.33041532
69	1608.49	37.82	108.22	0.023512736	60833.0918	0.000621701	0.224089371	8.47506	0.865309671	0.4573493	0.37235461
70	2275.06	34.84	115.07	0.015313882	79263.0904	0.000439549	0.158433409	5.51981998	0.68170931	0.451736	0.37766099
71	1732	41.26	111.75	0.023822171	71462.32	0.000577367	0.208109418	8.58659459	0.771760108	0.4432542	0.38575727
72	1972.08	47.44	120.93	0.024055819	93555.4752	0.000507079	0.182774285	8.67081208	0.648686896	0.4352505	0.39348501
73	2011.06	38.96	123.07	0.019372868	78350.8976	0.00049725	0.179231605	6.98286334	0.745402899	0.3404122	0.49207829
74	2609.42	46.15	104.86	0.017685923	120424.733	0.000383227	0.138132425	6.37481141	0.70945891	0.4669279	0.36339354
75	3155.21	26.47	213.64	0.008389299	83518.4087	0.000316936	0.1142382	3.02388516	1.036257431	0.355885	0.4750513

76	2059.44	46.15	104.86	0.022409004	95043.156	0.000485569	0.175021128	8.07722506	0.572696436	0.4611201	0.36881287
77	1908.62	39.07	99.02	0.020470287	74569.7834	0.000523939	0.188851375	7.37842323	0.667481095	0.5228617	0.3133169
78	2705.37	34.8	101.86	0.012863305	94146.876	0.000369635	0.133233351	4.63652063	0.523208901	0.3767649	0.45268083
79	8207.54	24.86	64.29	0.003028922	204039.4444	0.000121839	0.043916388	1.09176141	0.157487771	0.5774596	0.26786127
80	4079.43	28.23	69.84	0.006920084	115162.3089	0.000245132	0.088356832	2.49431337	0.306948442	0.4832089	0.34842771
81	5122.07	29.24	66.75	0.00570863	149769.3268	0.000195234	0.070371063	2.05764989	0.231016359	0.6504123	0.21181841
82	4868.24	22.21	100.45	0.004562224	108123.6104	0.000205413	0.07404021	1.64443306	0.408904645	0.3004422	0.53793837
83	2883.38	20.72	103.09	0.007186011	59743.6336	0.000346815	0.125007981	2.59016536	0.746970952	0.5862085	0.26086831
84	4089.02	21.22	98.76	0.005189508	86769.0044	0.000244557	0.088149608	1.87053469	0.49840669	0.9131892	0.04537494
85	3800.94	23.86	98.18	0.006277395	90690.4284	0.000263093	0.094830624	2.26265869	0.485043141	0.4337106	0.39498165
86	5630.9	24.76	92.07	0.004397166	139421.084	0.000177592	0.064012061	1.58493862	0.302040755	0.2907713	0.54946117
87	4505.05	21.24	89.91	0.004714709	95687.262	0.000221973	0.080009215	1.69939572	0.41869229	0.5178	0.31769667
88	5039.75	21.47	94.56	0.004260132	108203.4325	0.000198423	0.071520514	1.53554544	0.386517245	0.4706406	0.35995155
89	4816.75	19.22	120.65	0.003990242	92577.935	0.000207609	0.074831684	1.43826496	0.469742075	0.3462121	0.48565005
90	5529.16	20.19	97.86	0.003651549	111633.7404	0.000180859	0.065189923	1.31618454	0.381162477	0.5292036	0.30787032
91	2068.26	37.44	171.72	0.018102173	77435.6544	0.000483498	0.174274758	6.52484696	0.973592638	0.4943952	0.33833409
92	1916.11	31.61	168.02	0.016496965	60568.2371	0.000521891	0.188113163	5.94625707	1.188011096	0.3845623	0.44449986
93	2736.77	32.11	191.12	0.011732809	87877.6847	0.000365394	0.131704715	4.22903839	0.783911714	0.3213117	0.51364743
94	2008.91	27.92	160.16	0.013898084	56088.7672	0.000497782	0.179423425	5.00950202	1.208666109	0.4664455	0.36384201
95	2309.05	24.6	97.06	0.010653732	56802.63	0.000433079	0.156101216	3.84008991	0.772003006	0.38912	0.43976041
96	3120.9	32.26	100.01	0.010336762	100680.234	0.00032042	0.115494092	3.72583941	0.473540098	0.3165266	0.51914891
97	3466.01	41.17	128.82	0.011878212	142695.6317	0.000288516	0.103994366	4.28144804	0.429390388	0.4007196	0.4278375
98	1009.13	30.78	121.09	0.030501521	31061.0214	0.000990953	0.357184418	10.9941364	1.764105758	0.4250283	0.40348092
99	2755.08	33.86	67.56	0.012290024	93287.0088	0.000362966	0.130829418	4.42988408	0.391870041	0.3257343	0.50859792
100	2566.18	28.36	118.05	0.011051446	72776.8648	0.000389684	0.140459949	3.98344415	0.725131916	0.3236928	0.51092458
101	3619.14	36.37	160.74	0.010049349	131628.1218	0.000276309	0.099594244	3.62224265	0.539758632	0.6622536	0.20318584
102	4100.04	29.54	164.01	0.007204808	121115.1816	0.0002439	0.087912682	2.59694062	0.576015559	0.4909372	0.34143811

103	5058.92	2768	162.83	0.547152357	14003090.56	0.000197671	0.071249498	197.218611	0.004903808	0.599068	0.25072856
104	2647.62	20.21	198.81	0.007633271	53508.4002	0.000377698	0.136139443	2.75137814	1.475371638	0.6059902	0.24533764
105	5488.71	27.18	200.88	0.004951983	149183.1378	0.000182192	0.065670351	1.78492014	0.551022084	0.2248597	0.63284001
106	5016.11	25.09	205.09	0.005001884	125854.1999	0.000199358	0.071857577	1.80290661	0.659233841	0.6422198	0.21786374
107	4914.06	27.77	203.46	0.005651132	136463.4462	0.000203498	0.073349839	2.03692504	0.610755609	0.5345018	0.30335464
108	3305.77	33.09	195.53	0.010009771	109387.9293	0.000302501	0.109035266	3.60797696	0.753328574	-0.515682	3.12951568
109	4179.55	33.24	193.07	0.007953009	138928.242	0.00023926	0.086240268	2.86662651	0.587155086	0.4915194	0.34091447
110	3455.84	27.04	196.48	0.007824436	93445.9136	0.000289365	0.104300405	2.82028295	0.862175537	0.4738752	0.35696696
111	2207.18	22.01	207.08	0.009972	48580.0318	0.000453067	0.163305898	3.59436282	1.699761389	0.5551076	0.28608462
112	2955.67	25.29	205.72	0.008556436	74748.8943	0.000338333	0.121950526	3.08412881	1.113949823	0.4826183	0.34896491
113	4071.42	23.1	204.91	0.005673696	94049.802	0.000245615	0.088530663	2.04505832	0.873847466	0.4629651	0.36708661
114	4048.11	22.9	205.22	0.005656961	92701.719	0.000247029	0.089040444	2.03902617	0.886982798	0.6025293	0.24802711
115	5104.05	24.43	203.35	0.004786395	124691.9415	0.000195923	0.07061951	1.72523464	0.658440933	0.3028887	0.5350505
116	3925.58	23.06	200.55	0.005874291	90523.8748	0.000254739	0.091819683	2.11736189	0.890364237	0.5381698	0.30024659
117	2895.58	24.38	196.05	0.008419729	70594.2404	0.000345354	0.124481283	3.03485367	1.125488483	0.5104853	0.32407779
118	3008.14	29.11	193.03	0.009677076	87566.9554	0.000332431	0.119823383	3.48805869	0.91437878	0.4338732	0.39482343
119	4209.29	24.06	195.86	0.005715928	101275.5174	0.00023757	0.085630952	2.06028072	0.782708186	0.4514525	0.37793001
120	4700.03	22.79	183.76	0.004848905	107113.6837	0.000212765	0.076690045	1.74776612	0.695056112	0.4496987	0.37959703
121	5031.76	20.85	179.96	0.004143679	104912.196	0.000198738	0.071634083	1.49357062	0.689920394	0.3660419	0.46408389
122	2235.81	29.37	188.11	0.013136179	65665.7397	0.000447265	0.161214733	4.73487671	1.193768476	0.5795548	0.26617958
123	3703.85	24.66	193.61	0.006657937	91336.941	0.000269989	0.097316444	2.39982351	0.861364973	0.4783119	0.35289449
124	4011.67	28.06	201.18	0.006994593	112567.4602	0.000249273	0.089849243	2.52116975	0.734035655	0.4195542	0.40889303
125	2654.31	26.05	204.77	0.009814227	69144.7755	0.000376746	0.135796313	3.53749396	1.203243953	0.5006782	0.33273079
126	3802.22	25.15	184.92	0.006614557	95625.833	0.000263004	0.0947987	2.3841873	0.791823575	0.4098649	0.41857567
127	3001.11	23.54	188.07	0.007843764	70646.1294	0.00033321	0.120104065	2.8272497	1.079661053	0.4583196	0.37144151
128	2861.94	24.72	200.33	0.008637498	70747.1568	0.000349413	0.125944468	3.11334726	1.146593953	0.513015	0.32186393
129	3269.55	22.74	202.65	0.006955086	74349.567	0.000305852	0.110243156	2.50692938	1.092687112	0.4677865	0.36259601

130	3372.13	22.74	202.65	0.006743512	76682.2362	0.000296548	0.106889566	2.43066873	1.074019214	0.4584781	0.37129245
131	2649.08	21.1	210.01	0.007965029	55895.588	0.00037749	0.136064412	2.87095909	1.490324467	0.5379098	0.3004664
132	3001.44	27.22	203.23	0.00906898	81699.1968	0.000333173	0.12009086	3.26887322	1.016713398	0.4676623	0.36271134
133	4158.79	28.84	189.25	0.006934709	119939.5036	0.000240455	0.086670765	2.49958487	0.655410095	0.3507495	0.48065939
134	3581.57	27.99	187.18	0.007815009	100248.1443	0.000279207	0.100638969	2.81688474	0.773650838	0.4343158	0.39439304
135	4415.07	22.2	198.36	0.005028233	98014.554	0.000226497	0.081639818	1.81240396	0.811102624	0.3194612	0.51577017
136	2589.24	39.06	83.08	0.015085508	101135.7144	0.000386214	0.139209	5.43750355	0.435304333	0.4719458	0.35874571
137	3310.25	37.37	74.89	0.011289178	123704.0425	0.000302092	0.108887701	4.06913338	0.327100169	0.4221971	0.40627481
138	2794.08	30.83	92.18	0.011034043	86141.4864	0.0003579	0.12900329	3.97717142	0.514716014	0.4177648	0.41067127
139	4086.71	35.58	107.05	0.00870627	145405.1418	0.000244696	0.088199435	3.13813589	0.353566201	0.5545611	0.28653673
140	2998.81	38.01	98.11	0.012675028	113984.7681	0.000333466	0.120196182	4.56865687	0.430442102	0.5340456	0.30374217
141	3188.41	32.48	103.33	0.010186896	103559.5568	0.000313636	0.113048671	3.67182082	0.472695197	0.4632821	0.36679041
142	1349.1	18.73	44.44	0.01388333	25268.643	0.000741235	0.267174792	5.00418386	0.901090849	0.6967463	0.17872662
143	3301.49	28.83	51.78	0.008732421	95181.9567	0.000302894	0.109176618	3.14756189	0.305262823	0.4677647	0.3626162
144	2605.08	36.28	88.72	0.013926636	94512.3024	0.000383865	0.13836255	5.01979332	0.476717716	0.5420767	0.29695237
145	4102.83	26.31	83.91	0.006412647	107945.4573	0.000243734	0.0878529	2.31140979	0.368040541	0.3743354	0.45524884
146	2385.3	39.35	70.03	0.016496877	93861.555	0.000419234	0.151111186	5.94622517	0.420039175	0.602738	0.24786458
147	4031.85	37.38	67.23	0.009271178	150710.553	0.000248025	0.089399534	3.34175459	0.250189547	0.4270124	0.40152949
148	4394.27	37.28	72.79	0.008483775	163818.3856	0.000227569	0.082026255	3.05793879	0.242184278	0.5228914	0.31329125
149	3816.48	38.43	74.01	0.010069488	146667.3264	0.000262022	0.094444491	3.6295018	0.276329393	0.5192935	0.3164013
150	4355.68	36.72	73.36	0.008430371	159940.5696	0.000229585	0.082752983	3.03868953	0.248078659	0.3508282	0.4805732
151	3917.04	33.47	75.09	0.008544717	131103.3288	0.000255295	0.09201987	3.07990505	0.2984666	0.4604517	0.36943937
152	3148.35	43.96	48.89	0.013962869	138401.466	0.000317627	0.114487116	5.03285362	0.241813665	0.4295951	0.39899755
153	4303.91	38.55	53.58	0.008956972	165915.7305	0.000232347	0.083748385	3.22850024	0.200148864	0.3723576	0.45734606
154	4620.14	36.65	70.91	0.00793266	169328.131	0.000216444	0.078016145	2.85929171	0.228960888	0.4216214	0.40684429
155	4106.74	36.23	67.83	0.008822083	148787.1902	0.000243502	0.087769255	3.17988012	0.252091324	0.4135038	0.41492365
156	3410.32	28.96	70.69	0.008491872	98762.8672	0.000293228	0.105692578	3.06085705	0.363683197	0.5259	0.3107019

157	2065.26	23.46	90.24	0.011359345	48450.9996	0.000484201	0.17452791	4.09442478	0.845857774	0.4712853	0.35935564
158	1895.24	27.49	91.79	0.014504759	52100.1476	0.000527638	0.190184627	5.22817539	0.825217254	0.3728773	0.45679441
159	906.59	25.56	82.13	0.02819356	23172.4404	0.001103034	0.397583816	10.1622423	1.675109591	0.215851	0.64493846
160	803.23	27.71	102.81	0.034498213	22257.5033	0.001244973	0.448745082	12.4347262	2.113684883	0.4712514	0.35938702
161	1911.36	26.84	101.34	0.014042357	51300.9024	0.000523188	0.18858065	5.06150466	0.9006061	0.6207228	0.23401734
162	1209.45	24.15	204.03	0.019967754	29208.2175	0.000826822	0.298024318	7.19728729	2.815867034	0.4276595	0.4008943
163	126.08	32.15	226.11	0.254996827	4053.472	0.007931472	2.858863515	91.912462	22.96516614	0.3794207	0.44988403
164	442.38	27.68	228.08	0.062570641	12245.0784	0.0022605	0.814787088	22.5533066	7.528538498	0.3415544	0.49080803
165	511.26	28.25	253.26	0.055255643	14443.095	0.001955952	0.705014106	19.9166485	6.320420265	0.2718546	0.57250677
166	2061.26	30.94	186.11	0.015010236	63775.3844	0.00048514	0.174866592	5.41037237	1.226722488	0.347462	0.48427196
167	1850.61	21.97	207.85	0.011871761	40657.9017	0.000540362	0.19477119	4.27912305	2.037428989	0.353484	0.47766799
168	1270.4	31.75	82.23	0.024992128	40335.2	0.000787154	0.283726001	9.00830054	1.018554003	0.617102	0.23678035
169	1001.08	28.07	76.99	0.028039717	28100.3156	0.000998921	0.360056651	10.1067902	1.347614954	0.4544969	0.37504589
170	2356.3	35.36	103.46	0.015006578	83318.768	0.000424394	0.152970977	5.40905373	0.60054952	0.4881175	0.34397988
171	1865.59	33.52	102.75	0.017967506	62534.5768	0.000536023	0.193207249	6.47630699	0.785452023	0.6783296	0.19166102
172	3502.01	21.81	52.38	0.006227852	76378.8381	0.00028555	0.102925323	2.2448013	0.350115989	0.490566	0.34177221
173	2906.18	29.3	49.01	0.010081963	85151.074	0.000344094	0.12402725	3.63399841	0.334450274	0.4054302	0.42305184
174	2302.09	34.16	39.01	0.01483869	78639.3944	0.000434388	0.156573163	5.34853924	0.339226575	0.4121548	0.41627533
175	412.76	34.83	196.65	0.084383177	14376.4308	0.002422715	0.873256885	30.4155373	5.803660745	0.3167583	0.51888168
176	502.88	32.28	190.05	0.064190264	16232.9664	0.001988546	0.716762472	23.1370926	4.936734833	0.28356	0.55816638
177	513.65	30.11	189.93	0.058619683	15466.0015	0.001946851	0.701733694	21.1292015	5.12817941	0.2639483	0.5823432
178	893.2	32.9	103.3	0.036833856	29386.28	0.00111957	0.403544013	13.276598	1.670598619	0.3795714	0.44972559
179	687.03	24.12	75.88	0.035107637	16571.1636	0.001455541	0.524643046	12.6543903	1.650493961	0.2021762	0.66364962
180	1274.08	24.64	100.57	0.019339445	31393.3312	0.00078488	0.282906499	6.97081613	1.437610501	0.6535091	0.20954884
181	1004.04	30.35	34.93	0.030227879	30472.614	0.000995976	0.358995172	10.8955035	0.772164904	0.6058105	0.24547695
182	893.21	34.09	36.76	0.038165717	30449.5289	0.001119558	0.403539495	13.7566614	0.838685046	0.2623555	0.58433971
183	183.21	34.13	42.95	0.186288958	6252.9573	0.005458217	1.967389946	67.1470189	4.44320003	0.4880472	0.34404342

184	139.14	42.13	38.73	0.302788558	5861.9682	0.007187006	2.590524019	109.138777	4.971986047	-0.863149	13.6144814
185	619.08	31.91	50.06	0.051544227	19754.8428	0.0016153	0.58222768	18.5788853	1.49561902	0.2210332	0.63795715
186	809.18	28.73	56.92	0.035505079	23247.7414	0.001235819	0.445445404	12.7976465	1.327963761	0.3140246	0.52204151
187	938.08	37.31	46.72	0.039772727	34999.7648	0.001066007	0.384237498	14.335901	0.865383998	0.3162483	0.51947016
188	2008.19	24.66	89.43	0.012279715	49521.9654	0.000497961	0.179487754	4.426168	0.830403806	0.3336309	0.49966535
189	1950.06	30.54	92.18	0.015661057	59554.8324	0.000512805	0.184838165	5.64495756	0.742741965	0.2990565	0.53957898
190	1806.43	23.1	97.49	0.012787653	41728.533	0.000553578	0.199534724	4.60925213	1.041640362	0.3402157	0.49229708
191	2190.32	32.53	101.53	0.014851711	71251.1096	0.000456554	0.164562946	5.35323264	0.678183478	0.4233443	0.4051414
192	1850.64	34.62	99.46	0.018707042	64069.1568	0.000540354	0.194768033	6.74286929	0.754318251	0.4271945	0.40135067
193	3048.71	27.94	102.62	0.009164532	85180.9574	0.000328008	0.118228861	3.30331439	0.552468149	0.39555	0.43312677
194	1083.2	34.13	97.88	0.031508493	36969.616	0.000923191	0.332759889	11.357095	1.287068062	0.6448874	0.21588871
195	854.83	27.85	198.62	0.032579577	23807.0155	0.001169823	0.421657537	11.7431624	3.428825221	0.2711577	0.57336893
196	909.08	22.25	201.76	0.024475294	20227.03	0.001100013	0.396494821	8.82200977	3.991856398	0.1776455	0.69830394
197	1279.45	28.76	73.57	0.022478409	36796.982	0.000781586	0.281719107	8.10224153	1.00237539	0.3728386	0.45683548
198	1610.34	23.4	86.01	0.014531093	37681.956	0.000620987	0.223831931	5.23766719	1.046557759	0.3088388	0.52807209
199	2409.88	28.27	84.81	0.011730875	68127.3076	0.000414958	0.149569901	4.22834109	0.598279604	0.2792365	0.56343257
200	1405.36	26.16	210.62	0.018614448	36764.2176	0.000711561	0.256479131	6.70949408	2.321449871	0.3656978	0.46445285
201	1233.72	25.64	208.31	0.020782674	31632.5808	0.000810557	0.292161521	7.4910214	2.665802958	0.3896615	0.43919944
202	5014.74	26.07	142.09	0.005198674	130734.2718	0.000199412	0.071877208	1.87383882	0.463631427	0.4460672	0.38306161
203	4900.08	24.03	137.02	0.004904002	117748.9224	0.000204078	0.073559108	1.76762536	0.492996019	0.3429282	0.48928288
204	3711.9	35.42	73.32	0.009542283	131475.498	0.000269404	0.097105394	3.43947306	0.298115205	0.5675518	0.27587493
205	4069.11	23.02	96.09	0.005657257	93670.9122	0.000245754	0.088580921	2.0391328	0.458335078	0.3791012	0.4502199
206	2470.51	23.23	136.86	0.009402917	57389.9473	0.000404775	0.145899232	3.38923916	1.005467415	0.5553798	0.28585958
207	3390.65	25.9	138.53	0.007638653	87817.835	0.000294929	0.106305727	2.75331832	0.67489771	0.4693702	0.36112735

APPENDIX V

Random Selected Overlying Resistivity and Aquifer Parameters for the Study Area

VES NO	Overlying Resistivity	Aquifer Resistivity (Ohm-m)	Aquifer thickness (m)	Depth to Aquifer (m)	S (mhom)	TR(Ohm-m^2)	Conductivity (mho)	K (m/day)	T (m2/day)	Kz (m/day)	RC	FC
10	1913.07	1008.01	36.45	112.66	0.0361604	36741.965	0.0009921	0.3575813	13.033838	1.4627969	0.3098375	0.526907
8	1058.32	729.73	54.21	115.12	0.0742878	39558.663	0.0013704	0.4939437	26.776686	1.5428792	0.18377	0.6895174
9	5066.21	1308.77	64.75	112.94	0.0494739	84742.858	0.0007641	0.2754078	17.832657	0.7557872	0.5894042	0.2583332
37	30403	863.8	38.68	162.53	0.0447789	33411.784	0.0011577	0.4172789	16.140348	2.1706486	0.9447465	0.0284117
40	17742.38	3703.06	42.88	115.18	0.0115796	158787.21	0.00027	0.0973372	4.1738194	0.3587947	0.6546529	0.2087127
7	1599.32	926.11	46.54	113.12	0.0502532	43101.159	0.0010798	0.3892038	18.113544	1.3361214	0.2665724	0.5790649
29	14271.32	4063.06	30.82	163.25	0.0075854	125223.51	0.0002461	0.0887128	2.7341291	0.5586144	0.5567824	0.2847011
28	7666.11	2173.08	21.77	190.24	0.010018	47307.952	0.0004602	0.1658685	3.6109572	1.6153321	0.5582807	0.2834658
131	8816.56	2649.08	21.1	210.01	0.007965	55895.588	0.0003775	0.1360644	2.8709591	1.4903245	0.5379098	0.3004664
124	9811.05	4011.67	28.06	201.18	0.0069946	112567.46	0.0002493	0.0898492	2.5211698	0.7340357	0.4195542	0.408893
155	9897.58	4106.74	36.23	67.83	0.0088221	148787.19	0.0002435	0.0877693	3.1798801	0.2520913	0.4135038	0.4149237
5	518.976	276.08	39.3	115.06	0.14235	10849.944	0.0036221	1.305584	51.30943	5.1279868	0.305508	0.5319707
22	17894.27	3044.23	33.71	110.3	0.0110734	102620.99	0.0003285	0.1184029	3.9913601	0.5541506	0.7092218	0.1701232
19	11687	2611.3	43.89	168.19	0.0168077	114609.96	0.000383	0.138033	6.0582674	0.6669864	0.6347398	0.2234363
129	9017.06	3269.55	22.74	202.65	0.0069551	74349.567	0.0003059	0.1102432	2.5069294	1.0926871	0.4677865	0.362596
133	8652.26	4158.79	28.84	189.25	0.0069347	119939.5	0.0002405	0.0866708	2.4995849	0.6554101	0.3507495	0.4806594
106	23024.07	5016.11	25.09	205.09	0.0050019	125854.2	0.0001994	0.0718576	1.8029066	0.6592338	0.6422198	0.2178637
108	1056.32	3305.77	33.09	195.53	0.0100098	109387.93	0.0003025	0.1090353	3.607977	0.7533286	-0.515682	3.1295157
120	12381.63	4700.03	22.79	183.76	0.0048489	107113.68	0.0002128	0.07669	1.7477661	0.6950561	0.4496987	0.379597
152	7890.65	3148.35	43.96	48.89	0.0139629	138401.47	0.0003176	0.1144871	5.0328536	0.2418137	0.4295951	0.3989976
150	9063.51	4355.68	36.72	73.36	0.0084304	159940.57	0.0002296	0.082753	3.0386895	0.2480787	0.3508282	0.4805732

205	9038.05	4069.11	23.02	96.09	0.0056573	93670.912	0.0002458	0.0885809	2.0391328	0.4583351	0.3791012	0.4502199
202	13091.21	5014.74	26.07	142.09	0.0051987	130734.27	0.0001994	0.0718772	1.8738388	0.4636314	0.4460672	0.3830616
148	4394.27	4394.27	37.28	72.79	0.0084838	163818.39	0.0002276	0.0820263	3.0579388	0.2421843	0.522891	0.313291
147	10041.23	4031.85	37.38	67.23	0.0092712	150710.55	0.000248	0.0893995	3.3417546	0.2501895	0.4270124	0.4015295
142	7548.4	1349.1	18.73	44.44	0.0138833	25268.643	0.0007412	0.2671748	5.0041839	0.9010908	0.6967463	0.1787266
139	14262.43	4086.71	35.58	107.05	0.0087063	145405.14	0.0002447	0.0881994	3.1381359	0.3535662	0.5545611	0.2865367
136	7217.48	2589.24	39.06	83.08	0.0150855	101135.71	0.0003862	0.139209	5.4375036	0.4353043	0.4719458	0.3587457
196	1301.84	909.08	22.25	201.76	0.0244753	20227.03	0.0011	0.3964948	8.8220098	3.9918564	0.1776455	0.6983039
200	3025.84	1405.36	26.16	210.62	0.0186144	36764.218	0.0007116	0.2564791	6.7094941	2.3214499	0.3656978	0.4644529
179	1035.23	687.03	24.12	75.88	0.0351076	16571.164	0.0014555	0.524643	12.65439	1.650494	0.2021762	0.6636496
188	4019.07	2008.19	24.66	89.43	0.0122797	49521.965	0.000498	0.1794878	4.426168	0.8304038	0.3336309	0.4996654
175	795.48	412.76	34.83	196.65	0.0843832	14376.431	0.0024227	0.8732569	30.415537	5.8036607	0.3167583	0.5188817
97	8101.23	3466.01	41.17	128.82	0.0118782	142695.63	0.0002885	0.1039944	4.281448	0.4293904	0.4007196	0.4278375
92	4310.71	1916.11	31.61	168.02	0.016497	60568.237	0.0005219	0.1881132	5.9462571	1.1880111	0.3845623	0.4444999
77	6091.66	1908.62	39.07	99.02	0.0204703	74569.783	0.0005239	0.1888514	7.3784232	0.6674811	0.5228617	0.3133169
11	1331.11	1331.11	30.45	110.88	0.0228756	40532.3	0.0007513	0.2707857	8.2454236	1.256819	0.243294	0.60863
2	1336.08	692.43	22.29	210.47	0.032191	15434.265	0.0014442	0.5205516	11.603094	5.4357819	0.3173019	0.5182549
55	1429.11	864.26	46.25	49.88	0.053514	39972.025	0.0011571	0.4170568	19.288877	0.8668469	0.2462969	0.604754
4	882.08	606.81	24.96	206.12	0.0411331	15145.978	0.001648	0.5940006	14.826255	5.4992653	0.1848827	0.6879308
1	1824.09	886.43	28.7	209.83	0.0323771	25440.541	0.0011281	0.406626	11.670167	3.3795299	0.3459336	0.4859574
45	2076.07	1208.11	49.67	97.96	0.0411138	60006.824	0.0008277	0.2983549	14.819287	0.8867753	0.2642851	0.5819216
42	490.92	284.8	25.51	81.11	0.0895716	7265.248	0.0035112	1.2656092	32.285692	5.2896612	0.2657144	0.5801353
49	5166.08	2077.03	46.87	50.07	0.0225659	97350.396	0.0004815	0.1735389	8.1337685	0.358926	0.4264812	0.4020515
79	30641.01	8207.54	24.86	64.29	0.0030289	204039.44	0.0001218	0.0439164	1.0917614	0.1574878	0.5774596	0.2678613
82	9049.81	4868.24	22.21	100.45	0.0045622	108123.61	0.0002054	0.0740402	1.6444331	0.4089046	0.3004422	0.5379384
67	8759.53	2519.08	35.63	124.23	0.0141441	89754.82	0.000397	0.1430862	5.0981603	0.0427044	0.5532996	0.2875816
73	4086.87	2011.06	38.96	123.07	0.0193729	78350.898	0.0004973	0.1792316	6.9828633	0.7454029	0.3404122	0.4920783

186	1550.03	809.18	28.73	56.92	0.0355051	23247.741	0.0012358	0.4454454	12.797647	1.3279638	0.3140246	0.5220415
172	1550.03	3502.01	21.81	52.38	0.0062279	76378.838	0.0002856	0.1029253	2.2448013	0.350116	0.490566	0.3417722
166	1550.03	2061.26	30.94	186.11	0.0150102	63775.384	0.0004851	0.1748666	5.4103724	1.2267225	0.347462	0.484272
58	1550.03	2511.03	23.26	76.76	0.0092631	58406.558	0.0003982	0.1435449	3.338854	0.6172553	0.4153236	0.4131044
53	1550.03	1912.6	21.45	72.49	0.0112151	41025.27	0.0005228	0.1884584	4.0424324	0.8253511	0.4012741	0.4272725
170	1550.03	2356.3	35.36	103.46	0.0150066	83318.768	0.0004244	0.152971	5.4090537	0.6005495	0.4881175	0.3439799
162	1550.03	1209.45	24.15	204.03	0.0199678	29208.218	0.0008268	0.2980243	7.1972873	2.815867	0.4276595	0.4008943
157	1550.03	2065.26	23.46	90.24	0.0113593	48451	0.0004842	0.1745279	4.0944248	0.8458578	0.4712853	0.3593556
51	1550.03	1009.01	33.72	67.08	0.0334189	34023.817	0.0009911	0.3572269	12.045691	1.0678669	0.362552	0.467834

APPENDIX VI

Validation of Hydraulic Conductivity Calculated within the study area

Alluvium Sand

VES Point	Aquifer Resistivity (Ohm-m)	K (m/day)	K-calculated (m/day)
1	886.43	0.406626	0.437812
2	692.43	0.520552	0.560475
3	600.07	0.600672	0.646741
4	606.81	0.594001	0.639558

Benin Formation

VES Point	Aquifer Resistivity (Ohm-m)	K (m/day)	K-calculated (m/day)
5	276.08	1.305584	1.425565
6	890.66	0.404695	0.441886
7	926.11	0.389204	0.424971
8	729.73	0.493944	0.539336
9	1308.77	0.275408	0.300717
10	1008.01	0.357581	0.390443
11	1331.11	0.270786	0.295671

Ogwashi-Asaba Formation

VES Point	Aquifer Resistivity (Ohm-m)	K (m/day)	K-calculated (m/day)
12	1519.45	0.237221	0.233124
13	2205.19	0.163453	0.16063
14	3666.01	0.098321	0.096623
15	1538	0.23436	0.230312
16	233.6	1.543003	1.516353
17	3887	0.092731	0.091129
18	3678	0.098	0.096308
19	2611.3	0.138033	0.135649
20	1893.41	0.190368	0.18708
21	4196.26	0.085897	0.084413
22	3044.23	0.118403	0.116358
23	4118.16	0.087526	0.086014
24	1970.68	0.182904	0.179745
25	1490.8	0.24178	0.237604
26	3169.9	0.113709	0.111745
27	2347.01	0.153576	0.150924
28	2173.08	0.165868	0.163004
29	4063.06	0.088713	0.087181
30	2280.81	0.158034	0.155304
31	2580.06	0.139704	0.137291
32	2683.68	0.13431	0.13199
33	863.8	0.417279	0.410072

34	4451.8	0.080966	0.079568
35	2411	0.1495	0.146918
36	3523	0.102312	0.100545
37	863.8	0.417279	0.410072
38	4960.07	0.072669	0.071414
39	23.09	15.61046	15.34084
40	3703.06	0.097337	0.095656
41	2874.22	0.125406	0.12324

Ameki Formation

VES Point	Aquifer Resistivity (Ohm-m)	K (m/day)	K-calculated (m/day)
42	284.8	1.265609	1.320681
43	527.88	0.682817	0.712529
44	1311.08	0.274923	0.286886
45	1208.11	0.298355	0.311338
46	980.11	0.36776	0.383763
47	1044.9	0.344957	0.359967
48	2356.73	0.152943	0.159598
49	2077.03	0.173539	0.18109
50	1900.35	0.189673	0.197927
51	1009.01	0.357227	0.372771
52	970.41	0.371436	0.387599
53	1912.6	0.188458	0.196659
54	2311.03	0.155967	0.162754
55	864.26	0.417057	0.435205
56	995.11	0.362217	0.377978
57	860.15	0.41905	0.437284
58	2511.03	0.143545	0.149791
59	2296.7	0.156941	0.16377
60	606.23	0.594569	0.620441
61	579.42	0.62208	0.649149
62	710.23	0.507505	0.529589
63	782.33	0.460733	0.480782
64	848.23	0.424938	0.443429
65	839.08	0.429572	0.448265
66	1206.19	0.29883	0.311833
67	2519.08	0.143086	0.149312
68	3110.89	0.115866	0.120908
69	1608.49	0.224089	0.23384
70	2275.06	0.158433	0.165328
71	1732	0.208109	0.217165
72	1972.08	0.182774	0.190728
73	2011.06	0.179232	0.187031
74	2609.42	0.138132	0.144143
75	3155.21	0.114238	0.119209
76	2059.44	0.175021	0.182637

77	1908.62	0.188851	0.197069
78	2705.37	0.133233	0.139031
79	8207.54	0.043916	0.045827
80	4079.43	0.088357	0.092202
81	5122.07	0.070371	0.073433
82	4868.24	0.07404	0.077262
83	2883.38	0.125008	0.130448
84	4089.02	0.08815	0.091985
85	3800.94	0.094831	0.098957
86	5630.9	0.064012	0.066797
87	4505.05	0.080009	0.083491
88	5039.75	0.071521	0.074633
89	4816.75	0.074832	0.078088
90	5529.16	0.06519	0.068027
91	2068.26	0.174275	0.181858
92	1916.11	0.188113	0.196299
93	2736.77	0.131705	0.137436
94	2008.91	0.179423	0.187231
95	2309.05	0.156101	0.162894
96	3120.9	0.115494	0.12052
97	3466.01	0.103994	0.10852
98	1009.13	0.357184	0.372727
99	2755.08	0.130829	0.136522
100	2566.18	0.14046	0.146572
101	3619.14	0.099594	0.103928
102	4100.04	0.087913	0.091738
103	5058.92	0.071249	0.07435
104	2647.62	0.136139	0.142063
105	5488.71	0.06567	0.068528
106	5016.11	0.071858	0.074984
107	4914.06	0.07335	0.076542
108	3305.77	0.109035	0.11378
109	4179.55	0.08624	0.089993
110	3455.84	0.1043	0.108839
111	2207.18	0.163306	0.170412
112	2955.67	0.121951	0.127257
113	4071.42	0.088531	0.092383
114	4048.11	0.08904	0.092915
115	5104.05	0.07062	0.073692
116	3925.58	0.09182	0.095815
117	2895.58	0.124481	0.129898
118	3008.14	0.119823	0.125037
119	4209.29	0.085631	0.089357
120	4700.03	0.07669	0.080027
121	5031.76	0.071634	0.074751
122	2235.81	0.161215	0.16823
123	3703.85	0.097316	0.101551

124	4011.67	0.089849	0.093759
125	2654.31	0.135796	0.141705
126	3802.22	0.094799	0.098924
127	3001.11	0.120104	0.12533
128	2861.94	0.125944	0.131425
129	3269.55	0.110243	0.11504
130	3372.13	0.10689	0.111541
131	2649.08	0.136064	0.141985
132	3001.44	0.120091	0.125317
133	4158.79	0.086671	0.090442
134	3581.57	0.100639	0.105018
135	4415.07	0.08164	0.085192
136	2589.24	0.139209	0.145267
137	3310.25	0.108888	0.113626
138	2794.08	0.129003	0.134617
139	4086.71	0.088199	0.092037
140	2998.81	0.120196	0.125426
141	3188.41	0.113049	0.117968

Ebenebe Sandsone

VES Point	Aquifer Resistivity (Ohm-m)	K (m/day)	K-calculated (m/day)
142	1349.1	0.267175	0.29029
143	3301.49	0.109177	0.118622
144	2605.08	0.138363	0.150333
145	4102.83	0.087853	0.095454
146	2385.3	0.151111	0.164185
147	4031.85	0.0894	0.097134
148	4394.27	0.082026	0.089123
149	3816.48	0.094444	0.102615
150	4355.68	0.082753	0.089912
151	3917.04	0.09202	0.099981
152	3148.35	0.114487	0.124392
153	4303.91	0.083748	0.090994
154	4620.14	0.078016	0.084766
155	4106.74	0.087769	0.095363
156	3410.32	0.105693	0.114837

Imo Shale

VES Point	Aquifer Resistivity (Ohm-m)	K (m/day)	K-calculated (m/day)
157	2065.26	0.174528	0.16902
158	1895.24	0.190185	0.184182
159	906.59	0.397584	0.385036
160	803.23	0.448745	0.434583
161	1911.36	0.188581	0.182629
162	1209.45	0.298024	0.288619
163	126.08	2.858864	2.768639

164	442.38	0.814787	0.789073
165	511.26	0.705014	0.682764
166	2061.26	0.174867	0.169348
167	1850.61	0.194771	0.188624
168	1270.4	0.283726	0.274772
169	1001.08	0.360057	0.348693
170	2356.3	0.152971	0.148143
171	1865.59	0.193207	0.18711
172	3502.01	0.102925	0.099677
173	2906.18	0.124027	0.120113
174	2302.09	0.156573	0.151632
175	412.76	0.873257	0.845697
176	502.88	0.716762	0.694142
177	513.65	0.701734	0.679587
178	893.2	0.403544	0.390808
179	687.03	0.524643	0.508086
180	1274.08	0.282906	0.273978
181	1004.04	0.358995	0.347665
182	893.21	0.403539	0.390804
183	183.21	1.96739	1.9053
184	139.14	2.590524	2.508768
185	619.08	0.582228	0.563853
186	809.18	0.445445	0.431387
187	938.08	0.384237	0.372111
188	2008.19	0.179488	0.173823
189	1950.06	0.184838	0.179005
190	1806.43	0.199535	0.193237
191	2190.32	0.164563	0.159369
192	1850.64	0.194768	0.188621
193	3048.71	0.118229	0.114498
194	1083.2	0.33276	0.322258
195	854.83	0.421658	0.40835
196	909.08	0.396495	0.383982
197	1279.45	0.281719	0.272828
198	1610.34	0.223832	0.216768
199	2409.88	0.14957	0.14485
200	1405.36	0.256479	0.248385
201	1233.72	0.292162	0.282941

Nsukka Formation

VES Point	Aquifer Resistivity (Ohm-m)	K (m/day)	K-calculated (m/day)
202	5014.74	0.071877	0.076333
203	4900.08	0.073559	0.078119
204	3711.9	0.097105	0.103125
205	4069.11	0.088581	0.094072
206	2470.51	0.145899	0.154944
207	3390.65	0.106306	0.112896