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Geophysical Characterization of Basement Rocks and Aquifer Potentials of Odeda General Hospital and it Environ in Abeokuta, Ogun State, Southwestern, Nigeria

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DECLARATION

I hereby declare that this project report has been written by me and is a project of my research. It has not been presented in any previous application for a degree of this or any other University. All citations and sources of information are clearly acknowledged by means of references.

OLAMILEKAN, Akinbode Gafar.

Date

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CERTIFICATION

This is to certify that the details of this project work were effectively performed by **AKINBODE OLAMILEKAN GAFAR** with Matric No. 20143526 of the Department of Water Resources Management and Agro meteorology during the 2018/2019 academic session.

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DEDICATION

This project is dedicated to Almighty God, the Alpha and Omega. Also, to my parent Mr and Mrs AKINBODE and other members of the family for their love, care and encouragement.

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To everyone whose name were aforementioned and others that contributed to the success of this training programme in anyway, I say thank and God bless you all.

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ABSTRACT

Groundwater of the continent are found beneath the earth surface which are water found in the rocks, consolidated or unconsolidated, that are permeable enough to permit usable quantities of water to move into wells. For the assessment of Groundwater there is need for investigation of the potentiality which triggered the application of Very Low Frequency-Electromagnetic (VLF-EM) as Reconnaissance survey for Fractures which are five (5) Traverse within the study area and Vertical Electrical Sounding (VES) for the confirmation of the yield rate.

Ten (10) VES were carried out using schlumberger electrode arrangement and their results are interpreted using computer iteration technique.

Interpretation of VES curves has led to the classification of the curves into five (5) types which are HH, HHA, KHH, AAH and H. The curves are of four to five layers with varying resistivities and thickness. The results of the interpretation revealed six distinct layers viz Topsoil, sand clay, clayey sand, lateritic, weathered basement (sand) and fresh basement (sand stone). The topsoil is generally lateritic and is characterized by relatively high layer resistivity values.

The underlain material is mostly sandy clay or clayey sand with reasonable resistivity values. The third layer consist of clayey sand or sandy clay or shale and sand (weathered/fractures) in some with reasonable resistivity values also. The fourth and fifth layer are made up of fractured and fresh basement and is characterised by high layer resistivity values.

The results of this research indicate that the sandy clay and sand (weathered or fractured) constitutes the major aquifer material and the occurrence of thick aquifer in term of the weathered/fractured basement are responsible for existence of good groundwater prospect in the study area.

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CHAPTER ONE
INTRODUCTION

➤ *Background Study*

The need for an uninterrupted supply of potable water for human consumption, farming system and the tremendous amount of money in building visible artificial reservoirs and irrigation canals involving surface water and in the treatment of the latter tend to encourage the development of groundwater resource.

Groundwater is that water contained in the voids of the geologic materials that comprise the crust of the earth and exists at a pressure greater than or equal to atmospheric pressure (Al Sabahi., 2009). It has been reported that at least 1.1 billion people across the world lack access to safe, clean drinking water. Nigeria with a population of over 160 million people have invested heavily in borehole Projects throughout the Country to satisfy the fast-growing demand for safe water and to improve the socio-economic development of its populace (Eduvie. 2006). Groundwater is also widely used as a source for drinking supply and irrigation (UNESCO, 2004). According to (Alabi. 2010), about 53% of all population relies on groundwater as a source of drinking water. Groundwater is water that fills water saturated pathways, including springs that surface naturally. Groundwater is a vital source of water, especially in areas with no drains, streams and rain, and provides an indication of groundwater to the potential for community formation to the extent permitted by their validity in terms of quality and quantity (M. Mohamaden, et al., 2016). Groundwater of the continent are found beneath the earth surface which are water found in the rocks, consolidated or unconsolidated, that are permeable enough to permit usable quantities of water to move into wells. The Groundwater can be in the sedimentary terrain where it is less difficult to exploit or in the basement complex terrain in which it can be a bit difficult to locate especially in areas underlined by crystalline rocks (Fadele et al., 2013). Groundwater is recommended for its natural microbiological quality and its general chemical quality for most uses (McDonald et al. 2002). The intrusions that gave rise to the existence of rocks and minerals during the Santonian uplift account for several fractures within the shale. These fractures contain water, serving as aquifer.

Groundwater flow in fractured aquifers is very complicated, and accuracy in estimation of the hydraulic parameters depends on the hydraulic behavior in particular fractures, which is site specific (Singh 2005). Fractured crystalline bedrock aquifers are good sources of potable water in many parts of the world. However, sitting of highly productive wells in these rock units remains a challenging and expensive task because fracture development at the regional scale is both heterogeneous and anisotropic (Manda, 2006). Weathering is not a uniform phenomenon in any environment and results in heterogeneous and hydrological characteristics of the rock formations. The conceptual structure of hard rocks is that of a fresh basement overlain by materials which have undergone different stages of weathering. Groundwater availability is therefore attributed to weathering in the overburden and basement surface. Basement weathering presents themselves as zones of disintegration (K'Orowo, 2008). These zones appear as low electrical resistivity anomalies compared to the massive basement rocks that surround them. Consequently, basement troughs with deep weathering are points of disintegration which are hydro-geologically viable as far as groundwater aquifers are concerned (K'Orowo. 2008). Geological media capable of accumulating groundwater have always been the target of groundwater Explorationist in any environment (Kayode et al., 2016). The search may prove to be more challenging, especially in hard crystalline basement complex environment, were availability of fresh water is dependent on fractured crystalline bedrock and other favourable parameters, porosity, permeability, transmissivity and all the rest given the heterogeneous and anisotropic nature of basement rocks formations (Manda et al., 2006). Therefore, extensive groundwater exploration in the basement complex region recognised the fractured bedrock and thick-weathered regolith as the two major prolific formations from which water can be extracted. An intrinsically low porosity limits the quantity of water stored in fractured crystalline rock. Sustainable well yields for bedrock, may strongly depend on the quantity of water stored in surficial materials that can leak downward into bedrock and on periodic replenishment by recharge (Lyford, 2004). This research becomes very necessary as a result of the frequent high failure rate of boreholes, being much higher where the weathered overburden is thin; shallow occurrence and fissure permeability of the bedrock aquifer unit which makes for susceptibility to surface contaminants; and the low storage capacity of fractured aquifers which are easily depleted during dry seasons. Therefore, to meet the ever-increasing demand of water in the study area, there is need for a detailed geophysical survey so as to site viable locations for withdrawal wells. This will also require understanding the geologic and hydrogeologic characteristics of the crystalline bedrock as well as the regional tectonic setting which are critical to identifying favourable areas to site large groundwater wells (Talkington. 2004).

Several works have been carried out on the assessment, abstraction, development and management of groundwater within the hard rock terrain of Nigeria. In areas underlain by crystalline rocks, groundwater occurs in fracture zone or in highly weathered basement (Ariyoet al. 2003). The types of geophysical method used for a survey depends mainly on the extent or size of area to be surveyed, the cost of the survey, geology of the area and the ease of the interpretation of data obtained. It also provides information on the depth of water table, the lithology in the subsurface layering and ensures a higher degree of accuracy in the location of hydro resources (Omosuyi et al. 2003). The geoelectric resistivity method is considered to be the most suitable and efficient method for groundwater exploration. It is based on the concept of subsurface determination, which can yield useful information on the structure, composition and water content of the soil. Geoelectric can also be used to determine the aquifer depth, stratigraphy and water quality of the aquifer (M. Mohamaden, et al., 2016).

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However, groundwater investigation in hard rock areas are often more difficult. It is very difficult to perform resistivity soundings everywhere without *a-priori* information.

Therefore, a combined study of VLF and DC resistivity has potential to be successful (Bernard and Valla 1991: Benson et al. 1997: Sharma and Baranwal 2005). The VLFEM method was adopted as a fast reconnaissance tool to map possible linear features such as; fault, and fracture zones while the electrical resistivity method was used to investigate prominent electromagnetic anomalies and provide a geo-electric image or section of the subsurface sequence. The advantage of VLF-EM is that it is relatively fast compared to many other geophysical methods. Hence, this method has probably been the most popular electromagnetic tool for quick mapping of near surface geologic structures in mineral exploration. However, it is being increasingly used for shallow groundwater exploration (Palacky et al. 1981) as a reconnaissance tool for weathered layer investigations. Also, VLF-EM has proved to be successful in identifying deep water bearing fractures in bedrock (Sundararajan et al. 2007).

A detailed knowledge of the subsurface geology and structure is provided by the geophysical surveys. The electrical resistivity method has been the most commonly used geophysical tool for groundwater investigation because of its advantage which include simplicity in field technique and data handling procedure (Anomohanran. 2013).

Electrical resistivity methods are effectively used for groundwater exploration in areas where good electrical resistivity contrast exists between the water bearing formation and the underlying rocks (Nejad. 2009). The method enables the determination of subsurface resistivity by sending an electric current into the ground and measuring the electrical potential produced by the current. Electrical resistivity method has been used successfully in delineation and exploitation of groundwater (Evans et al. 2010; George et al. 2010; Ibuot et al. 2013). It gives detailed information about hydrogeological settings and groundwater repositories. The electrical resistivity method and seismic refraction method are the surface geophysical methods commonly used for groundwater exploration (Odumodu et al, 2012). The method has been recognized to be more suitable for hydrogeological survey of sedimentary basin (Alabi., 2010 and Emekeme., 2004).

Nowadays the used of geophysical techniques for groundwater exploration and water quality evaluation has increases due to rapid advances in computer software and other numerical modelling techniques. The use of Vertical Electrical Sounding (VES) has become very popular with groundwater prospecting due to simplicity of the technique.

The purpose of electrical geophysical survey method is to detect the surface effects that produce by flow of electric current inside the earth. This technique has been used in a wide range of geophysical investigation such as mineral exploration, archaeological investigation, engineering studies, geothermal exploration, permafrost mapping and geological mapping (Fadele et al., 2013). The reason for its wide use is because the instrument is simple; field logistics are easy and straight forward while the analysis of data is less tedious and economical. This is the reason why many researchers such as Olowofela. (2005), Oseji. (2005, 2006), Iserhien-Emekeme. (2004), Okolie. (2005), Omosuyi. (2007), Batayneh (2009), Ezeh and Ugwu (2010), Nwankwo (2011), Batayneh. (2010) and Tammaneni. (2006) have all used this method for the determination of aquifer boundary. Potential field methods like gravity and magnetics have been successfully used to map regional aquifers and large-scale basin features.

Subsurface geological characterizations using surficial geo electrical resistivity technique are sufficient to address variety of problems related hydrological investigations in complex geological terrains such as crystalline basement. In groundwater exploration, vertical electrical sounding (VES) employing Schlumberger electrode configuration is a common geophysical technique (Ezeh and Ugwu 2010; Olawuyi and Abolarin 2013; George. 2011; Ibuot. 2013). The resistivity method is aimed at measuring the potential differences on the surface due to the current flow within the ground. Since the mechanisms that control the fluid flow and electric current and conduction are generally governed by the same physical parameters and lithological attributes, the hydraulic and electrical conductivities are dependent on each other (George. 2015). The geoelectric resistivity method is considered to be the most suitable and efficient method for groundwater exploration. It is based on the concept of subsurface determination, which can yield useful information on the structure, composition and water content of the soil. Geoelectric can also be used to determine the aquifer depth, stratigraphy and water quality of the aquifer (Mohamaden, et al, 2016). It is one of the geophysical methods that study the nature of electrical current in the earth and to know the change of resistance of rock layers beneath the soil surface by passing a DC current (direct current) that has high voltage into the ground. This method is more effective for superficial exploration, such as determination of depth of bedrock, Water reservoir search, and also for geothermal exploration.

This capacity is used by humans to distinguish the type of rock without having to make physical contact or drilling that takes a long time and high cost, yet the accuracy level of data is reliable because the pumping test can provide important information on transmissivity and storativity of groundwater aquifers (Mahmoud et al, 2017). The electromagnetic and resistivity methods are both responsive to water bearing basement fracture columns due to the relatively high bulk electric conductivities, both methods were, therefore, found relevant and were hence integrated in the geophysical investigation.

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➢ *Problem Statement*

The need for water in the study area has aroused interest in the use of groundwater due to lack of surface water both saline and fraught with coliform. Most of the hand-dug wells or drilled boreholes have been done without any preliminary geophysical investigations. This has resulted to failures of some boreholes and contamination of water which has resulted to various waterborne diseases. None of the surface water is as hygienic or as economical for exploitation as the groundwater (Singh. 2007). Since there is no evenly distribution of water within the study area, however there is need for vast water supply for municipal uses which enhances efficient therapy for patient in the general hospital and within the environ for domestic and irrigation uses by local farmers.

➢ *Justification*

Electrical Sounding (VES) technique, had been found effective in achieving good spatial coverage for mapping of aquifer units (Ojo et al., 2007). The geoelectrical method is capable of mapping both low and high resistive formations and therefore a valuable tool for vulnerability studies (Sørensen et al. 2005). This technique has been used in a wide range of geophysical investigation such as mineral exploration, archaeological investigation, engineering studies, geothermal exploration, permafrost mapping and geological mapping (Fadele et al., 2013). The electrical resistivity method and seismic refraction method are the surface geophysical methods commonly used for groundwater exploration (Odumodu et al. 2012). The Electrical Resistivity method amongst several other geophysical methods has been used to solve environmental problems (Shevnin et al., 2005; Tse and Nwankwo, 2013; Atakpo, 2013).

➢ *Broad Objectives*

The objective of this study is to locate areas of weathered or fractured zones in the fresh basement for the investigation geophysical characterization of basement rocks and the aquifer potentiality of Odeda general hospital and its environment.

➢ *Specific Objectives*

- To determine the number and properties of the geo electrical layer vis a vis the apparent resistivity values, thickness and depth to basement.
- To determine the types distribution and continuity of the aquiferous zone such as fractures, faults and joints in the study area.
- To determine degree of weathering and thickness of the overburden and their variation relating to the topography of the selected points.
- To develop a geo-hydrological database for the study area that will guide government and individuals in groundwater development on the characteristics of the aquifers, the distribution of the aquifers as well as the depths boreholes could be drilled for sustainable water supply.

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CHAPTER TWO
LITERATURE REVIEW

Science of Geophysics applies the principles of physics to the study of the earth. Geophysical investigation of the earth involves taking measurement at or near the earth's surface that are influenced by the internal distribution of physical properties. The Very Low Frequency – Electromagnetic (VLF-EM) technique is a passive method that uses radiation from ground-based military radio transmitters as the primary EM field for geophysical survey. These transmitters generate plane EM waves that can induce secondary eddy currents, particularly in electrically conductive elongated 2-D targets. The EM waves propagate through the subsurface and are subjected to local distortions by the conductivity contracts in this medium. These distortions indicate the variations in geoelectrical properties which may be related to the presence of groundwater (Shendi., 1997). The subsurface occurrence of these conductive bodies creates a local secondary field which has its own components. Measurement of these components may be used as an indicator for locating the subsurface conductive zones. The VLF-EM waves travel in three modes: skywave, space wave (wave-guided by the ionosphere and earth surface), and groundwave. As the groundwave is attenuated through long distances, only the skywave and space wave are received as the primary wave (Jeng. 2004). VLF –EM ground surveys provide a quick and powerful tool for the study of geologic features within distance of 100 m of the surface. The magnetic component of the VLF wave is mainly used for field measurement. According to the basic EM theory, the primary EM field is shifted in phase when encountering a conductive body and the conductive body then becomes the source of a secondary field. The VLF instrument detects the primary and secondary fields, and separates the secondary field into in-phase and quadrature components based on the phase lag of the secondary field. These two components of the secondary field are sometimes referred to as the tilt (in-phase) and ellipticity (quadrature). When the VLF-EM method is used for geophysical survey, the in-phase response is sensitive to metal or good conductive bodies. The quadrature response, on the other hand, is sensitive to the variation of the earth electrical properties (Jeng., 2004).

Geophysical surveys have been most widely used because of the basic advantage of providing more accurate results than other methods. For instance, (Gabr et al. 2012) successfully used the seismic refraction method to investigate the groundwater level in the Wadi Al-an area of United Arab Emirates. The objective was to confirm or not the assumption that groundwater level can primarily be revealed by seismic refraction technique. (Ayolabi et al. 2009) used the seismic refraction shooting to determine the structural setting of subsurface materials and groundwater potential in Igbogbo Township. This method was able to delineate the formation layers and the aquifer characteristics of the location under study. (Lawrence and Ojo., 2012) applied the low frequency electromagnetic and the electrical resistivity methods to evaluate the aquifer potential of a typical basement complex terrain of Ado-Ekiti in Nigeria. Other researchers such as Oseji et al., 2006; Nejad, 2009; Egbai, 2011; Anudu et al., 2011; Sirhen et al., 2011; Ibrahim et al. 2012; Utom et al., 2012; and Anomohanran, 2013 have all used the electrical resistivity method to explore for groundwater in different locations. The geoelectric resistivity method is considered to be the most suitable and efficient method for groundwater exploration, it is based on the concept of subsurface determination, which can yield useful information on the structure, composition and water content of the soil. Geoelectric can also be used to determine the aquifer depth, stratigraphy and water quality of the aquifer (Mohamaden. 2016). The types of geophysical method used for a survey depends mainly on the extent or size of area to be surveyed, the cost of the survey, geology of the area and the ease of the interpretation of data obtained. It also provides information on the depth of water table, the lithology in the subsurface layering and ensures a higher degree of accuracy in the location of hydro resources (Omosuyi et al. 2003). This capacity is used by humans to distinguish the type of rock without having to make physical contact or drilling that takes a long time and high cost, yet the accuracy level of data is reliable because the pumping test can provide important information on transmissivity and storativity of groundwater aquifers. (Mahmoud and Ghoubachi. 2017). Geophysical investigations of the buried strata can be made either from the land surface or in a drilled hole in the formation, there are many numbers of geophysical exploration techniques which can give insight on the nature of the water bearing layers and these include geoelectric, electromagnetic, seismic and geophysical borehole logging (Alile., 2008). Based on the configuration of potential electrodes and current electrodes, there are several types of resistivity methods, such as Schlumberger Method, Wenner Method, Gradient, Poledipole and Dipole Sounding Method. These methods measure of formation materials, which determine whether such formation may be sufficiently porous and permeable to serve as an aquifer. A detailed knowledge of the subsurface geology and structure is provided by the geophysical surveys. Electrical resistivity method has been used successfully in delineation and exploitation of groundwater (Evans. 2010; George. 2010; Ibuot. 2013). The electrical resistivity method and seismic refraction method are the surface geophysical methods commonly used for groundwater exploration (Odumodu et al. 2012). Conrad schlumberger in 1920 was the first person to conduct experiment in the field of Normandy and at the end, he perfected the techniques in geophysical method. Electrical resistivity has been successfully used in several countries, including U.S.S.R, Spain, Egypt and Nigeria for the study of sub-structures of petroliferous interest to depth of several kilometres. Some deep crustal studies which has effective depth of tens of kilometre have been carried out in France, U.S. A and U.S.S.R. The procedure has been widely applied also to hydrologic investigations (Habibou. 2003). Thus, they concluded that the highest transverse resistance (T) corresponds to the zone with the highest borehole yield and determined the strike of foliation of concealed solid rock (in which the predominant structural feature is the foliation or where the fracture/joint direction are generally in line with strike of foliation). The electrical resistivity method has been used successfully in location site for borehole development in south western basement of Nigeria. It is unique because of its ability to detect increases in pore water conductivity (Abdul Nasir., 2000, Adepelumi. 2008). The studies reviewed show that geophysical methods are applicable to hydrological investigation and the delineation of geologic structures and

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materials. A lot of geophysical investigations have been carried out in different parts of the world for groundwater investigation: Bayor (2004) applied the electromagnetic and electrical resistivity methods in groundwater exploration at the Tolon-Kumbugu district of the Northern Region of Ghana. The study aimed at locating good yielding wells to be fitted with hand pumps to supply the communities with potable water. Results showed that, major aquifers were confined to hard, fractured sandstone formation and no water was found in the weathered zone or fresh rock aquifers. (Bayewu. 2017) proclaimed the prospecting location for groundwater yield at Awa-Ilaporu near, Ago Iwoye southwestern Nigeria using VLF-EM and VES survey methods. He used this method to delineate regions of fractured zones, faults, and thickness of the top layer, conductivity and impermeable strata which gave clues to the presence of groundwater. Ariyo and Banjo (2008) used the same method to study groundwater zone in a sedimentary terrain of Ilara-Remo, southwestern Nigeria. Their investigation involved the utilization of vertical electrical sounding (VES) technique with schlumberger array system; applied in ten (10) stations and the results were interpreted using the spatial curve-matching method and computer assisted iteration technique. Badmus and Olatinsu (2012) also used Vertical Electrical Sounding to determine the geophysical characteristics and groundwater potentials in Odeda quarry site, southwestern Nigeria and presumed groundwater to be very low within the study area as outcrops of gneissic rocks dominate the area.

- *Theory of Very Low Frequency-Electromagnetic (Vlfem)*

The VLF-EM method uses radio signals in the bandwidths of 15 – 30 KHz and is powerful tool for quick detection of near surface structures. Powerful radio transmitters set up for the purpose of military communication with submarines create such magnetic flux. In radio technology, the frequencies are called very low frequencies (VLF) since the frequency of ordinary radio programs is more than ten times as high. In the reconnaissance mode, Very Low Frequency profiles can be run quickly to identify anomalous areas which may require further investigation with more detailed geophysical measurements. It may be used wherever as electrical conductivity contrast is present between geological units. This may include fault mapping, groundwater investigations, overburden mapping, contaminant mapping and mineral exploration (Oluwafemi and Oladunjoye. 2013). Because of the easy operation of the instrument, speed of field survey and low operation cost, this method is suitable for rapid preliminary surveys and has been widely used in many geophysical investigations (Milson. 2002, Sharma and Baranwal. 2015). The existence of fracture zone in a geological medium can assist in creating ground water conduit medium and aids groundwater accumulation. Therefore, the use of VLF as geophysical tool is very crucial as it is very sensitive to changes in lithology and can detects zones of relatively low conductivity (fractures). The results can serve as primary information for the relevant ministries to set overall picture of migrating Leachate plume which will go a long way in preserving the abundant natural ground water as well as safe guarding the health of the nation, thereby preventing waste of public funds. One big advantage with the method is that it does not need direct contact with the ground which eliminates problems associated with rocky surface or bad contact due to dry conditions (Nils and Lennart, 2005).

- *Concept of Very Low Frequency- Electromagnetic (VLF-EM)*

Data filtering are applied in other to eliminate errors and enhance interpretation of data. This is done by applying a filter operator (Q) which transform true anomaly inflection to peak positive anomalies also referred to as conductivity because they are proportional (Parasnis., 1986). The filter operation is given by Fraser (1969):

$$F1 = (Q3 + Q4) – (Q1 + Q2)$$

Fraser filtering; where Q1, Q2, Q3 and Q4 are consecutive readings of the measured raw data obtained on the field.

- *Theory of Electrical Resistivity Method*

The electrical resistivity involves use of a direct current produced by artificial sources and the study of the electric field. For this study we restrict attention to the more important application of this method, viz vertical electrical sounding (VES). VES finds its principal use in areas where the geological structure can be approximated by layers which are horizontal or nearly so. The goal of VES is to determine the depth to the sub surfaces layers together with their electrical resistivities of conductivities from surface measurements. The less important application of this method, geoelectrical profiling using a constant electrode spacing will not be specifically used for detecting and delineating horizontal changes in electrical resistivity.

- *Concept of Apparent Resistivity*

Data from resistivity surveys are customarily presented and interpreted in the form of values of apparent resistivity ƒa. Apparent resistivity is defined as the resistivity of an electrically homogeneous and isotropic half-space that would yield the measured relationship between the applied current and the potential difference for a particular arrangement and spacing of electrodes (Wightman et al., 2003). An equation giving the apparent resistivity in terms of applied current, distribution of potential, and arrangement of electrodes can be arrived at through an examination of the potential distribution due to a single current electrode. For the general case of a set of four electrodes arbitrarily located on the flat surface of an electrically homogeneous and isotropic half space. The two current electrodes may be identified by letters A and B and the two potential electrodes by M and N. Let I be intensity of the total current that flows into the Earth at A and B, and Let ƒ (Rho) designates the electrical resistivity (assumed constant) of the subsurface. Aside from an additive constant (usually taken as zero to satisfy the boundary condition at infinity), the potential V at a distance r from a single point on the surface of a uniform half space is given by;

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$$V = \rho I/2\pi r \ldots\ldots (1)$$

Considering the first potential electrode M, the potential V1 at a distance AM is:

$$V1 = \rho I/2\pi AM \ldots\ldots (2)$$

The potential V2 at distance BM is

$$V2 = \rho I/2\pi BM \ldots\ldots (3)$$

The combined effects of A and B on M will be analogous to a potential gradient which can be expressed as:

$$\Delta v' = v1 - v2$$

$$= \rho I/2\pi\ (1/AM - 1/BM) \ldots\ldots (4)$$

Considering the second potential electrode N, the potential V3 at distance AN is:

$$V3 = \rho I/2\pi AN \ldots\ldots (5)$$

The potential V4 at distance BN is:

$$V4 = \rho I/2\pi BN \ldots\ldots (6)$$

The potential gradient $\Delta V'' = V3 - V4$

$$= \rho I/2\pi\ (1/AN - 1/BN) \ldots\ldots (7)$$

Thus, the potential difference which will observed between M and N is:

$$\Delta V = \Delta V' - \Delta V''$$

$$= \rho I/2\pi\ [(1/AM - 1/BM) - (1/AN - 1/BN)]$$

$$= \rho I/2\pi K \ldots\ldots (8)$$

With $K' = [(1/AM - 1/BM) - (1/AN - 1/BN)]$

Solving for ρ in this equation:

$$\rho = \Delta V 2\pi/IK,$$

$$= (\Delta V/I)\ K \ldots\ldots (9)$$

With $K = 2\pi/k' = 2\pi\ [(1/AM - 1/BM) - (1/AN - 1/BN)]$

Wherever these measurements are made over a real heterogeneous earth, as distinguished from the fictitious homogeneous half-space, the symbol ρ is replaced by ρa for apparent resistivity. The resistivity surveying problem is, reduced to its essence, the use of apparent resistivity values from field observations at various locations and with various electrode configurations to estimate the true resistivities of the several earth materials present at a site and to locate their boundaries spatially below the surface of the site.

An electrode array with constant spacing is used to investigate lateral changes in apparent resistivity reflecting lateral geologic variability or localized anomalous features. To investigate changes in resistivity with depth, the size of the electrode array is varied. The apparent resistivity is affected by material at increasingly greater depths (hence larger volume) as the electrode spacing is increased, Because of this effect, a plot of apparent resistivity against electrode spacing can be used to indicate vertical variations in resistivity (Wightman et al., 2003). The goal of geo-electrical interpretation is to delineate the nature of subsurface geologic variations from the observed variations in apparent resistivity (Habibou. 2003).

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- *Electrode Configuration*
  There are various electrodes arrangements:

✓ Gradient
✓ Dipole-Dipole
✓ Pole-dipole
✓ Schlumberger
✓ Wenner Array

The electrode arrangement configuration for the aforementioned geophysical methods in (fig. 1).

For VES, the two most important are Schlumberger and Wenner. They are used in measuring the Earth resistivity and their variation with depth. This is primarily based on their arrangement relative to one another. For the purpose of this study, Schlumberger array, which is the most widely used is employed for the qualitative interpretation (Habibou., 2003).

✓ *Schlumberger Arrangement*
In Schlumberger arrangement the distance between the two inner potential electrodes (MN) is kept constant for some time and the distance between the current electrodes (AB) is varied.

The apparent resisitivity ʃ a for a measured Resistance R = (V/I) is given by:

ʃ a = π [((AB/2)2 – (MN/2)2) /MN] R, AB > MN ……………………… (10)

ʃ a = πAB2/4MN, if AB > 5MN …………………………………………… (11)

For practical application, accurate and good results can be obtained if AB > 5MN

(Habibou. 2003).

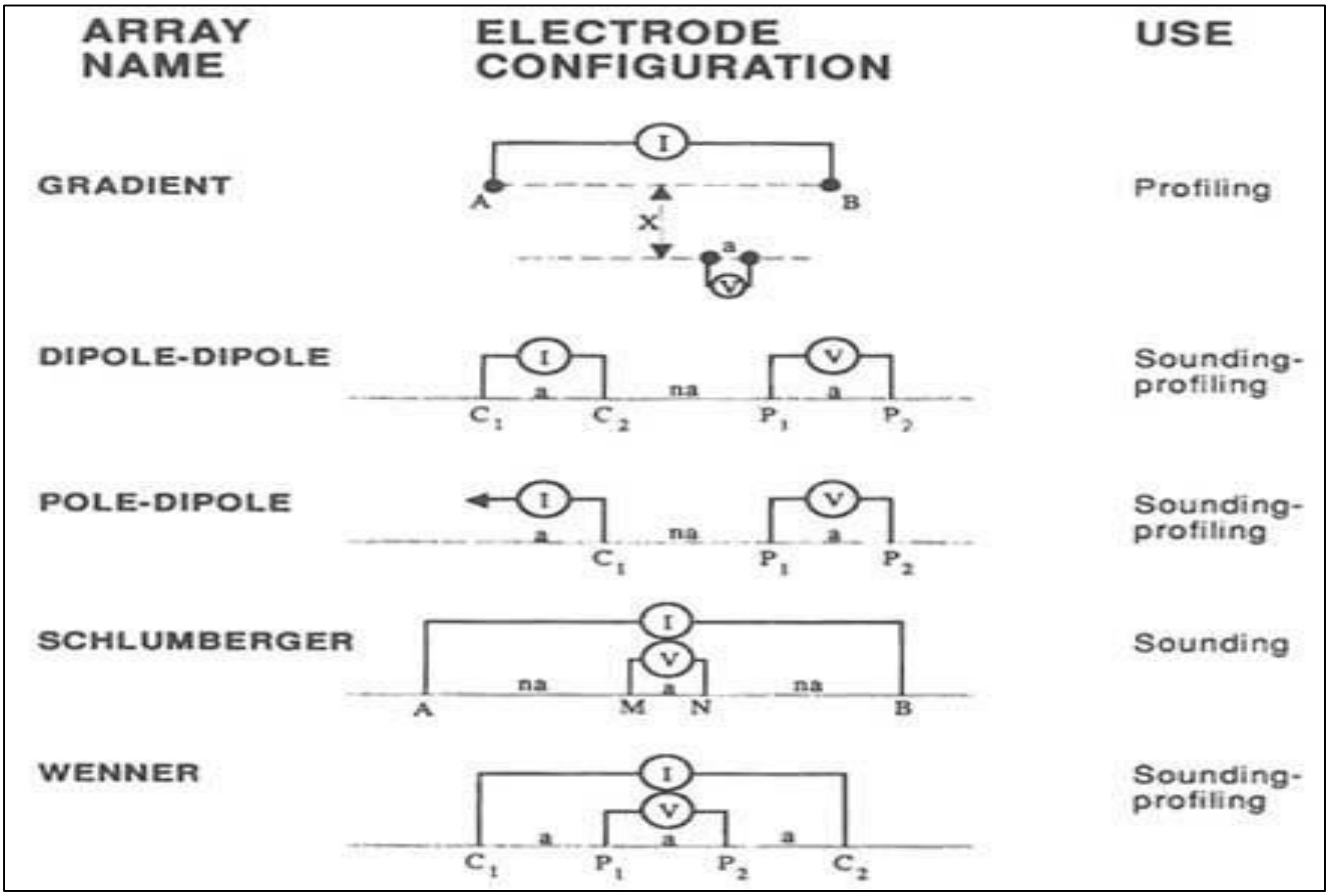

Fig 1 Electrode arrangements

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CHAPTER THREE
STUDY AREA

The study area is Odeda general hospital and it environ situated within Odeda town, along Abeokuta-Ibadan express road. It lies between longitude 3o 31’23’’E and 3o 31’39’’E and between latitude 7o 14’06’N’ and 7o 14’43’’N. The elevation increases from 167 to 180m above sea level. The study area falls within the basement complex of southwestern Nigeria. The entire area of Odeda is approximately 1560km2 (https://en.m.wikipedia.org), while the study area covers only area of about 2km2.

- *Climate and Vegetation*

The study area falls within the humid tropical lowland region of the south-western Nigeria with two distinct season viz rainy season and dry season which generally characterized, by high rainfall and high relative humidity. This is attributable to the prevalence of moisture laden tropical Maritime air mass over the state for about nine months in a year. The mean relative humidity varies from 66.2% in January to 88.4% in July (Akanni. 2000). The rainfall shows a double maxima distribution reaching the peak during the months of June and September. The average monthly rainfall for the state ranges between 7.1mm in the month of January to 208.27mm in the month of June. The mean annual temperature is 26°C; although with some variations over time. The mean diurnal minimum temperature varies from 21.80oC in December to 24.34°C in April while the mean diurnal maximum temperature varies from 33.92°C to 37.1°C at the onset of the wet season (March and April) (Akanni., 2000). On the basis of climatic features, the state is characterized by two distinct weather seasons: the wet and dry. The wet season marked by lower mean temperature, higher total rainfall and higher relative humidity is usually experienced between the months of February and October. However, little dry season is sometimes experienced in August, a phenomenon characterized by drastic reduction in the frequency and intensity of rainfall and referred to as August break. The dry season sets in by November and persists till the end of January. It is usually accomplished by harmattan cold, brought by the prevailing north-west winds. In terms of vegetation, the state can be divided into three distinctive zones. Where the state shares a boundary with the Atlantic Ocean, the vegetation is of a swampy type with mangroves and other edaphic trees. There is also rainforest vegetation in some section of the state while the state capital (Abeokuta) and some areas are characterized by derived forest vegetation, having been altered by human activities.

- *Geology and Hydrogeology*

The study area is underlain by basement complex, and the basement complex rocks of Nigeria are well-represented in the selected study areas of Ogun State (Figure 2). These rocks are of Precambrian to early Palaeozoic age and they extend from the north-eastern part of the Ogun state running southwest and dipping towards the coast (Ako. 1979). The basement complex metamorphic rocks are characterized by various folds, structures of various degrees of complexity, faults and foliation. These structural features have a predominant North-South or North-North-East-South-South-West (NNE-SSW) orientation which is particularly strong within the low grade metamorphic. The common metamorphic rocks encountered are gneiss, schist, quartzite and amphiboles. The study area is characterized by various rock types ranging from, granite granitic gneiss and pegmatite. The individual rocks have various hydro-geologic characteristics and belongs to the stable plate which was not subjected to intense tectonics in the past. Therefore, the underground faulting system is minimal and this has contributed to the problem of underground water occurrence in this area (Adeleke et al., 2015). When fresh such rocks will have practically no porosity or permeability due to the interlocking crystal structure.

Crystalline rocks are formed by interlocking silicate minerals such as quartz, feldspars, micas, hornblende, pyroxenes, olivine and a host of minor accessories. Chemical weathering involves the dissolution of these minerals resulting in the formation of both soluble as well as solid phase products. The groundwater potential in crystalline rock terrains depend on post emplacement processes such as tectonics and weathering which could lead to the development of secondary porosity and permeability. Basement aquifers are developed within weathered residual overburden known as regolith (relatively high storage but low permeability) or the fractured bedrock (low storage capacity with a relatively high permeability).6

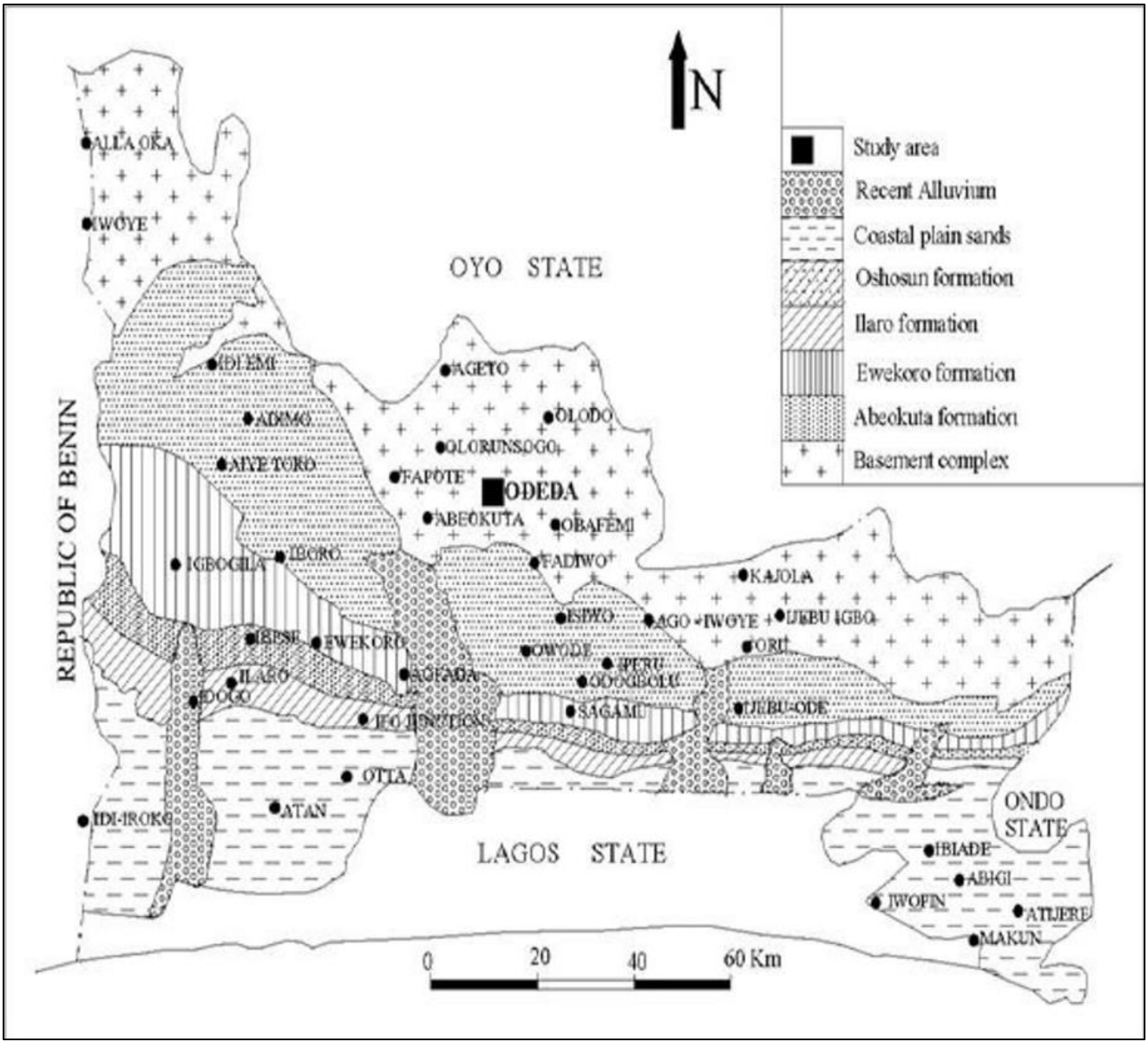

Fig 2 Ogun State Geological Map Showing Study Area.

➢ *Methodology*

This study is divided into two components:

- Data Collection
- Data analysis and interpretation using computer iteration technique.

➢ *Data Collection*

Two geophysical methods were used for this work; the Very Low Frequency Electromagnetic (VLF-EM) and Vertical Electrical Sounding (VES). The location and arrangement of the VES method in the area is shown in (Fig. 1.).

- *Instrumentation*

✓ *Very Low Frequency- Electromagnetic (VLF-EM)*

VLF-EM data were collected using VLF-EM16 instrument manufactured by GEONICS. For the purpose of this work, five traverses were conducted at interval of five metres (5) at five different locations where vertical electrical sounding were later conducted.

✓ *Vertical Electrical Sounding (VES)*

The geophysical survey using electrical resistivity method was be carried out for the purpose of this research. The instrument used in the survey was APEX RESISTIVITY TERRAMETER, and its accessories.

- *Reconnaissance Survey*

Reconnaissance survey involves the following:

The VLF-EM equipment used measured the real (in phase) and quadrature (out of phase) components of the vertical to horizontal magnetic field ratio.

Followed by;

- ✓ VES stations were selected within the study area with respect to their topographic features. This is because the topography of an area has been reported to have influence on the thickness of the overburden in the crystalline basement areas (Davies and Dewiest 1966).
- ✓ The Resistivity Meter was placed at the middle from which the spacing of both electrodes (current and potential) was measured.
- ✓ Care was taken for checking both electrode and battery connection to the Resistivity Meter.
- ✓ The resistance (R=V/I) was read up directly from Resistivity Meter at each point before changing the electrodes spacing.
- ✓ Points were selected to avoid interference (electric lines, rails, pipes etc.) which may affect the readings.

- *Field Procedure*

The VLF-EM survey was carried out at different stations and were surveyed at 5m interval along five traverses approximately east–west direction ranging from 0 to 200 metres in length using ABEM 16 VLF-EM unit. The VLF-EM was used to initially delineate areas with conductive or fractured zone. And for VES survey, ten points were selected within the VLF-EM area of study (fig. 2). At each point, vertical electrical sounding (VES) using Schlumberger array was carried out. Each current electrode spacing range from 1m to 100m while that of potential electrode spacing range from 0.25 to 10m.

➢ *Data Analysis*

From the field data obtained, apparent resistivity values were computed using the Schlumberger electrode array formula with Geometric factor and Resistance given by:

ƒ a=KR

With K= πAB2/4MN for AB>5MN

Where ƒ a = apparent resistivity (Ohm-m)

K = geometric factor

MN = potential electrode spacing (m)

AB = current electrode spacing (m)

R = resistance (ohm)

π = 3.14

The apparent resistivity values obtained from the field (show in table) were plotted against half of the current electrodes spacing, therefore AB/2 on a log-log paper and on computer system for all the VES stations obtain the field resistivity curve.

The field resistivity curve was first quantitatively and Qualitatively analysed by curve matching method using Orellena and Mooney (1966) master curve so as to determine the respective number of geoelectric layers, apparent resistivity values, thickness and depth to the bedrock. The result obtained is used as a model for the computer iteration analysis through which the best fit and the final accepted model for each VES were obtained.

- *Analysis of Dar-Zarrouk Parameters*

Dar-Zarrouk parameters (D-Z) termed by (Maillet, 1947) play an important role in geoelectrical resistivity soundings. They have been used in computing a distribution of surface potential and the section consists of *n* geoelectric layers with thicknesses h1, h2, h3, …., hn and resistivity ρ1, ρ2, ρ3, …. ρn for a block of unit square area and thickness. The D-Z parameters, therefore, S, T, ρl, ρ*t* & λ are defined as following. A geoelectric unit is characterized by two basics parameters the layer resistivity (ρ*i*) and the

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layer thickness (hi) for i th layer (i =1 for the surface layer). Two further electrical parameters can be derived for each layer from the respective resistivity and thickness; these are called the Longitudinal Conductance, Transverse Resistance.

S = $\Sigma hpni$=1.................... (1) Longitudinal conductance

The longitudinal resistivity of the current flowing parallel to the layers are given by,

ƒ l = H/S..................... (2) Longitudinal resistivity

T =$\Sigma h*pni$=1.................... (3) Transverse resistance

This is the "transverse resistance".

The transverse resistivity to the current flowing perpendicular to the layers are given by,

ƒ t = T/H

Where H = Σhi

H is the depth to the bottom most geoelectric layer.

ƒ t = T/H..................... (4) Transverse resistivity

The coefficient of pseudo-anisotropy (λ) is given by:

λ =√ƒ tƒ l......................... (5) Anisotropy

The reflection coefficients (RC) and fracture contrast (FC) of the fresh basement rock of the study area were calculated using the method of Olayinka (1996); Bhattacharya and Patra (1968) and Loke (1999):

RC = ƒ n-ƒ n-1/ ƒ n +ƒ n-1 ………………………. (6)

FC = ƒ n/ ƒ n-1 ………………………………………... (7)

Where, ƒ n is the layer resistivity of the nth layer and is the layer resistivity overlying the nth layer.

- *Interpretation*

The apparent resistivity values of the geoelectric layers were interpreted in term of lithology taking into consideration the geology of the study area.

The state of weathering or fracturing of basement rock and the aquifer potential of different geoelectric layers can be inferred from the apparent resistivity values.

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CHAPTER FOUR
RESULTS AND DISCUSSION

➢ *Results*

The VLF-EM Traverse data obtained from research which include filtered real and imaginary values were presented in figure 3. (See appendix). And; The apparent resistivity values are computed using equation 11 and these are presented in Table 1. (See appendix). The results obtained from the analysis of the resistivity curves are presented in number of geoelectric layers, apparent resistivity values, depth thickness and Dar zarrouk parameters of each VES station (See Table 2 and 3. in appendix).

➢ *Analysis of Results and Discussion*

• *Analysis of Very Low Frequency-Electromagnetic Results*

Each of the Traverses has 200m in length (fig.3) (see appendix). Traverse 1, The filtered real values range from 109 to 300 siemens, while the filtered imaginary ranges from -34 to 46 Siemens. The traverse shows the maximum peak at both positive and negative region with a more prominent filtered real peak at horizontal distance of 100–125m. This usually signifies or corresponds to the area of high conductivity or area with the presence of fracture. The correspondent Karous–Hjelt pseudosection filtering confirms the moderately high conductivity which extends below 30 m depth. This conductivity could be due to the presence of fracture or accumulation of clayey materials. (McNeil and Labson 1992).

Traverse 2, 4 and 5 filtered real values range from 105 to 420 siemens, 103 to 370 siemens and 102 to 380 siemens while the filtered imaginary ranges from -36 to 45 Siemens, -30 to 46 siemens and -32 to 45 siemens respectively. Fractures at traverse 2, 4 and 5 observed where the positive peak of the filtered real near to the negative peak of the imaginary at stations 95 to 105 meters, 130 to 150 meters and 130 to 140 meters respectively on the traverses, the extent of the fractured identified is below 28 m depth, this can either be a localized zone of fracture or thick clayey materials in the region.

Traverse 3 is 200 m in length. The filtered real values range from 105 to 410 Siemens, while the filtered imaginary ranges from -20 to 48 Siemens. A positive anomalous value of filtered real is observed at distance between 120 and 130 m and it is identified as a fracture.

Area of thick overburden is observed at distance interval of 70 and 85 m. The Karous–Hjelt pseudosection also agrees with the plot and showed the extent of the identified fracture and the thick overburden to be 30 m.

• *Analysis of Vertical Electrical Sounding (VES)*

Six geoelectric layers have been recognized in this study area namely topsoil, sand clay, clayey sand, lateritic, weathered basement (sand) and fresh basement (sand stone). However, all the six geoelectric layers do not occur throughout the study area.

The first layer for all the VES is generally topsoil, is usually laterite and sandy, it has a range greater than underlying layer in all VES stations except for stations 3 and 4. It has an apparent resistivity values ranging from 54 to 305 ohm-m with a thickness ranging from 0.4 to 6.2m.

VES 02, 05, 06, 09 and 10 are distinct such that they have some attributes in common property which is same curve type that is HHA curve.

The second layer under these VES are made up of clayey (VES 02, 05 and 09) and clayey sand (VES 06) and/or sand clay materials with an apparent resistivity values ranging from 10.3 to 110.0 ohm-m and thickness ranges from 0.3 to 4.8 m.

The third layer of VES 02, 05, 06, 09 and 10 are made up of mainly sand, sandy clay and laterite (VES 02). The apparent resistivity value varies from 18.5 to 141.0 ohm-m with 0.6 to 53.1 m as thickness range.

The fourth layer are made up of fractured and fresh basement except VES 02 with sandy clay. The apparent resistivity ranges from 46.3 to 19714.0 ohm-m and thickness 31.1 m.

VES 02 have fifth layer consist of fresh basement with high apparent resistivity value.

For other five VES (01, 03, 04, 07 and 08) the type of curves identified are HH, KHH, AAH and H.

The second layer of VES 01 and 03 consist of sand clay and laterite respectively. The apparent resistivity ranges from 31.3 to 334.7 ohm-m with thickness ranges of 5.3 to 11.3 m.

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The third layer is made of weathered basement with apparent resistivity ranges of 12.3 to 17.9 ohm-m and thickness ranges from 12.6 to 16.6 m.

The fourth layer is made of fractured basement with high apparent resistivity.

VES 04 second, third and fourth layer consist of lateritic, clay and fresh basement respectively. The apparent resistivity of the second layer, third and fourth layer are 389.2, 18.2 and 2951.0 ohm-m respectively with thickness of 7.1 m for second layer and 20.0 m for third layer.

The second layer for VES 07 and 08 is made up of clayey sand/sand clay. The apparent resistivity ranges from 35.0 to 107.2 ohm-m and the thickness ranges from 11.2 to 25.2 m.

The third layer is made up of fresh basement with high apparent resistivity ranging from 8822.2 to 13065.3 ohm-m.

Resistivity curves and tables showing thickness for all VES are in figure 4 (see appendix).

- *Groundwater Potential*

The groundwater potentials of the area are evaluated based on the following indices; weathered layer thickness and resistivity, overburden thickness, transverse resistance, coefficient of anisotropy, reflection coefficient and fracture contrast. The weathered/or weathered fractured layer constitute the water saturation zone or aquifereous units. Areas where weathered layer thickness is greater than 13 m and reflection co efficient less than 0.8 (Table2) and of low clay content as indicated by the resistivity (> 12) value is categorized to be area of high groundwater potentials. The spatial distribution of the weathered layer and fractured layer is presented in Figure 4(a and b). From the figure, area around VES stations 01, 03 and 09 have very high yield (in the range of 11.3 to 16.6 m) weathered layer thickness while area around VES stations 02, 04, 05, 06, 08 and 10 have medium yield (in the range of 20.0 to 53.1 m) weathered layer thickness since Overburden thickness is greater 13 m and reflection coefficient is greater or equal to 0.8 and low yield is identified at VES station 07 (Overburden thickness is less than 13 m and reflection coefficient is greater than 0.8). Correlation of the geoelectric logs are shown in figure 5 (see appendix) using the VES relative position.

- *Groundwater Protection*

In present study, the longitudinal conductance values were classified according to (Oladapo and Akintorinwa. 2007; Olusegun *et al.*, 2016) into poor, weak, moderate, good, very good and excellent protective capacity zones showed in Table 4 below.

Table 1 Aquifer Protective Capacity Classification Table

Longitudinal Conductance (Ω-1)	**Protective Capacity Rating**
>10	Excellent
5 – 10	Very good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
<0.1	Poor

The aquifer protective capacity was determined using the parameters longitudinal conductance and transverse resistance presented in table 3. The contour map of the aquifer protective capacity is shown in figure 6 while figure 7 (see appendix) shows the surface map of the aquifer protective capacity for the study area. The result shows that all the aquifers in VES 04, VES 05, VES 06, VES 07, VES 09 and VES 10 show evidence of moderate aquifer protective capacity having longitudinal conductance values ranging from 0.24 to 0.41 and transverse resistance values ranging from 240.94 to 9237.5. The aquifer in this area may be protected from contamination resulting from short residence time in the coarse sand layers. The thicknesses of the overlain layers for the aquifers are relatively enough to protect the aquifers from percolating fluids except for VES 04. The thicknesses of the overlain layers range from 6.2 m to maximum of 55.7 m. The other VES have good aquifer protective capacity except for VES 09 that have weak aquifer protective capacity. Usually, groundwater is given protection by geologic barriers having sufficient thickness and also called protective layers and low hydraulic conductivity.

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CHAPTER FIVE
CONCLUSION AND RECOMMENDATION

- *Conclusion*

In this study, geoelectric soundings have been used to assess the aquifer potential of Odeda general hospital and its environment. Six geoelectric layers have been recognized in this study area namely topsoil, sand clay, clayey sand, lateritic, weathered basement (sand) and fresh basement (see table 3 in appendix). Presence of thick weathered materials essentially sandy clay, clayey sand, shale/clay and sand underlying by fractured bedrock is desirable for groundwater development for the area.

In the study area the weathered materials constitute aquifer unit and is generally thick and is thickest at VES 01, 03 and 09 making these stations relevant for groundwater development in the area. The occurrence of high annual rainfall which provide recharge to the aquifers and the occurrence of thick aquifer in term of the weathered/fractured basement are responsible for existence of good groundwater prospect in the study area. However, the VES with clayey material and fresh basement are adequate for aquifer protective especially VES 09 but also station for groundwater development due to fractured basement beneath clayey layer.

- *Recommendation*

According to the research, the following suggestions for groundwater exploitation in the study area may be useful:

- VES 01, 03 and 09 are most viable to produce groundwater for industrious and municipal purpose.
- Alternative stations recommended for borehole drilling are VES 02, 04, 05, 06, 08 and 10.
- Drilling should not be less than 50m since the study area falls within basement terrain.
- To ensure safe consumption of groundwater in the study area, potential sources of contamination site should be sited far away from viable aquifer units because the area is vulnerable to pollution if there is leakage of buried underground septic tank, sewage channels or infiltration of leachate from decomposing refuse dumps in the area.

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APPENDIX

Table 2 Vertical Sounding Resistivity Field Record.

CURRENT	POTENTIA	GEOMETR	VES 1		VES 2		VES 3		VES 4		VES 5		VES 6		VES 7		VES 8		VES 9		VES 10	
ELECTROD	L ELECTRO	C FACTOR																				
E(AB/2)	DE(MN/2)	(K)	R1(Ω)	ρ1(Ωm)	R2(Ω)	ρ2(Ωm)	R3(Ω)	ρ3(Ωm)	R4(Ω)	ρ4(Ωm)	R5(Ω)	ρ5(Ωm)	R6(Ω)	ρ6(Ωm)	R7(Ω)	ρ7(Ωm)	R8(Ω)	ρ8(Ωm)	R9(Ω)	ρ9(Ωm)	R10(Ω)	ρ10(Ωm)
1	0.25	6.284	9.97	63	10.538	66	12.703	80	10.576	66	20.48	129	39.455	248	38.654	243	44.48	280	13.79	87	34.817	219
1.3	0.25	10.61996	4.78	51	5.21	55	5.84	62	4.787	51	7.327	78	20.982	223	21.43	228	21.169	225	4.276	45	16.375	174
1.7	0.25	18.16076	2.54	46	2.395	43	2.986	54	3.177	58	1.729	31	9.382	170	0.364	7	10.626	193	1.663	30	8.462	154
2.8	0.25	49.26656	0.67	33	1.133	56	1.08	53	1.063	52	1.513	75	1.978	97	1.482	73	2.956	146	0.218	11	2.561	126
3.6	0.25	81.44064	0.43	35	0.816	66	0.811	66	0.667	54	0.885	72	0.856	70	0.165	13	1.58	129	0.63	51	1.506	123
4.6	0.25	132.9694	0.26	35	0.618	82	0.476	63	0.45	60	0.617	82	0.281	37	0.297	39	0.798	106	0.386	51	0.891	118
4.6	1	33.24236	0.95	32	1.308	43	0.552	18	1.794	60	2.586	86	0.555	18	0.44	15	3.523	117	0.765	25	3.513	117
7.5	1	88.36875	0.39	34	1.19	105	0.745	66	0.724	64	1.13	100	1.501	133	0.419	37	1.21	107	0.762	67	1.406	124
10	1	157.1	0.22	35	0.501	79	0.263	41	0.226	36	0.662	104	0.735	115	0.218	34	0.707	111	0.447	70	0.765	120
13	1	265.499	0.12	32	0.446	118	0.323	86	0.333	88	0.407	108	0.274	73	0.103	27	0.436	116	0.275	73	0.548	145
13	3	88.49967	0.39	35	0.535	47	1.048	93	3.455	306	1.652	146	1.351	120	0.108	10	1.378	122	0.994	88	1.822	161
17	3	151.3397	0.2	30	0.588	89	0.667	101	0.794	120	0.94	142	0.603	91	0.349	53	0.749	113	0.571	86	1.149	174
28	3	410.5547	0.06	25	0.035	14	0.26	107	0.292	120	0.343	141	0.256	105	0.189	78	0.301	124	0.296	122	0.457	188
35	3	641.4917	0.04	26	0.056	36	0.133	85	0.181	116	0.152	98	0.167	107	0.072	46	0.238	153	0.226	145	0.29	186
40	3	837.8667	0.02	17	0.067	56	0.106	89	0.171	143	0.173	145	0.124	104	0.094	79	0.206	172	0.17	142	0.248	208
40	6	418.9333	0.13	54	0.153	64	0.095	40	0.122	51	0.415	174	0.146	61	0.092	39	0.521	218	0.302	127	0.474	199
50	6	654.5833	0.06	33	0.767	502	0.128	84	0.11	72	0.317	208	0.216	141	10.714	7013	0.389	255	0.105	69	33	21601
60	6	942.6	0.08	28	0.423	399	0.091	86	0.06	57	0.149	140	0.138	130	0.882	831	0.272	256	0.064	60	0.275	259
70	6	1282.983	0.027	35	0.073	94	0.076	98	0.079	101	0.022	28	0.11	141	0.034	44	0.219	281	0.088	113	0.201	258
80	6	1675.733	0.024	40	0.103	173	0.066	111	0.05	84	0.117	196	0.084	141	0.198	332	0.154	258	0.164	275	0.188	315
90	6	2120.85	0.029	62	0.094	199	0.073	155	0.069	146	0.111	235	0.059	125	0.357	757	0.167	354	0.085	180	0.164	348
100	6	2618.333	0.0279	73	0.251	657	0.046	120	0.083	86	0.098	257	0.068	178	0.192	503	0.16	419	0.063	165	0.165	432

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Table 3 Geoelectric Layers, Apparent Resistivity Values, Depth Thickness

VES . NO	No. of Geoelectric Layers	Resistivity Layer (Ωm)	Thickness (m)	Depth to basement (m)	Curve Type	Portable Lithology
1	I II III IV	76.8 31.3 12.3 3670.0	0.6 11.3 16.6	0.6 11.9 28.5	HH	Top soil Sand clay layer Weathered basement Fractured basement
2	I II III IV V	136.6 13.2 578.9 46.3 12875.3	0.4 0.4 0.6 31.1	0.4 0.9 1.5 32.6	HHA	Top soil Clay layer Lateritic soil Sand clay Fresh basement
3	I II III IV	61.2 334.7 17.9 5527.8	6.2 5.3 12.6	6.2 11.5 24.1	KHH	Top soil Lateritic soil Weathered basement Fractured basement
4	I II III IV	54.0 389.2 18.2 2951.0	5.7 7.1 20.0	5.7 12.7 32.7	AAH	Top soil Lateritic soil Clay layer Fresh basement
5	I II III IV	221.0 18.5 123.0 10276.0	0.5 0.4 47.1	0.5 0.9 48.0	HHA	Top soil Clay layer Sand clay layer Fresh basement
6	I II III IV	164.0 63.5 141.0 11119.0	0.6 2.0 53.1	0.6 2.6 55.7	HHA	Top soil Clayey sand layer Sand layer Fresh basement
7	I II III	189.4 35.0 13065.3	0.6 11.2	0.6 11.8	H	Top soil Clayey sand layer Fresh basement
8	I II III	321.7 107.2 8822.2	0.7 25.2	0.7 25.9	H	Top soil Sand clay layer Fresh basement
9	I II III IV	154.0 10.3 75.2 332.0	0.5 0.3 11.3	0.5 0.8 12.1	HHA	Top soil Clayey layer Sand clay layer Fractured basement
10	I II III IV	305.0 110.0 119.0 19714.0	0.5 4.8 43.0	0.5 5.3 48.3	HHA	Top soil Sand clay layer Sand layer Fresh basement

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Table 4 Dar Zarrouk Parmeters

VES. NO	ƒa	H (m)	S	Total S	T	Total T	Total H(m)	ƒl	ƒt	λ	RC	RF	Portable Lithology	Remark
1	76.8	0.6	0.007813		46.08									
	33.1	11.3	0.34139		374.03									
	12.7	16.6	1.307087		210.82									
	3670			1.66		630.93	28.5	17.21	22.14	1.13	0.99	288.98	Fracture	High yield
2	136.6	0.4	0.002928		54.64									
	13.2	0.4	0.030303		5.28									
	578.9	0.6	0.001036		347.34									
	46.3	31.1	0.671706		1439.93									
	12875.3			0.71		1847.19	32.5	46.04	56.84	1.11	0.99	278.08		Medium yield
3	61.2	6.2	0.101307		379.44									
	334.7	5.3	0.015835		1773.91									
	17.9	12.6	0.703911		225.54									
	5727.8			0.82		2378.89	24.1	29.35	98.71	1.83	0.99	320	Fracture	High yield
4	54	0.5	0.009259		27									
	389.2	0.2	0.000514		77.84									
	18.2	5.5	0.302198		100.1									
	2951			0.31		204.94	6.2	19.87	10.31	0.72	0.99	162.14	Fracture	Medium yield
5	221	0.5	0.002262		110.5									
	18.5	0.4	0.021622		7.4									
	123	47.1	0.382927		5793.3									
	10276			0.41		5911.2	48	117.99	123.15	1.02	0.98	83.54		Medium yield
6	164	0.6	0.003659		98.4									
	63.5	2	0.031496		127									
	141	53.1	0.376596		7487.1									
	11119			0.41		7712.5	55.7	135.28	138.46	1.01	0.98	78.86		Medium yield
7	189.4	0.6	0.003168		113.64									
	35	11.2	0.32		392									
	13065.3			0.32		505.64	11.8	36.51	42.85	1.08	1	373.29		Low yield
8	321.7	0.7	0.002176		225.19									
	107.2	25.2	0.235075		2701.44									
	8822.2			0.24		2926.63	25.9	109.17	113	1.02	0.98	82.3		Medium yield
9	154	0.5	0.003247		77									
	10.3	0.3	0.029126		3.09									
	75.2	11.3	0.150266		849.76									
	332			0.18		929.85	12.1	66.25	76.85	1.08	0.63	4.41	Fracture	High yield
10	305	0.5	0.001639		152.5									
	110	4.8	0.043636		528									
	199	43	0.21608		8557									
	19714			0.26		9237.5	48.3	184.81	191.25	1.02	0.98	99.07		Medium yield

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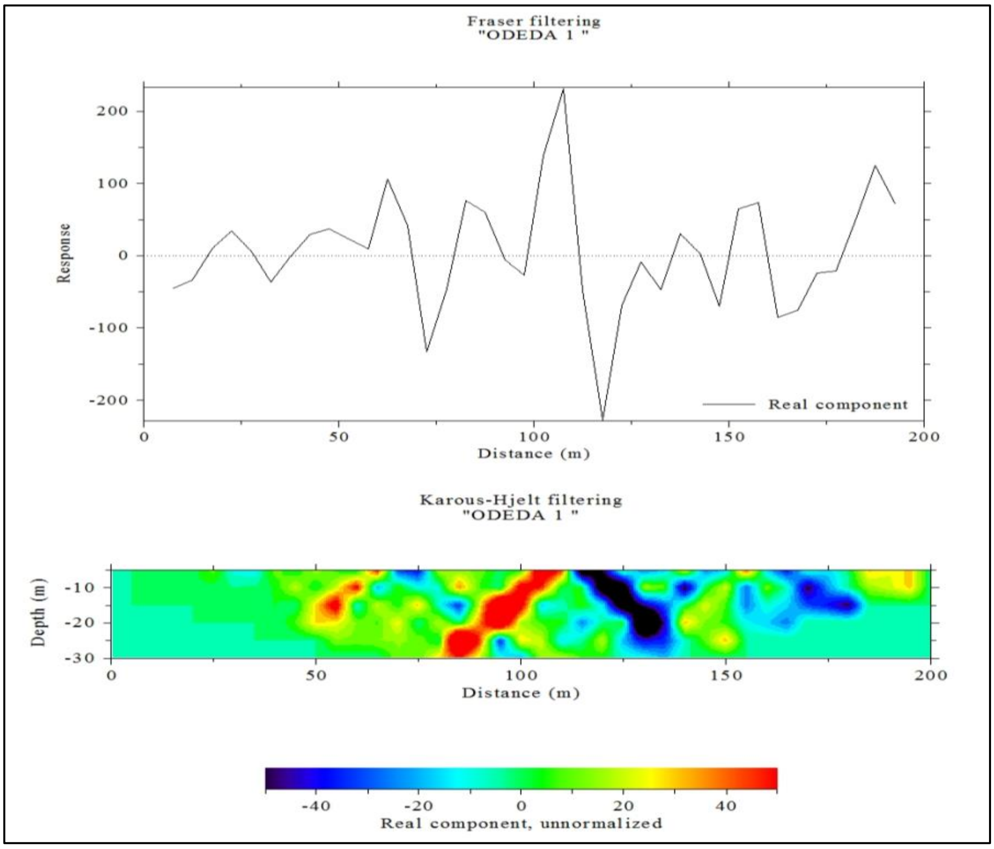

Fig 3 (A) Filtered Real and Karous-Hjelt Pseudosection for Traverse 1

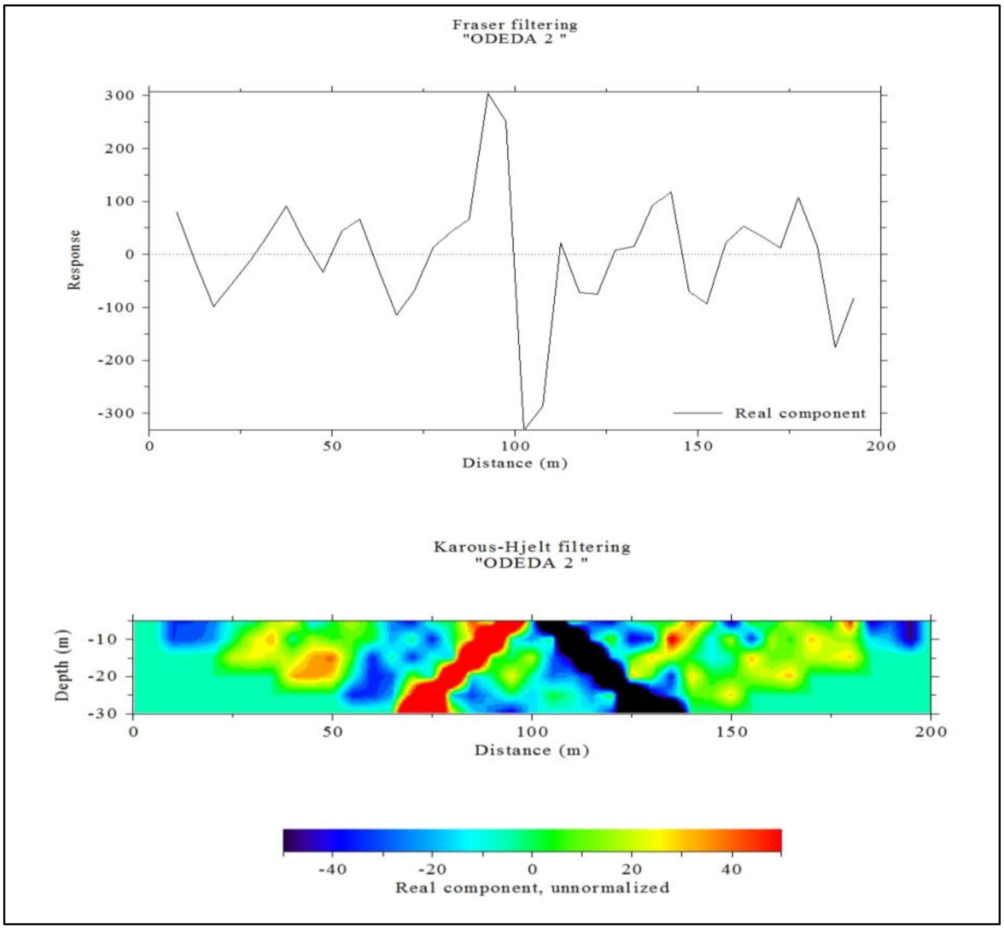

Fig 3 (B) Filtered Real and Karous-Hjelt Pseudosection for Traverse 2

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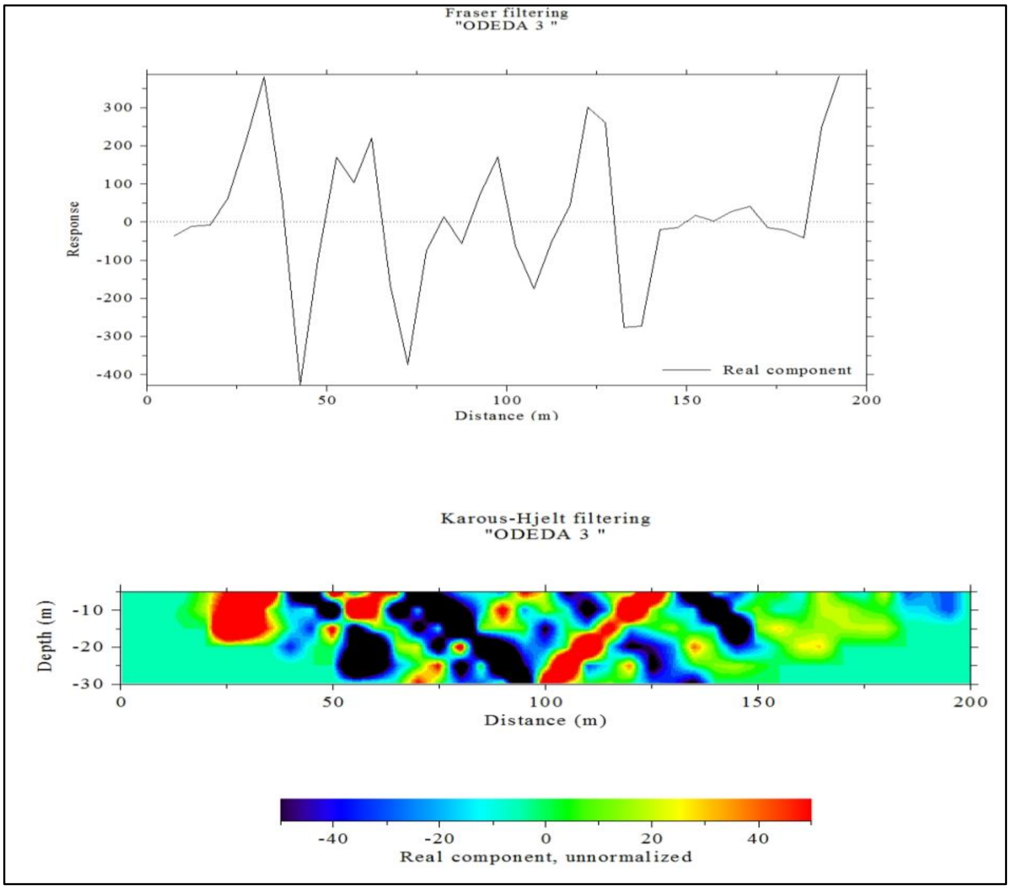

Fig 3 (C) Filtered Real and Karous-Hjelt Pseudosection for Traverse 3

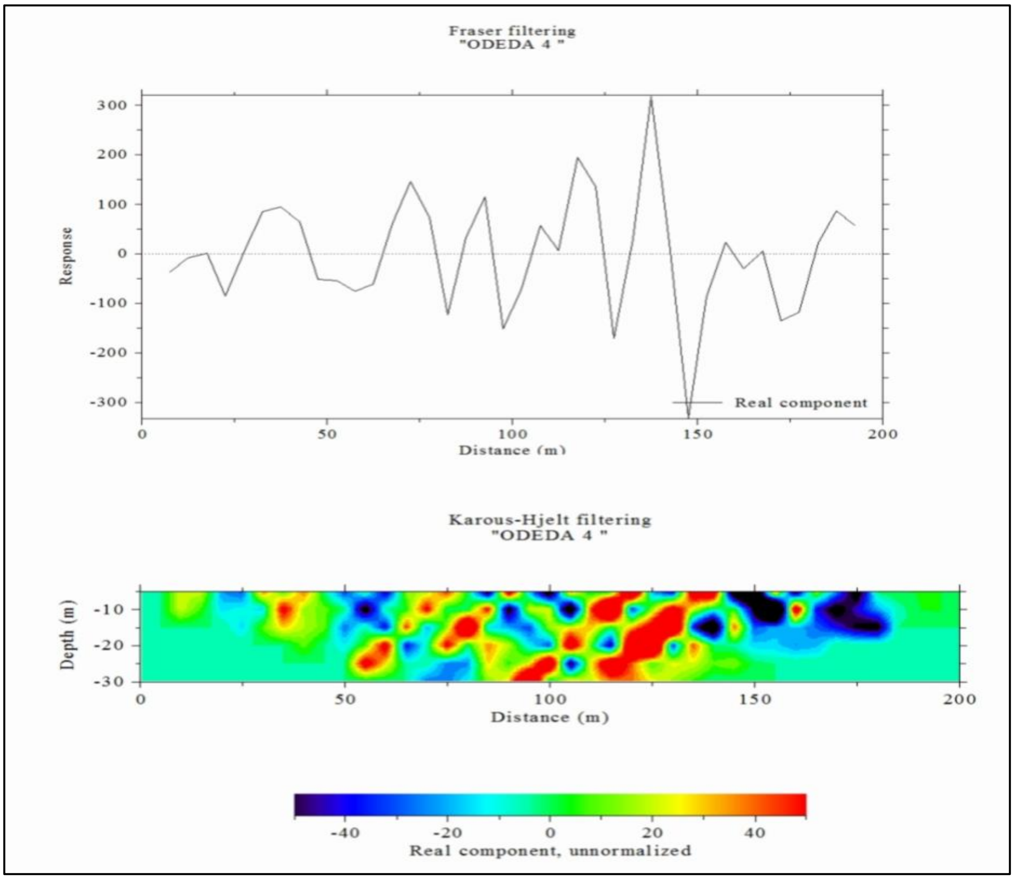

Fig 3 (D) Filtered Real and Karous-Hjelt Pseudosection for Traverse 4

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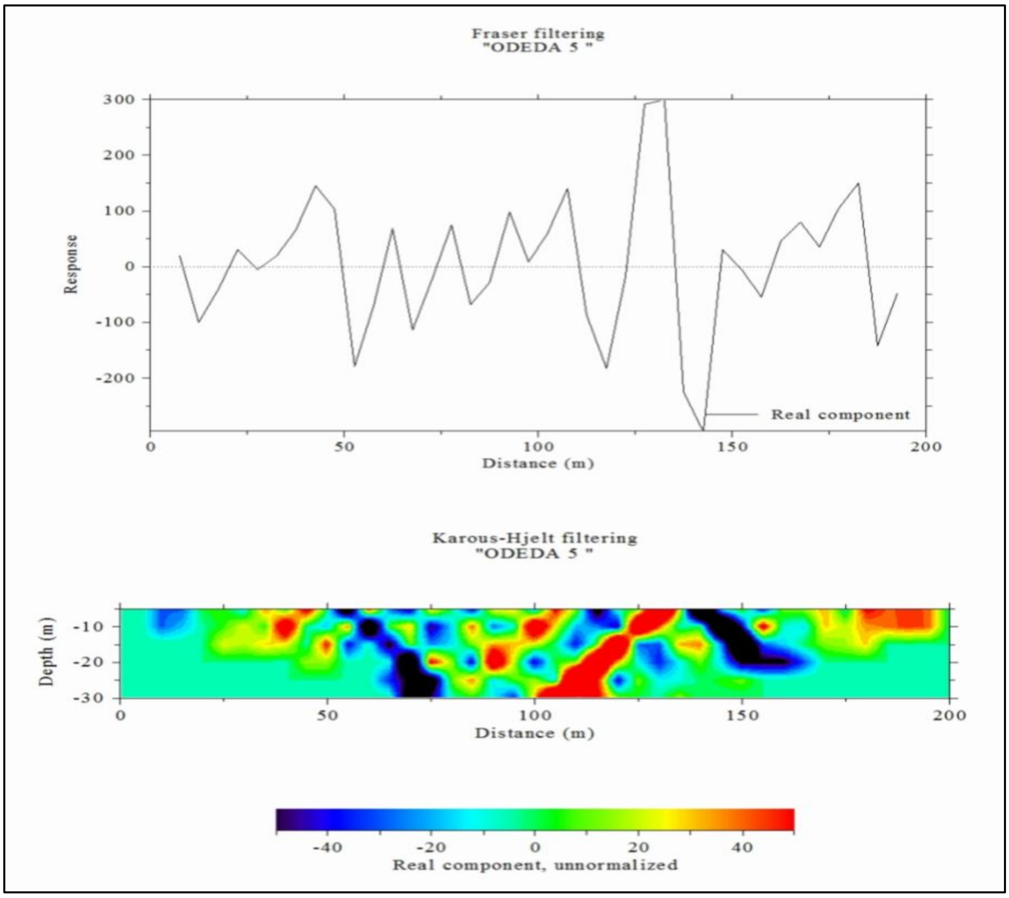

Fig 3 (E) Filtered Real and Karous-Hjelt Pseudosection for Traverse 5

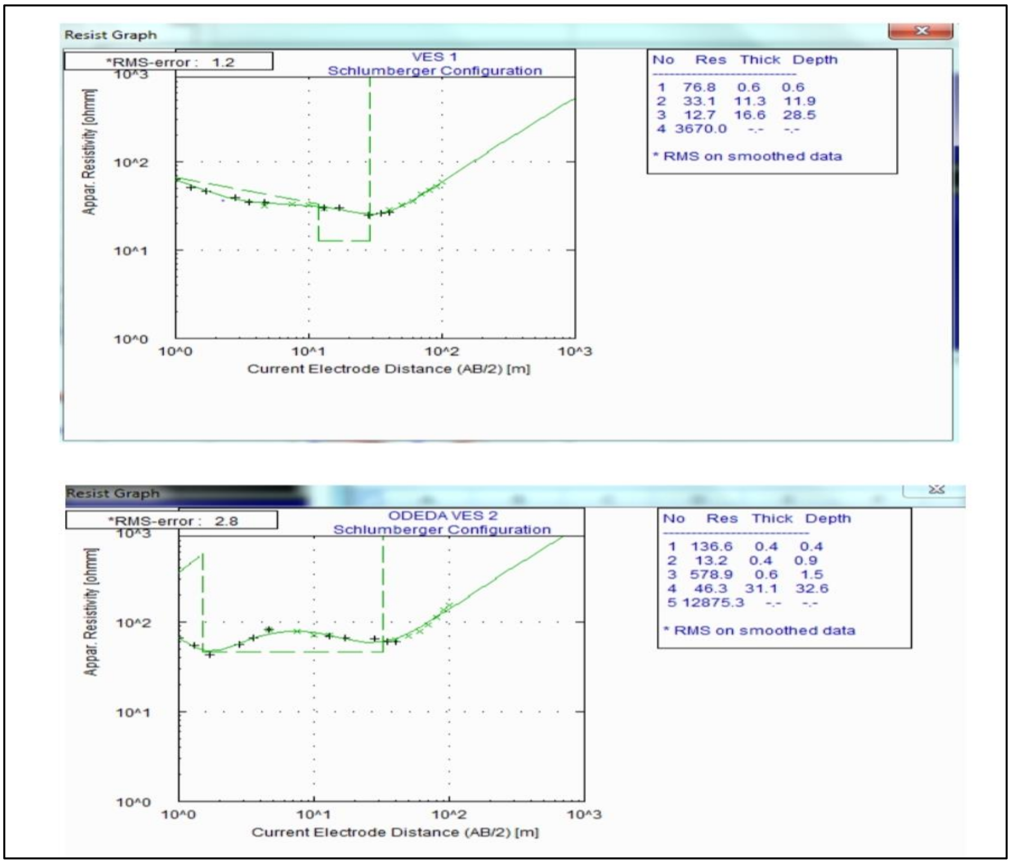

Fig 4 (A) & (B) Computer Iteration Analysis for VES 01 and 02

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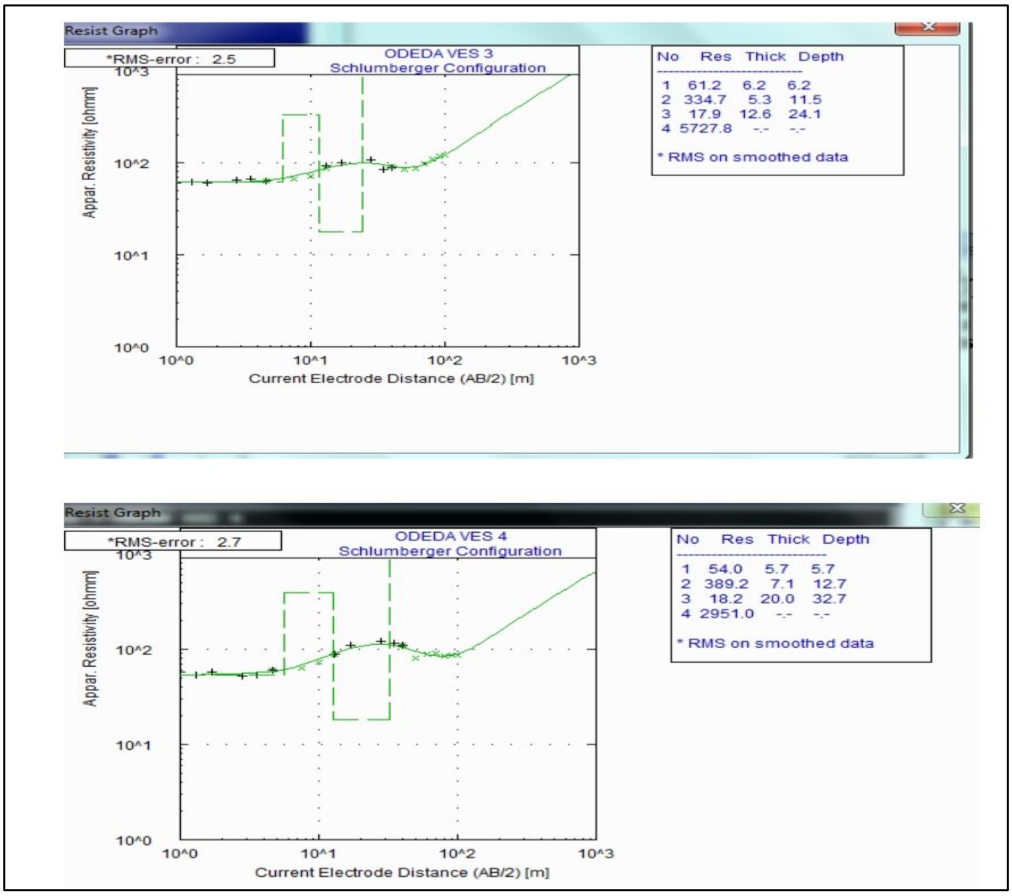

Fig 4 (C) & (D) Computer Iteration Analysis for VES 03 and 04

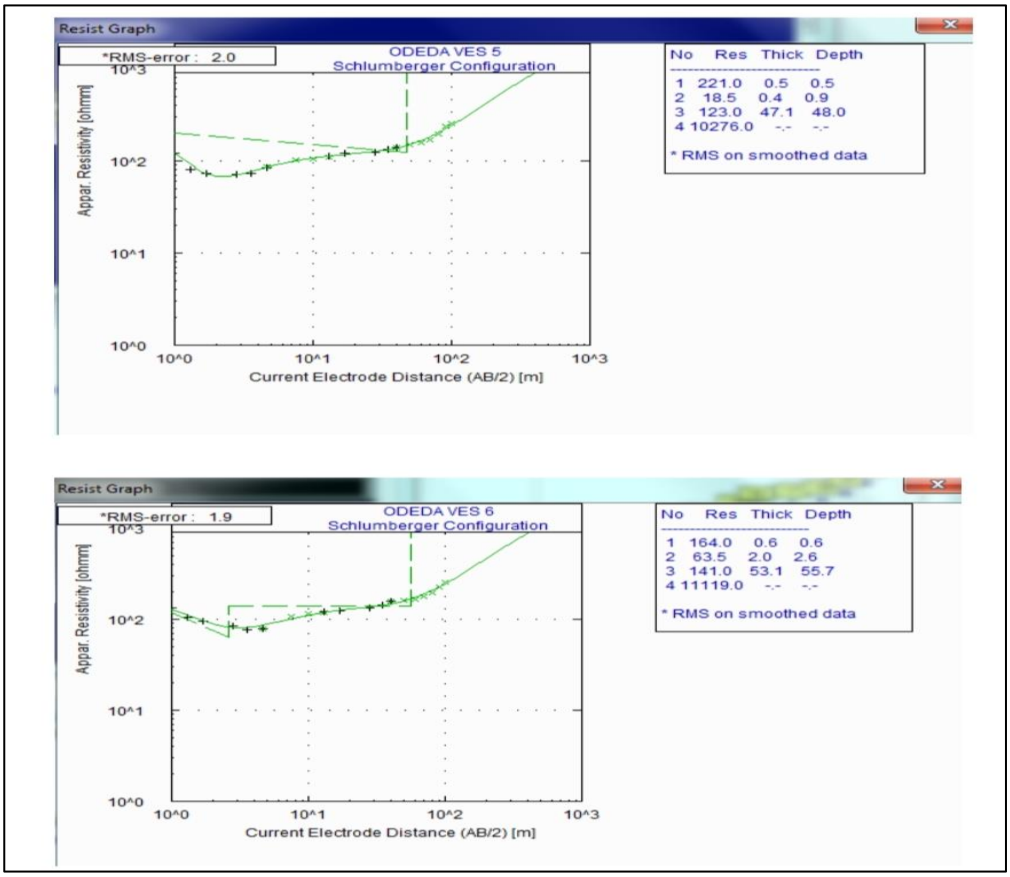

Fig 4 (E) & (F) Computer Iteration Analysis for VES 05 and 06

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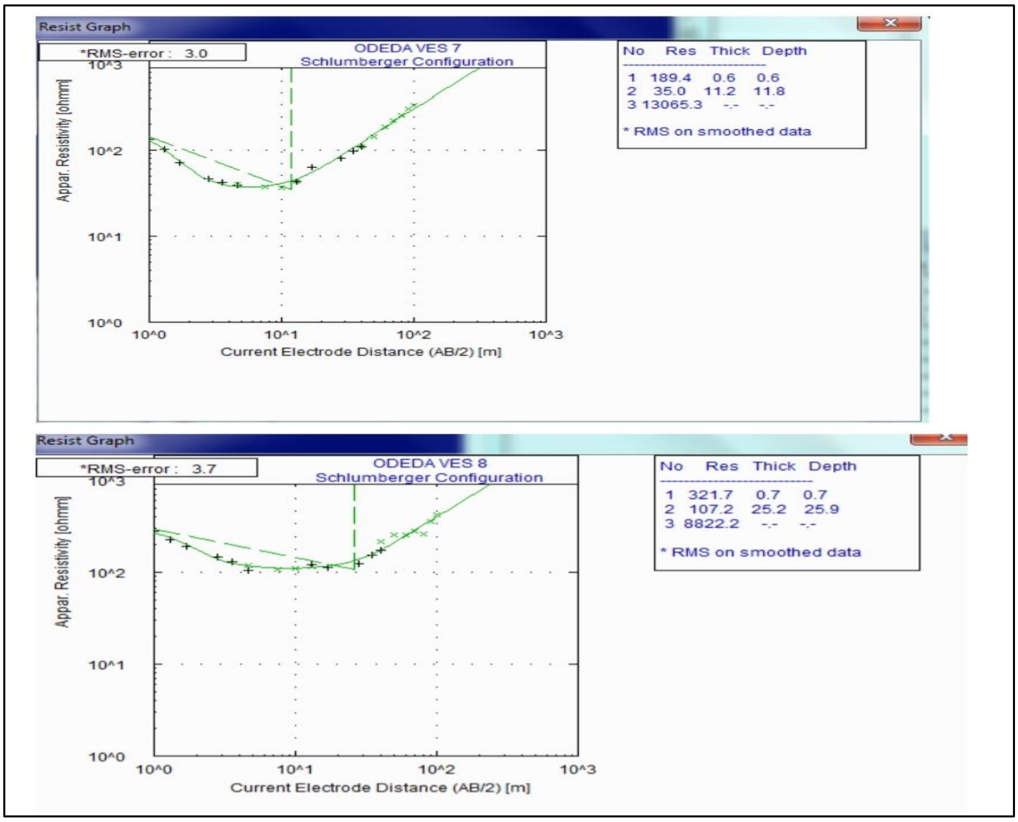

Fig 4 (G) & (H) Computer Iteration Analysis for VES 07 and 08

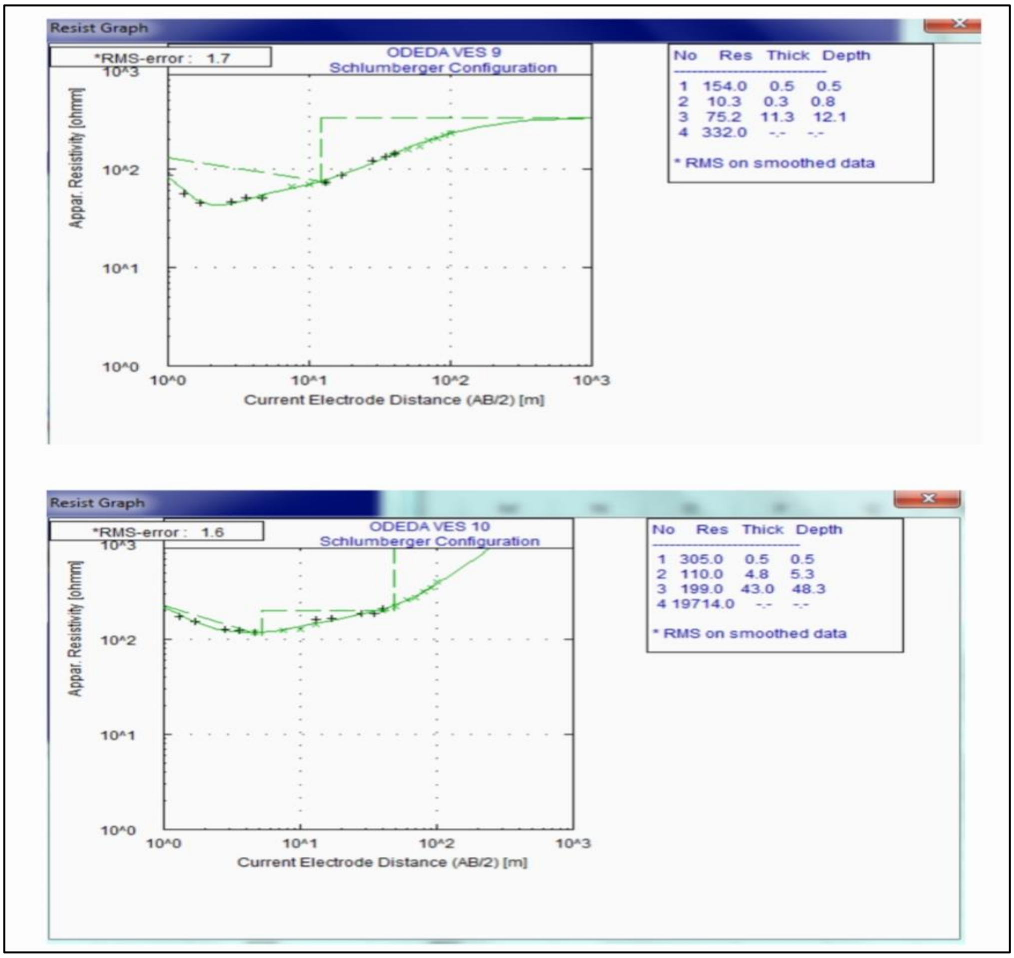

Fig 4 (I) & (J) Computer Iteration Analysis for VES 09 and 10

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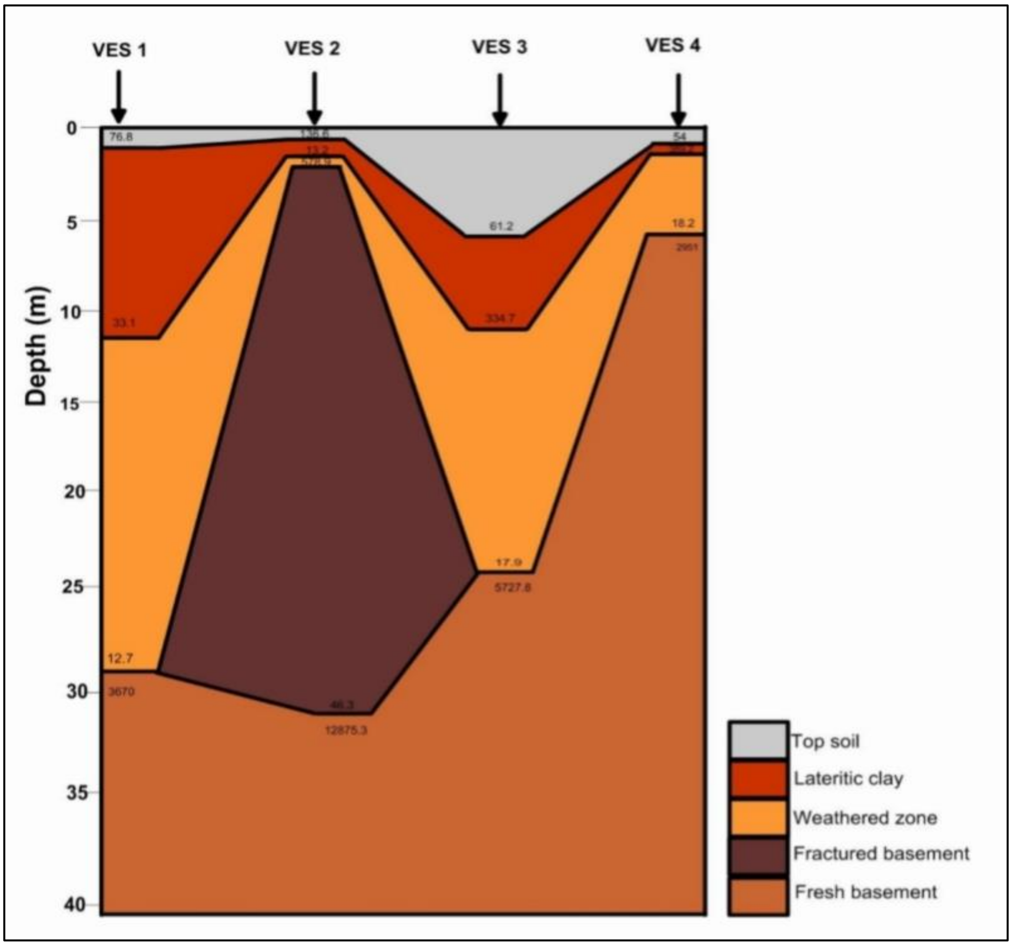

Fig 5 Correlation of the Geoelectric Logs Section A

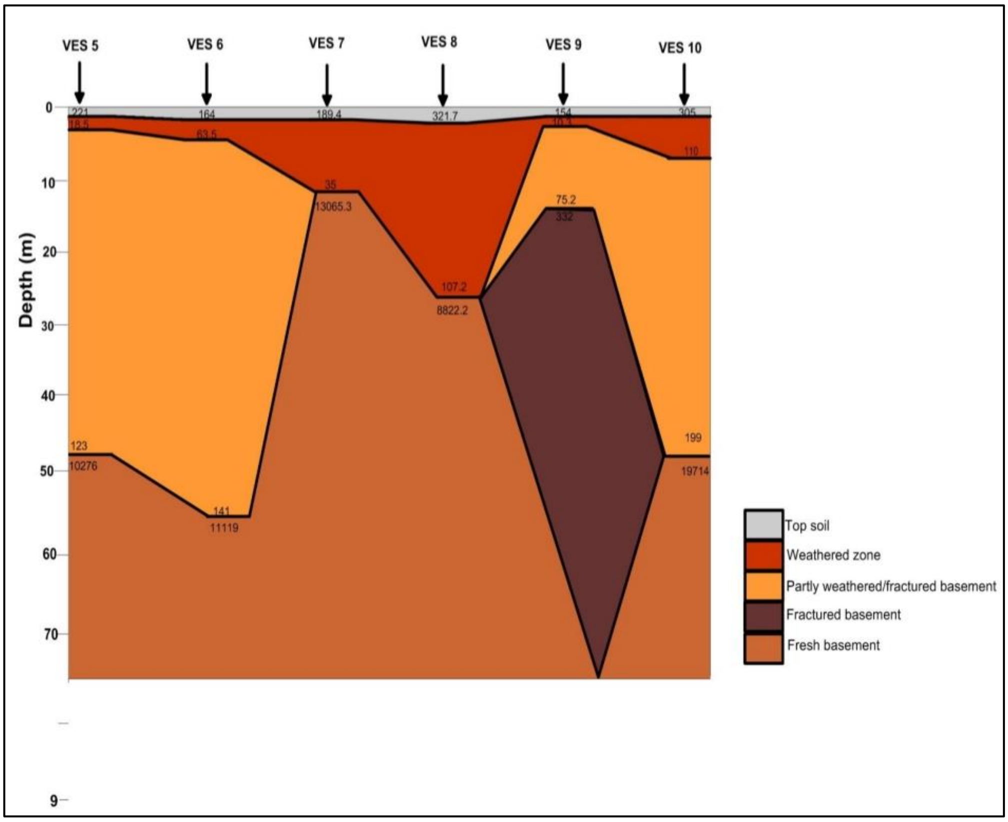

Fig 5 Correlation of the Geoelectric Logs Section B

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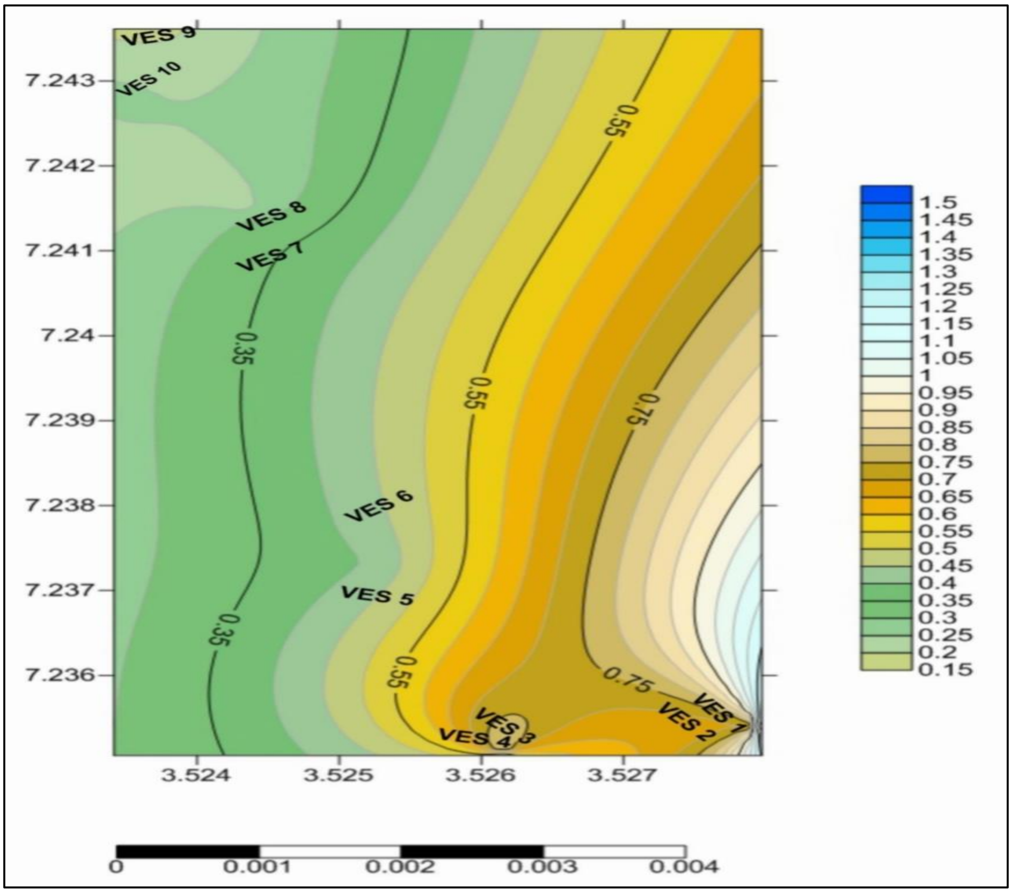

Fig 6 Contour Map of the Aquifer Protective Capacity

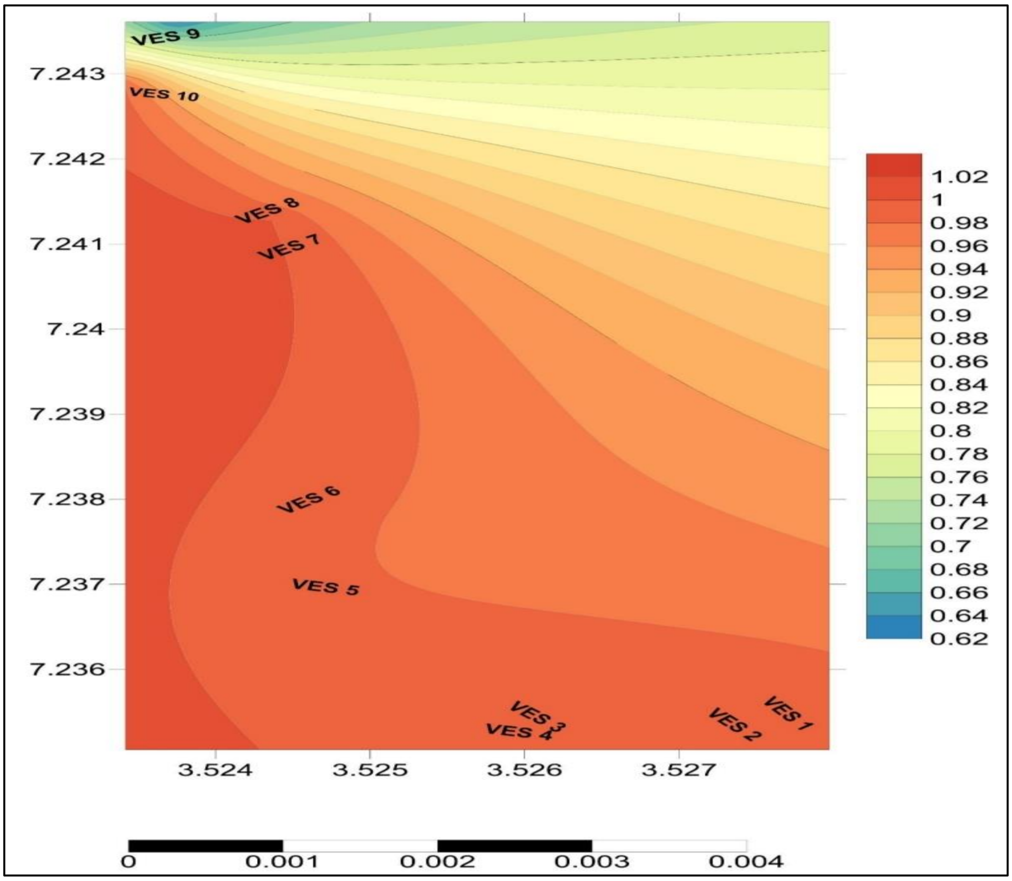

Fig 7 Surface Map of the Aquifer Protective Capacity

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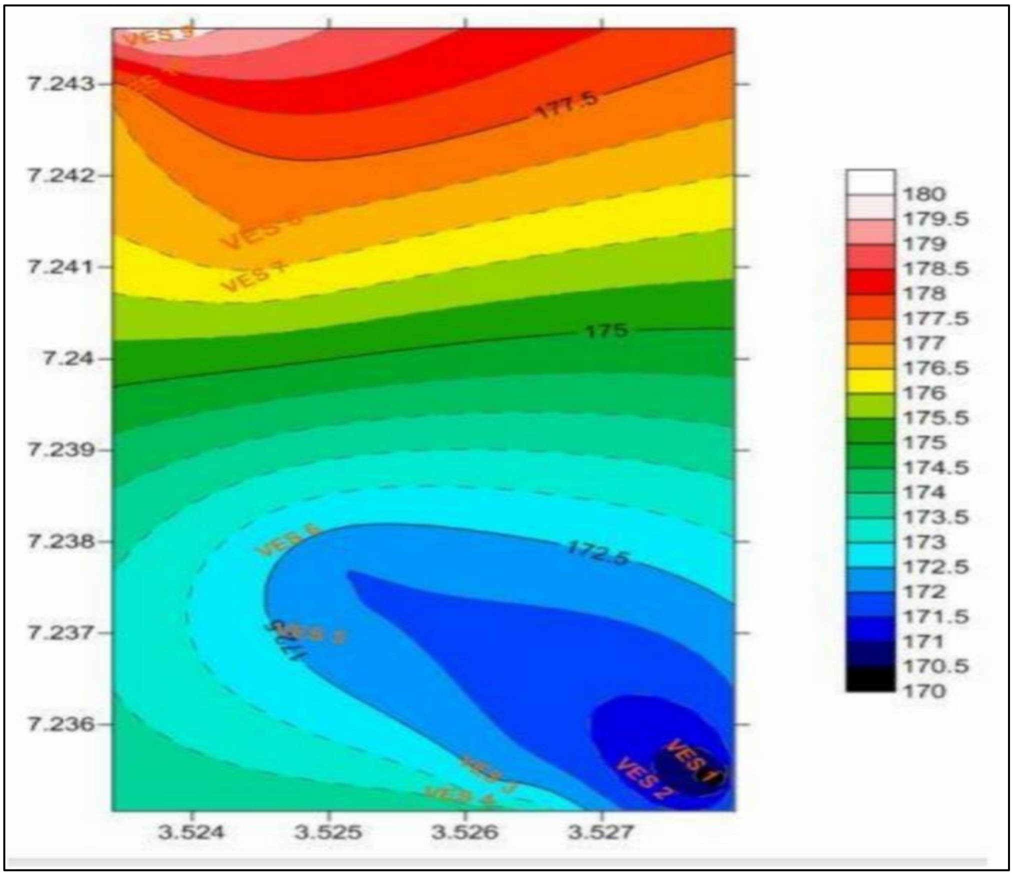

Fig 8 Topography Map of the Study Area

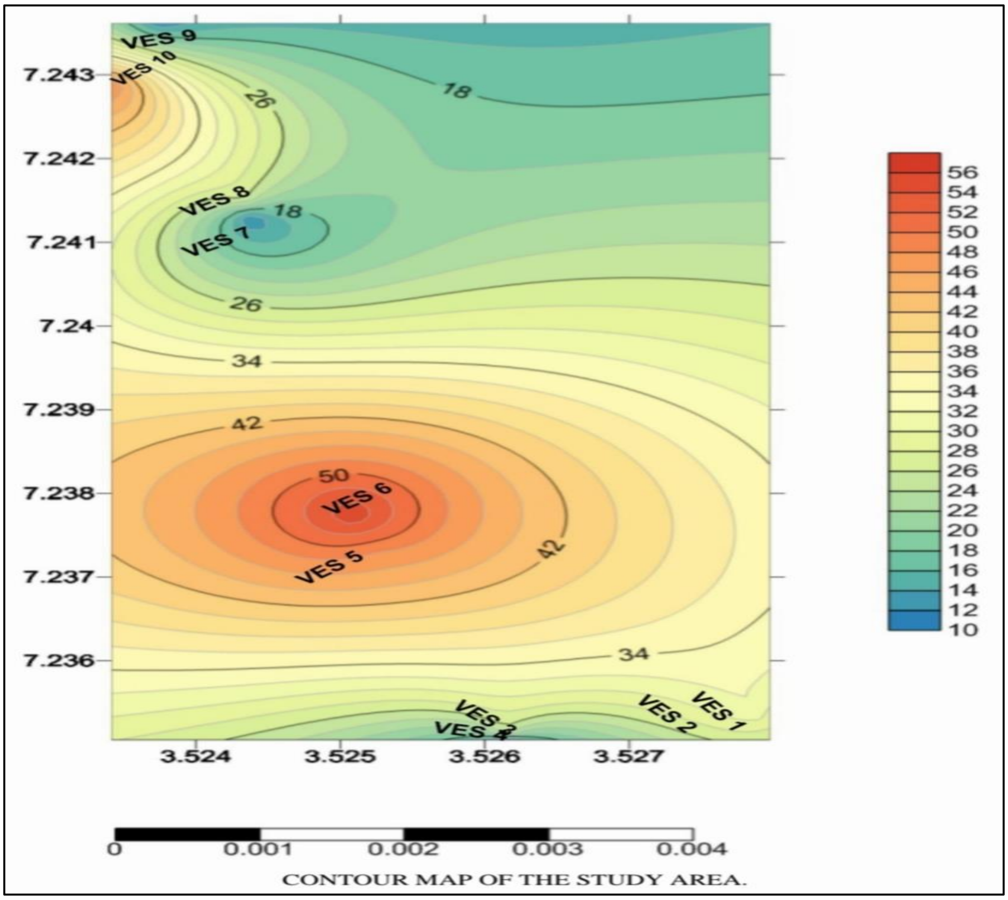

Fig 9 Contour Map of the Study Area

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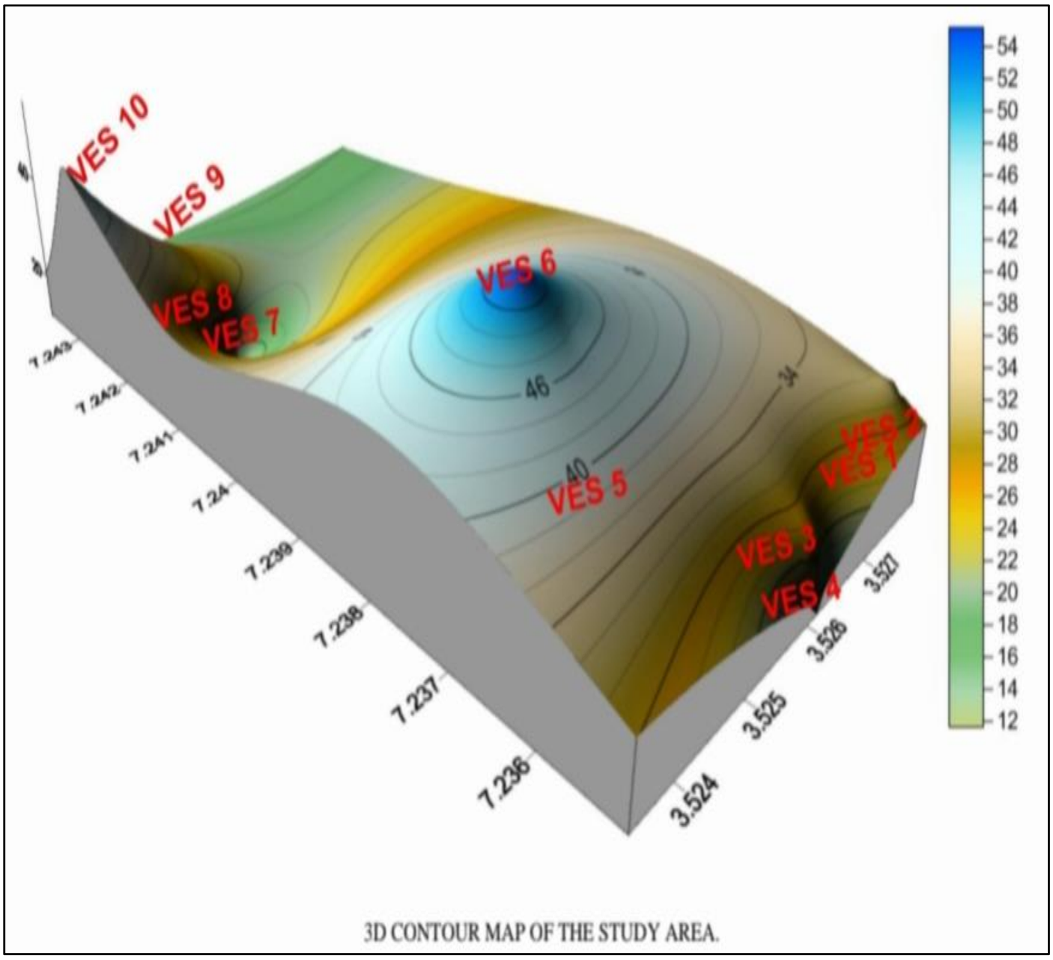

Fig 10 3D Contour Map of the Study Area