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Geophysical subsurface characterization of a complex geological terrain for groundwater resource development: case study of Iju, Nigeria

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Abstract: Access to potable water facilitates rapid civilization, health and social stability in different regions of the world. Subsurface exploration involving detailed geological, geophysical; very low frequency electromagnetic (VLF-EM), electrical resistivity method using vertical electrical sounding (VES) techniques and hydrogeological survey was carried out to characterize the subsurface geological and hydrogeological conditions with a view to developing a contemporary groundwater resources scheme. This is to meet the demand for water and improve the lives of the residents in the study area. Groundwater flows from eastern, northeastern and northern directions to the central, northwestern, southeastern, southern and western parts of the area. Conductive zones within the subsurface established by the VLF-EM survey constitute the forty-seven locations further investigated by VES techniques. Three to five geologic layers were identified, while the weathered and fractured bedrock form the aquifer units with depth in the range 3.5m to over 100 m. The fractured aquiferous unit represents the target aquifer due to its characteristic thick sandy geological formation (mean resistivity; 602 ± 140 Ohm-m) being more prolific in groundwater yielding capacity. Bedrock depressions with thick overburden (¿ 25 m) were identified as viable groundwater potential zones. Hydrogeological maps generated give insight into geological conditions of the aquiferous units. Groundwater potential map of the area categorizes aquiferous zones based on their yield potential. High groundwater yield potential zones of the area can be harnessed for massive groundwater development scheme. Other zones can be of use as the need arises.
Keywords: Groundwater development; Electromagnetic investigation; Geoelectrical characteristics; Hydrogeological parameters; Aquifer characterization; Groundwater flow pattern

Abstrak: Akses terhadap air minum menyebabkan percepatan budaya, kestabilan kesehatan dan status sosial di seluruh dunia. Eksplorasi bawah permukaan melibatkan very low frequency electromagnetics (VLF-EM), metode kelistrikan menggunakan Vertical Electrical Sounding (VES), dan survey hidrogeologi untuk melakukan karakterisasi kondisi bawah permukaan untuk pengembangan skema air tanah yang idgunakan untuk meningkatkan taraf hidup masyarakat di sekitar area studi di Iju Nigeria. Sumber air tanah berasal dari timur, timur laut dan utara ke bagian tengah, barat laut, tenggara, selatan dan barat daerah. Zona konduktif di bawah permukaan yang ditetapkan oleh survei VLF-EM mencakup empat puluh tujuh lokasi yang diselidiki lebih lanjut dengan teknik VES. Tiga sampai lima lapisan geologi diidentifikasi, sedangkan batuan dasar membentuk unit-unit akuifer dengan kedalaman berkisar 3,5m hingga lebih dari 100m. Target akuifer mempunyai karakteristik formasi batupasir tebal (dengan rata-rata resistivitas; 602 ± 140 Ohm-m) yang produktif dalam menampung air tanah. Batuan dasar dengan lapisan penutup yang tebal (¿ 25 m) diidentifikasi sebagai zona potensial air tanah. Peta hidrogeologi yang dihasilkan memberikan wawasan tentang kondisi geologi unit akuifer. Peta potensi air tanah di wilayah tersebut mengkategorikan zona akuifer berdasarkan potensi kapasitasnya. Zona potensi hasil air tanah yang tinggi di daerah tersebut dapat dimanfaatkan untuk skema pengembangan air tanah secara masif. Sementara zona lain dapat digunakan sesuai kebutuhan
Kata kunci: Pengembangan air tanah; Investigasi elektromagnetik; Karakteristik geolistrik; Parameter hidrogeologi; karakterisasi akuifer; Pola aliran air tanah

1 INTRODUCTION

Water as an essential natural resources plays major roles in the economic development and social stability of the world. We derive water through surface water (water from rivers, lakes, streams and storage reservoirs) and groundwater (water from hand-dug wells and boreholes) through water bearing rock layers (aquifers). Access to potable water facilitates rapid civilization in different parts of the world and can be supplied by the groundwater. The attention is diverted to groundwater abstraction because of its numerous advantages over surface water and consideration as world's safest fresh available water (Ademila & Saloko, 2018). Groundwater commences with rainfall that percolates into the ground with the volume which varies from different locations according to the topography, quantity and rainfall intensity, climatic condition, geomorphological features and geological setting. The inevitable development of water resources for human consumption and other domestic purposes involve adequate knowledge of its quantity and protective capacity of the aquifer unit. Many people have been exposed to water-borne diseases due to inadequate water resources and consumption of unsafe drinking water. Groundwater is considered adequate for potable supplies because of its exceptional natural quality with little or no treatment and comparatively low cost of management and development. Continuous demand for water in Iju, Nigeria, the study area has constituted pressure on water resources due to increase in population of the town. It is worst during the dry season as the source of water supply in the area is surface water with seasonal major rivers draining the area which dry up during this season. Presently, two boreholes and few hand-dug wells which serve as groundwater scheme are used to augment the seasonal surface water supply in the area have been abandoned due to their failure in water yield, which make access to potable water difficult. Geophysical methods have been used as tools for mapping groundwater resource and discrimination of water bearing rock form non-water bearing rock (groundwater character discrimination). Most geophysical techniques widely used for groundwater exploration, mapping and monitoring contamination and groundwater characterization are electrical resistivity, seismic refraction and electromagnetic methods but the electrical and electromagnetic methods proved most appropriate for groundwater studies with huge success (Oluwafemi and Oladunjoye (2013), Ademila and Saloko (2018), Ademila and Ololade (2018)). The successful utilization of these techniques (electrical and electromagnetic techniques) in groundwater geophysical investigations is as a result of the connectivity between electrical characteristics, geologic materials and their fluid content (McNeill, 1990). This is because the geological formation characteristics significant to hydrogeology, that is the hydrogeological parameters; porosity, transmissivity, permeability and conductivity of rocks can be linked to electrical resistivity/conductivity signatures. Increasing trend in the use of different geophysical techniques in hdrogeological studies have been linked to ever increasing human consumption of potable water and the necessity to locate new productive groundwater sources and to protect the existing water sources from contamination. Crystalline basement rocks are non-water bearing rocks because of their characteristic low porosity and impermeability. Groundwater exploration becomes difficult in hard rock terrain in which the study area falls because of the poor water absorption and flow capacity possessed by the rocks. This challenge associated with poor groundwater exploration condition can be solved by secondary porosity and permeability, which can be achieved by fractures and weathering. The possession of these hydrogeological features make them suitable water-bearing rocks (aquifer), capable of producing substantial quantity of water. Detailed knowledge of the direction of groundwater flow is needed to assess the groundwater potential of an area as well as in determining the recharge zones so that human activities do not affect groundwater quality for sustainability of the resources (Ademila & Saloko, 2018). Groundwater exists under pressure (unconfined condition) in the weathered layer of impermeable soil or crystalline rocks and confined condition in the fractured basement beneath the weathered layer. This is because fractured layers are more porous and permeable than clayey weathered basement. However, the water productivity of aquifers in basement complex terrain is influenced by the nature and type of geologic materials, location and extent of fractures, interconnectivity of pore spaces within aquifer materials and sources of water seepage. The secondary porosity influences variation of resistivity of rocks which offer electrical resistivity method preference over other geophysical techniques in groundwater exploration. The attraction to very low frequency electromagnetic (VLF-EM) and electrical resistivity techniques is in its simplicity of implementation, computing capacity and processing algorithms involved in the inversion of results (geophysical data) for evaluation of subsurface geologic parameters to image the subsurface (Loke, 2002). The method is competent of delineating subsurface structures of groundwater potential interest that could not be revealed by any drilling programme (Oluwafemi & Oladunjoye, 2013). Public access to substantial quantities of water in Iju is negligible despite huge efforts by private sector and the state government. Field observations showed that the two boreholes and a number of hand-dug wells in the study area are no longer productive, while the other hand-dug wells are seasonal with low average groundwater yield all through the year. However, this does not commensurate with the population needs of the town and has limited the urbanization and socio-advancement of the town. Rising demand of people andexpansion plans to improve the lives of residents prompted this study. This is to delineate the water bearing zones and preferential groundwater flow pattern of the study area with a view to have a contemporary water resources scheme in the area. Thus, the study involves geological, geophysical; very low frequency electromagnetic (VLF-EM), electrical resistivity method using vertical electrical sounding (VES) technique and hydrogeological measurement to investigate the geological condition of Iju, in order to understand the subsurface structural disposition and hydrogeological characteristics for appropriate siting of groundwater abstraction points. This study also intends to offer effective means of managing the surface and groundwater resources to cushion the effects of health problems associated with inaccessibility to potable water in the area under study.

2 STUDY AREA (DESCRIPTION, GEOLOGY AND HYDROGEOLOGY)

The study area is between latitudes 7° 05' N - 7° 30' N and longitudes 5° 05' E - 5° 30' E. (Fig. 1) and falls within the tropical rain forest region of southwestern Nigeria. It is in the uplifted regions (western uplands) of southwestern Nigeria. It is characterized by rainy and dry seasons with high rainfall of about 1,750 mm per annum which constitute groundwater recharge in the area with uniform temperature of 27°C and over 75% relative humidity. Quantity of water is influenced by the climate of the area, controlled by moist, moderately cool southwest monsoon wind that brings rainfall, dry, hot northeast trade winds and high equatorial eastern tides which brings dry weather. This climatic belt favours the growth of a dense forest characterized by tall trees of different kinds with broad-leaves in the study area. It covers an area extent of about 39.3 km2. It shares border with Ekiti State to the north and east, Ifedore Local Government to the west and Itaogbolu to the south (Fig. 1). It is drained by some streams and major Rivers; Ogbese, Olaoluwa and Ono. The drainage pattern of the area is dendritic with dom-

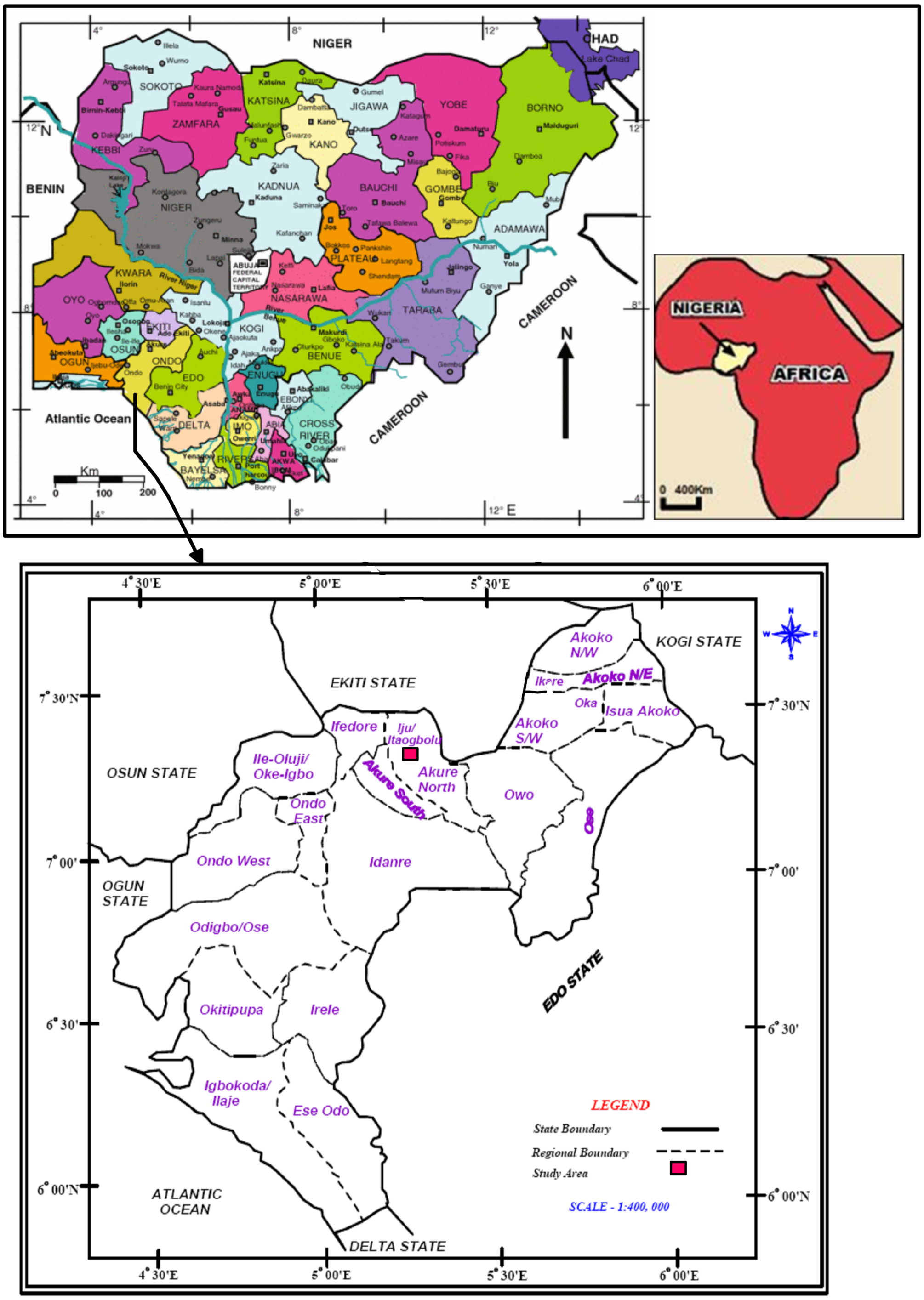

Figure 1. Map of Ondo State showing Iju, the study area

inance of the rivers. The topography is gently undulating, from flat terrain to low lands and hilly terrain with elevation above 350 m above sea level (Oluwafemi & Oladunjoye, 2013).

2.1 Geology and Hydrogeology of the area

Geologically, the area under study is within the Precambrian basement complex rocks of Southwestern Nigeria, situated in the Pan-African Mobile Belt between the West African and Congo Cratons. Lithologic units of this region include the migmatite-gneiss-quartzite complex and older granites. Rahaman (1989) classified the basement complex as mixed (heterogeneous) rock units comprising migmatite, basic to ultrabasic metamorphosed rocks, schists and gneisses. The conducted field geological mapping revealed the dominance of porphyritic biotite and biotite-hornblende granite, migmatite, medium to coarse grained biotite granite and charnockite in the study area as shown in Fig. 2. Crystalline basement rocks are impermeable, charac-

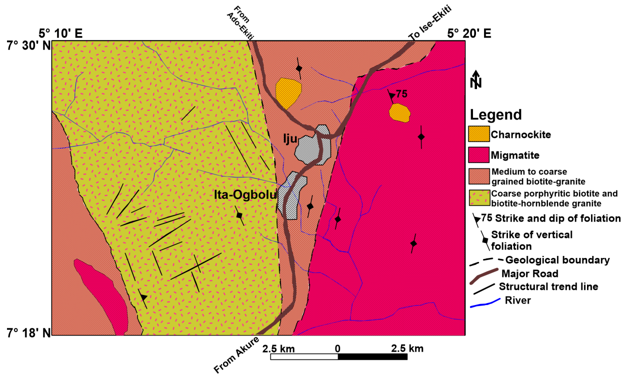

Figure 2. Geological map of Iju and its environment

terized by low porosity and insignificant permeability. Rainfall, geological factors and friendly climatic conditions offer sufficient recharge of groundwater in the area. The lateritic soil of the area with the impervious clay beneath constitute protective layer for the water-bearing units (aquifer). Information gathered from the geological field mapping exercise showed that the residents of the area experience shortage of water particularly during dry season due to the seasonal nature of the available streams, hand-dug wells and unproductive two boreholes in the area. Groundwater in complex geological terrain is concealed in the weathered and fractured basement aquifers (Olayinka, 1992). The groundwater occurrence in crystalline basement restricted in fractures or weathered zones vary in production yield with respect to location. It may also be accumulated in buried stream channels consequent to weathered and fractured geologic units beneath the weathered substratum. Noticeable geological structural features in rocks of the study area are faults, folds, foliations, joints, others are dykes, xenoliths, solution holes, lithological contacts and veins infillings. These features support storage (accumulation) and groundwater flow as they enhance rock weathering which boost groundwater storage. These in turn help to pin-point the groundwater abstraction points in this area. The rivers draining the area are; River Ogbese, Olaoluwa and Ono, which took their source from geological contact. Thus, it is emphasized that such areas be explored for groundwater development. The capability of a rock to hold, store water and have free flow of water dictates its hydrogeological potential with respect to groundwater yielding capacity. These hydrogeological characteristics rely on the texture and mineralogical composition of rocks which tend to increase significantly by weathering and fracturing (Offodile, 1983). Groundwater yield in this area of hard rock settings is enhanced by the existence of thick, porous weathered and fractured zones, which is a function of the existence, extent and location of fractures coupled with type and composition of overburden.

3 DATA AND METHODS

Field geological mapping was conducted to describe the various rock formation encountered. The coordinates and surface elevations above mean sea level of each location were measured with a global positioning system (GPS). This was done to produce the geological map and geophysical field layout map of the area. Structural features such as fractures, folds and foliations which characterized the granitic rocks were identified and delineated. These structures serve as pathway for groundwater, thus selection of such areas may form viable sites for groundwater development with maximum yield. The hydrogeological investigation involves static water level measurement of forty-six hand-dug wells distributed across the area using measuring tape and GPS with a view of mapping the groundwater flow directions. Most of the wells visited during the survey are seasonal in groundwater yield. Combined very low frequency electromagnetic method (VLF-EM) and vertical electrical resistivity sounding techniques were utilized. Ten traverses in the range 400 and 1200 m were established with respect to the existing roads along which the geophysical data were acquired (Figure 3). The VLF-EM measurements were conducted along the traverses with 20 m station interval along each traverse using ABEM WADI VLF system. Horizontal (Hp) and vertical (Hs) components of magnetic field in form of real and imaginary parts of vertical magnetic field component were measured with the VLF instrument. This reconnaissance survey located points of anomalous electromagnetic responses on which forty-seven VES stations were established (Figure 3). At each station, both real and imaginary components of the VLF-EM field were measured. These data are displayed as profiles by plotting raw real and filtered real components against distance (Figures 5a – 14a). The qualitative interpretation of the profile presents the conductive zones of the subsurface as intersection of the points of crossover and positive peaks of the real and filtered real anomaly (Nabighian, 1988). The real anomalies which indicate near surface geologic structures were thereafter processed also for qualitative interpretation. The data were inverted with the aid of KH Filt software and illustrated as pseudosections (Figures 5b – 14b) (Pirttijarvi, 2004). The electrical resistivity method adopted the measurement of forty-seven locations with vertical electrical sounding techniques using Schlumberger array. The resistivity measurements involving forty-seven soundings were conducted with ABEM SAS 1000 terrameter system with maximum current electrode spread (AB/2) of 150 m, with field data of each sounding recorded on Schlumberger data recording sheet. These sounding stations were as a result of the anomalous points (conductive zones) of the VLF surveys (Figure 3), to investigate the vertical changes in the resistivity distribution with depth. The resistivity field sounding data (VES data) were presented as field curves (VES curves) by plotting apparent resistivity (ρ_a) versus electrode spacing (AB/2) on a log-log graph paper. Field curves were interpreted qualitatively and quantitatively with the aid of partial curve matching (Koefoed, 1979) and master curves (Orellana & Mooney, 1966) with appropriate supplementary graphs (Keller & Frischknecht, 1966; Zohdy, 1965) to get first values of geoelectrical parameters at different stations. Curve matching is an approach used to estimate the true resistivities of subsurface materials. This technique is a way to match field measurements of apparent resistivity (ρ_a) and scaled electrode spacing to theoretical curves that have been calculated for various layer thicknesses and resistivities. The concluding phase of the interpretation was done with *Win-Resist*, an iteration modeling technique, where the model derived from the preliminary interpretation was inputted in

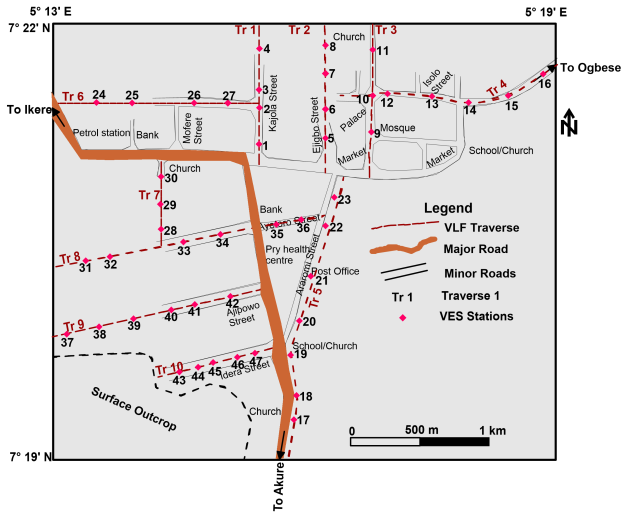

Figure 3. Base map/geophysical data acquisition map of Iju showing the VLF-EM traverses and VES stations

the inversion algorithm (Vander Velpen, 2004). The values of resistivity and thickness obtained from the final model derived from the software were used to construct geoelectric sections, (Figures 16-25) which provide composite information of the different geologic formations encountered at depth.

3.1 Estimation of hydrogeological parameters

These parameters serve as fundamental and vital tools for the interpretation and understanding of geoelectrical model of layered earth for in-depth information of the subsurface lithology and attributes. The main hydrogeological parameters; porosity, transmissivity, permeability and conductivity can be estimated from surface geophysical measurements because of their connectivity with electrical conductivity signatures derived from the correlation that exist between electrical properties, geologic materials and their fluid content (McNeill, 1990).

3.1.1 Porosity

The porosity of geologic formation (φ) is the ratio of the volumes of the pores to that of the rock unit which determines its capacity to hold and store water which influences its resistivity value. It is evaluated using Equation 1

$$\phi = (\frac{\rho_w}{\rho_r})^{\frac{1}{2}} \tag{1}$$

Where ρ_w is the resistivity of water in the geological formation and ρ_r is the geoelectrical resistivity of the rock unit/geological formation

3.1.2 Reflection Coefficient and Geophysical Resistivity Contrast

The reflection coefficient (Rc) and geophysical resistivity contrast are important hydrogeological parameters used for evaluating groundwater potential of an area to determine the extent of freshness or fissures/fractures of the bedrock. They can be evaluated using Equations (2 and 3) proposed by Olayinka (1996) as:

$$R_c = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \tag{2}$$

$$ResistivityContrast = \frac{\rho_n}{\rho_{n-1}} \tag{3}$$

Where ρ_n is the resistivity of the nth layer and ρ_{n-1} is the geoelectrical resistivity of the layer above the nth layer.

3.1.3 Aquifer Longitudinal Layer Conductance

The longitudinal layer conductance (SL) was evaluated to determine the protective ability of the aquiferous unit in the area, which in turn predicts the safety level of the layer. Naturally, the earth or impervious clay/lateritic clay unit over the aquifer serves as a filter to infiltrating water, thus its capacity to hinder and filter infiltrating polluting fluid determines its groundwater protective capability (Olorunfemi, Olarewaju, & Alade, 1991).

$$S_L = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \tag{4}$$

S_L can therefore as well be represented as:

$$S_L = \frac{h_i}{\sigma_1}, where \sigma_i is conductivity \tag{5}$$

3.1.4 Transverse Layer Resistance

The transverse layer resistance (R_T) is proportional to the resistivity and thickness of aquifer. The transverse layer resistance is denoted by:

$$R_T = \sum_{i=1}^{n} h_i \rho_i \tag{6}$$

Where h_i, ρ_i and σ_i are the layer thickness, resistivity and conductivity of the ith layer respectively in the geological section. This layer conductivity is equivalent to the layer hydraulic conductivity K_c applied in hydrogeology. The S_L and R_T of equations 4 and 6 above are the Dar Zarrouk parameters, estimated from geoelectric (VES) measurements; layer resistivity and thickness are very important for the interpretation and understanding of groundwater investigation data for appropriate selection of suitable borehole locations.

3.1.5 The aquifer longitudinal resistivity

The aquifer longitudinal resistivity is expressed as

$$\rho_L = \frac{H}{S_L} \tag{7}$$

where $H = \sum_{i=1}^{n} h_i$, and then the aquifer transverse resistivity is denoted by:

$$\rho_T = \frac{R_T}{H} \quad (8)$$

3.1.6 Electrical anisotropy

Electrical anisotropy (anisotropy coefficient), the directional dependence of electrical resistivity (or its inverse, conductivity) dictates the direction of flow of currents and the resultant induced potential fields. It is as a result of inhomogeneities and the extent of fracturing of the geological units of the area. It serves as one of the indicators used to predict groundwater yield of aquifer systems (Olorunfemi et al., 1991).

$$\lambda = (\frac{\rho_T}{\rho_L})^{\frac{1}{2}} = \frac{(R_T \times S_L)^{\frac{1}{2}}}{H} \quad (9)$$

3.1.7 Transmissivity

A measure of the capability of a saturated aquifer of thickness h and hydraulic conductivity K to transmit water, that determines the lateral flow of groundwater in the aquifer and influences aquifer potentiality. Tr, is the product of hydraulic conductivity (K) and aquifer thickness with units of square meters per day.

$$T_r = K\ h \quad (10)$$

Where K is the hydraulic conductivity of the thickness h. T_r can also be obtained from R_T and S_L (Patra & Nath, 1999) as

$$T_r = K\ \sigma\ R_T \quad (11)$$

$$T_r = (\frac{K}{\sigma})S_L \quad (12)$$

3.1.8 Hydraulic conductivity

The capability of a porous medium to transmit fluid is dependent on both the properties of the fluid and the medium. The hydraulic conductivity decreases very rapidly as the medium becomes unsaturated, because the larger pores of the subsurface become air filled first, causing flow to occur in smaller pores which conduct water at much lower flow rates according to Poiseuille's law. The hydraulic conductivity in unsaturated systems is a function of the volumetric moisture content.

$$K = 10^{-5}97.5^{-1}\rho^{1.195}606024 = 8.861510^{-3}\rho^{1.195}(m/day) \quad (13)$$

Hydraulic conductivity considers the permeability of the aquifer substratum and the fluid transmitted through the aquifer, thus, hydraulic conductivity and geoelectrical resistivity influence the nature of aquiferous layer.

4 RESULT AND DISCUSSION

The field geological mapping resulted in production of the geological map of the area and most of the geological structural features observed (faults, dykes and joints) are significant in groundwater exploration.

4.1 Hydrogeological Investigation

The major aquiferous zones of the area are derivative from weathered rocks and fractured bedrock from which substantial quantity of water is obtained and available for optimum use to the residents through hand-dug wells and boreholes. The depth to fresh bedrock (overburden thickness), occurrence and extent of fissures/fractures of the basement rocks determine the amount of groundwater obtainable and its storage capacity within the subsurface. Thus, for utmost and persistent yields, borehole should be drilled where it would penetrate maximum thickness of weathered overburden (Olayinka, 1992). The two boreholes in the study area were abandoned because of their inability to function appropriately and most of the wells visited during the survey are seasonal in groundwater yield. This could be as a result of the wells not taping water from the aquiferous zones in the area. The depth to water table (static water level) of different hand-dug wells of the area varies from 1.3 – 9.4 m with a mean 5.23 ± 1.97 m. The variation in the water level is influenced by geological condition, overburden thickness and topography of the area. At times, the movement of surface water does not depict groundwater movement in aquifer, so determination of groundwater flow pattern is required to identify the recharge zones and ensure that the zones are free from human activities that could pose risk to groundwater quality to guarantee sustainable groundwater resources (Ademila & Saloko, 2018). The arrows on the groundwater head map (Figure 4) shows the direction of groundwater flow from eastern, northeastern and northern directions to the central, northwestern, southeastern, southern and western parts of the area. These regions of the area correspond to the converging centres of maximum groundwater potential for groundwater resource development. From the groundwater flow pattern, Iju can be categorized as groundwater converging and diverging zones. Most of these converging zones are situated closely to the identified lithologic boundaries. The groundwater flow direction correlates with the drainage pattern of the area, as it is towards the rivers which indicate that the rivers are recharged through groundwater flow. Groundwater development scheme is recommended in the converging zones of the area for sustainable water supply. Also, waste disposal sites are proposed towards the southwestern region to prevent groundwater contamination.

4.2 Geophysical Investigation

4.2.1 VLF – EM profiles and their corresponding 2-D inverted models

The VLF-EM technique proves to be effective in superficial detection of inhomogeneities especially near-surface, steeply-dipping conductors (faults/fractures). The results of the VLF-EM profiling; raw real and filtered real components taken along the ten established traverses were plot-

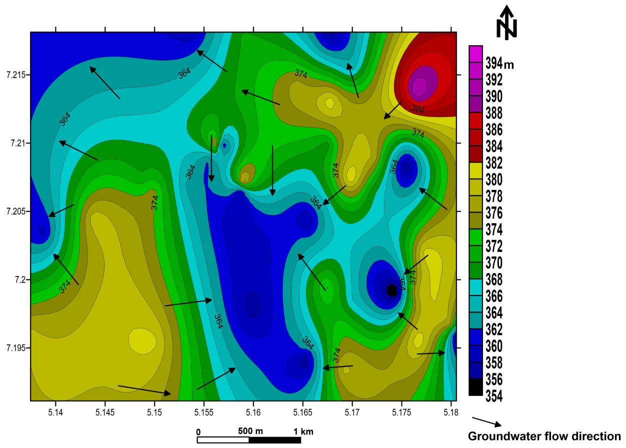

Figure 4. Groundwater head map of Iju

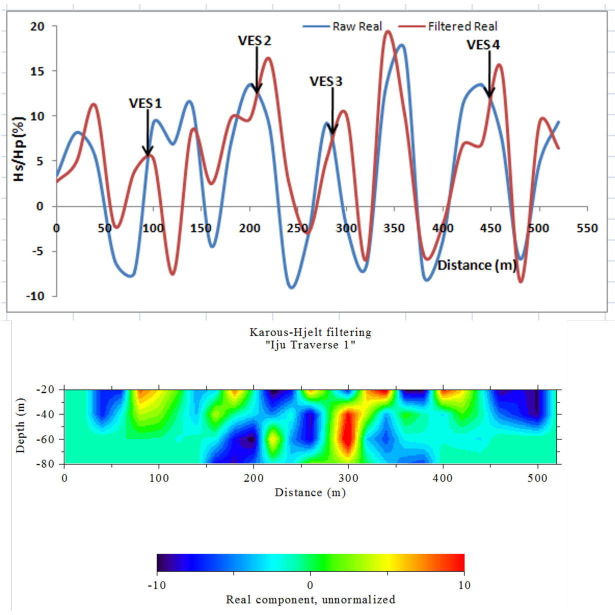

Figure 5. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 1

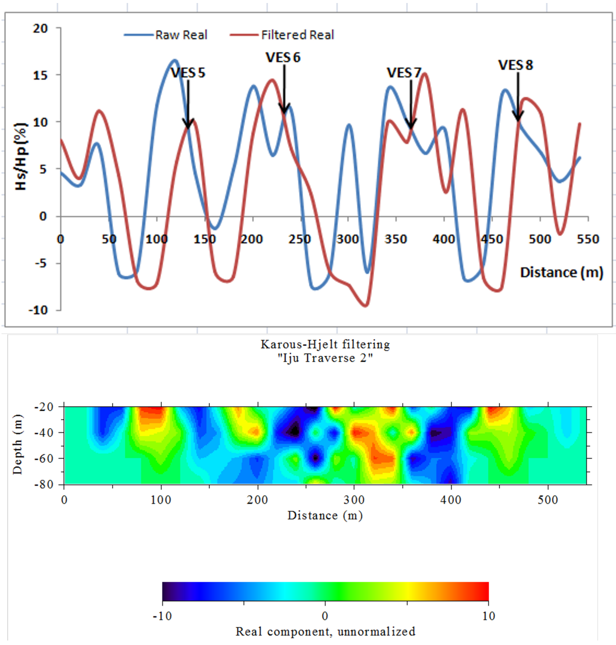

Figure 6. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 2

ted against their distance as VLF-EM anomaly curves (Figures 5a – 14a). This enables qualitative identification of conductive zones within subsurface at the points of coincident of crossovers and positive peaks of the real and filtered anomaly. Forty-seven major conductive geological interfaces suspected to be faults/fractured zones were identified from the composite plots, which were used to locate the points for VES survey. These conductive zones are indicative of faults/fractures, lithologic contacts, weathered bedrock and other weak zones that enhance accumulation of water and form pathways for groundwater. The Karous-Hjelt 2D inverted models give the distribution of anomalous subsurface conductive/resistive geologic features (Figures 5b – 14b). The conductivity is shown as colour codes (green to red), with the response (conductivity) increasing from left to right (i.e. from negative to positive). Different features of varying degrees of conductivity trending in different directions were delineated. The major conductive bodies are shown in green to yellow to red colours on the 2-D model sections which indicate the presence of geologic features such as fractures, faults, geologic contacts or weathered basement. The VLF sections are characterized by alternating bands of low and relatively high conductive materials of varied depths trending in different directions. This indicates variable conductivity changes of the subsurface materials. Areas associated with high conductivity, as reflected in the K-H pseudosections, are considered to be zones of weaknesses such as fractures, faults, and lineaments (Ademila, Olayinka, & Oladunjoye, 2020). These conductive zones are relevant in groundwater development of the area as they serve as potential sites for groundwater supply.

4.2.1.1 ***Traverses 1 and 2*** The points of anomalous conductivity identified at 95, 210, 285 and 450 m and 135, 230, 370 and 475 m along traverses 1 and 2 respectively (Figures 5a and 6a) suggested significant points in groundwater abstraction in hard rock terrain. The 2-D inverted models reveal points showing major conductive features of varying degree of conductivity trending in different directions on the sections. The observations of the conductive features on the VLF-EM profiles correspond with the conductive zones delineated by the 2-D sections at distances 70 – 120, 270 - 320 and 390 – 550 m (Figure 5b) and 60 – 140, 250 – 370 and 420 – 500 m (Figure 6b). These conductive zones are relevant in groundwater development of the area as they serve as potential sites for groundwater supply and facilitate high groundwater yield of the area.

4.2.1.2 ***Traverses 3 and 4*** The geological interfaces delineated at distance 175, 325 and 500 m (Figure **??**a) and 170, 345, 485, 655 and 795 m (Figure 8a) from traverses 3 and 4 indicate conductive bodies like faults, frac-

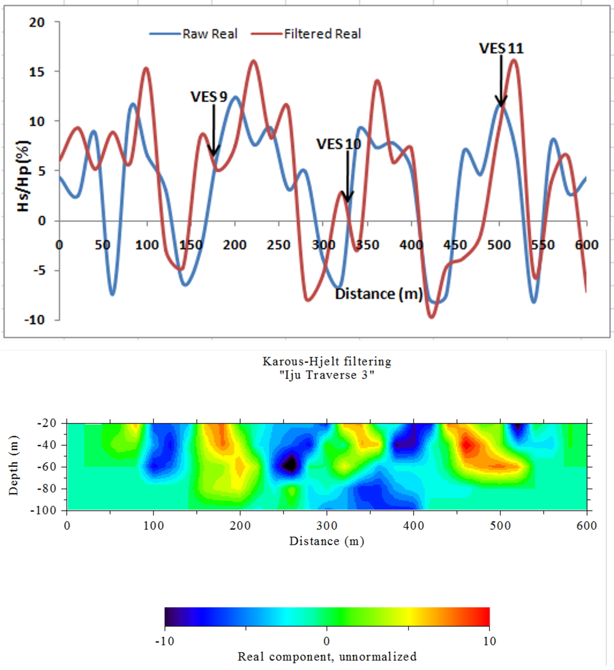

Figure 7. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 3

tures, depressions and geologic contacts which are suitable for groundwater development. The 2-D inverted model identified series of high conductive bodies across the area which suggest accumulation zones of water between station distance 30 – 90, 150 – 250, 300 - 350 and 420 – 550 m (Figure 7b) and 100 – 200, 250 – 500, 560 – 700 and 750 – 820 (Figure 8b). Identified conductive features on the VLF-EM profiles and its 2-D inverted models are geologic unit with groundwater potential. These conductive zones serve as possible sites for groundwater development of substantial quantity where boreholes could be sited for community supply throughout the season.

4.2.1.3 ***Traverses 5, 6 and 7*** Conductive geological interfaces at distance 175, 260, 430, 575, 720, 900 and 1060 m (Figure 9a), 150, 270, 510 and 680 m (Figure 10a) and 95, 185 and 325 m (Figure 11a) along traverses 5, 6 and 7 respectively constitute significant zones of interest for groundwater resource development. The 2-D inverted models reveal points showing major conductive features of varying degree of conductivity trending in different directions on the sections. The identified conductive features on the VLF-EM profiles correspond with the conductive zones delineated on the 2-D sections at distances 30 – 260, 300 - 950 and 1000 – 1100 m along traverse 5 (Figure 9b), 20 – 100, 150 – 470 and 530 – 680 m along traverse 6 (Figure 10b) and 80 – 180 and 260 – 400 m along traverse 7 (Figure 11b). These conductive zones indicate the presence of basement depression, faults or fractured zones that are relevant in groundwater development of the area as they serve as potential sites for groundwater abstraction. The conductive features facilitate movement and occurrence of groundwater and act as groundwater storage zones that guide easy identification of aquiferous units suitable for groundwater supply.

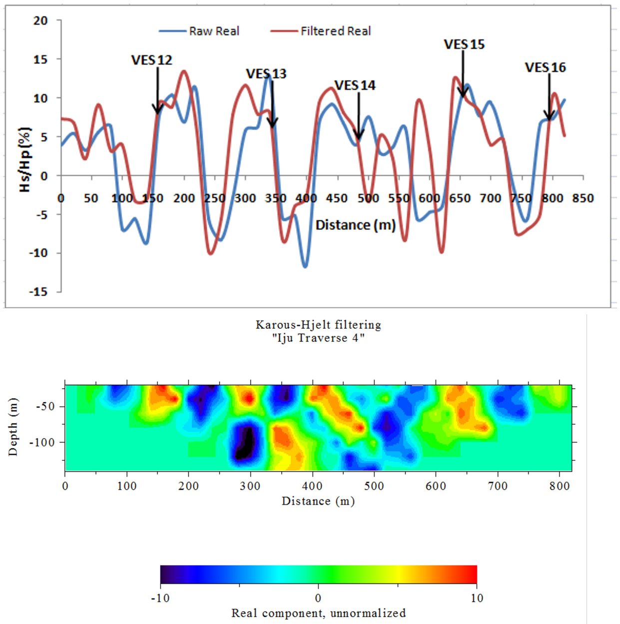

Figure 8. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 4

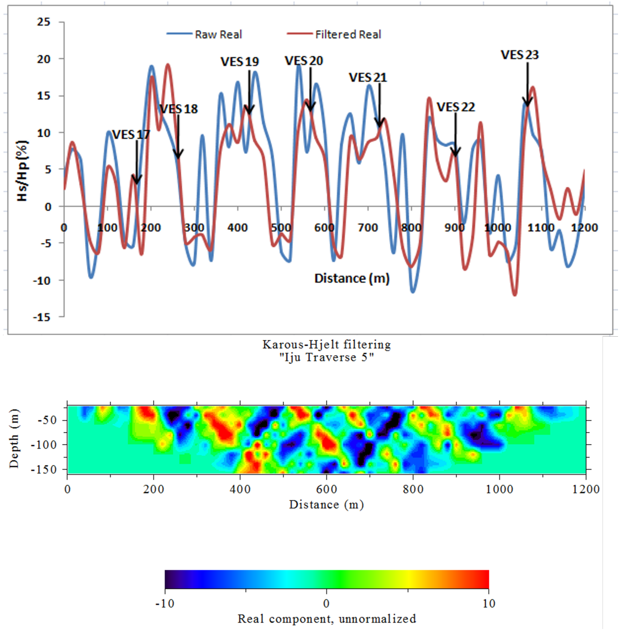

Figure 9. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 5

4.2.1.4 ***Traverses 8, 9 and 10*** Positive response peaks indicative of the presence of conductive zones; basement depression or fractured zones are identified at surface distance expression of 130, 220, 520, 660, 850 and 940 m (Figure 12a), 50, 180, 320, 450, 545 and 700 m (Figure 13a) and 105, 175, 220, 315 and 375 m (Figure 14a) along traverses 8, 9 and 10 respectively. The inverted sections in the area depict an uneven subsurface topography reflecting different degree of conductivities. Subsurface conductive structures

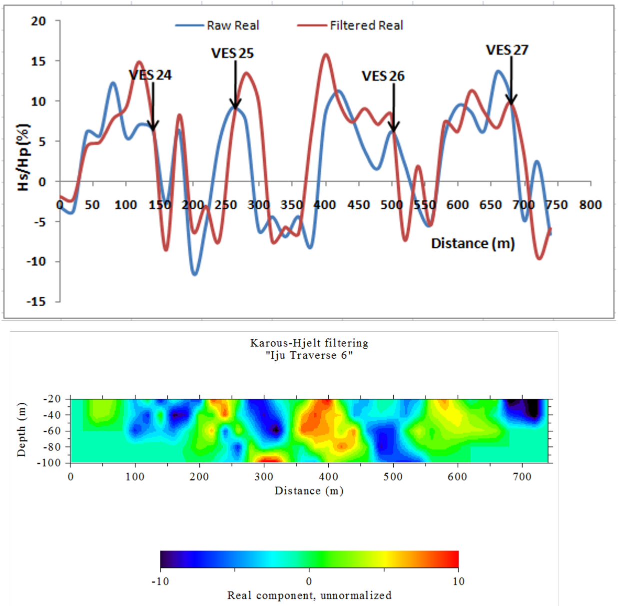

Figure 10. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 6

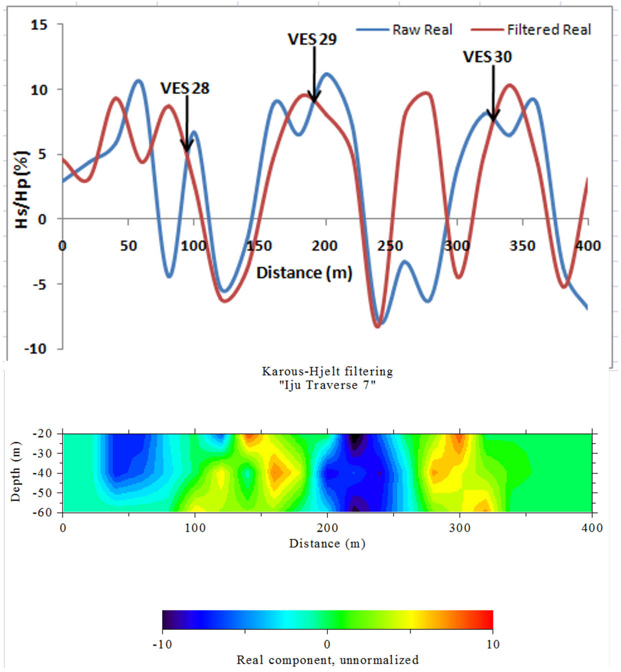

Figure 11. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 7

are observed on their corresponding VLF-EM 2-D sections at stretch of 10 – 570 and 750 – 900 m (Figure 12b), 80 – 180, 200 – 530 and 610 – 750 m (Figure 13b) and 50 – 130, 160 – 210 and 230 – 360 m (Figure 14b) along these traverses. The presence of subsurface conductive features are indications of water saturated geologic formation underlying the locations which can boost the exploitation of groundwater resources in the area. The observed conductive features at these locations suggest conductive geologic materials at depth, indicative of the presence of fractures and basement depressions constituting water collection zones and saturated geologic formation, suitable to support massive groundwater development scheme.

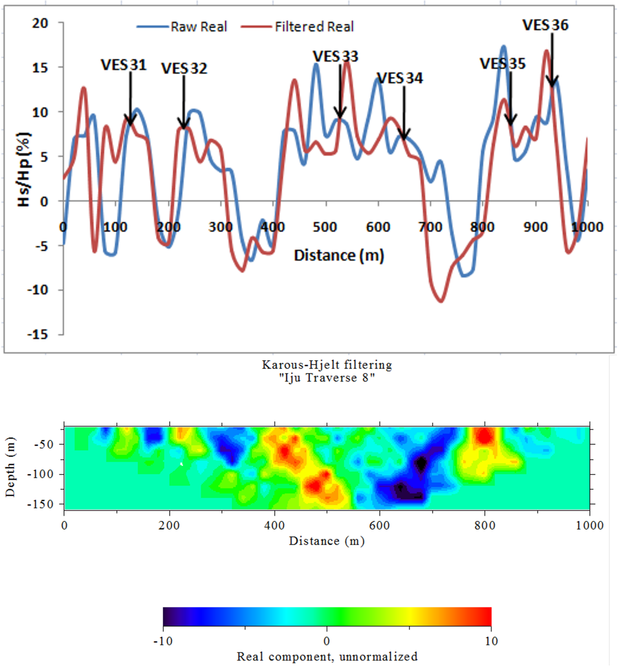

Figure 12. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 8

4.2.2 Subsurface Hydrogeoelectrical characteristics of the area

Accurate and in-depth knowledge of the geoelectrical parameters are of essence in evaluation of subsoil profiles in a complex geological setting (Telford, Telford, Geldart, & Sheriff, 1990). The results of the acquired forty-seven VES stations investigated based on the VLF-EM results were processed and displayed as sounding curves, tables, geoelectric sections and maps. The quantitative interpretation of the sounding curves provides geoelectric parameters (layer resistivity and thickness) used to generate the geoelectric sections (Figures 16 – 25). The geoelectric sections represent the geologic sequence mapped with respect to depth. The subsurface resistivity was interpreted with respect to subsurface lithology using the resistivity distribution values and in turn determined the capability of each geologic layer to groundwater yield. Results from the electrical resistivity method revealed the pattern of resistivity variations within the study area with insight to the geoelectric characteristics of the geologic units giving the precise groundwater viability and storage capacity of each layer. Nine different curve types were identified from the study; A, AA, HA, KH, HK, AAA, HAA, HKH and KHA curve types (Table 1 and Figure 15). The curve types represent three to five distinctive lithologic layers; topsoil, sand, weathered bedrock, partially weathered/fractured bedrock and fresh bedrock (Figures 16 – 25). The HA-curve type dominates the study area with

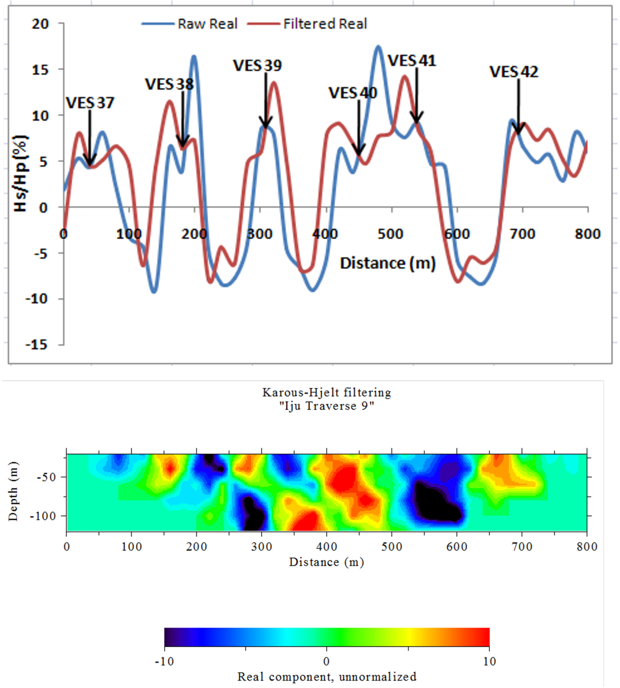

Figure 13. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 9

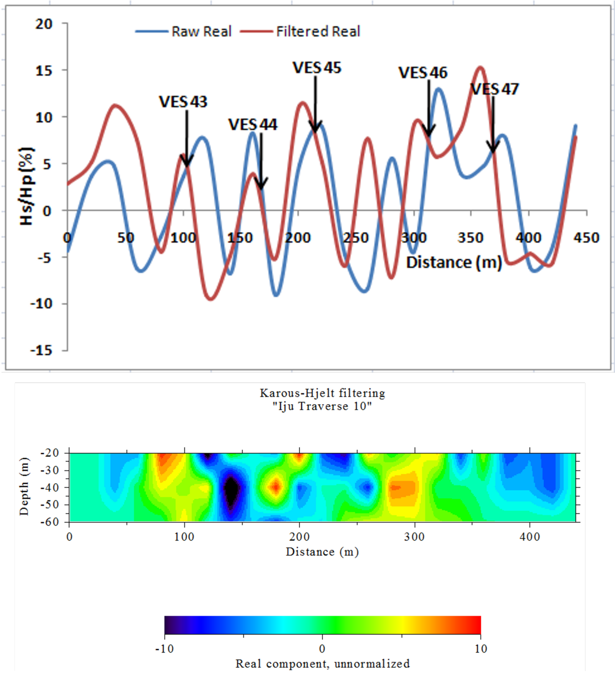

Figure 14. (a) Top plot is a VLF-EM real components and (b) Bottom plot is a corresponding 2-D inverted section of Iju Traverse 10

percentage frequency of 55.3%, followed by AA-curve type with 19.2% of occurrence, A-curve type (12.8%) and others with 2.1% each. Suitability of subsoil for groundwater development was assessed from the distributed layer resistivity and thickness to present favourable zones of maximum groundwater yield. The inference from the study is that the weathered and fractured bedrock form the aquiferous zones of the area. From the interpretation of the data, the electrical characteristics of the subsurface layers (geoelectric sections) were derived which provide geologic properties of each layer.

4.2.2.1 ***Traverses 1 and 2*** Four subsurface layers are delineated at these locations (Figures 16 and 17), resistivity of topsoil vary from 154 – 260 Ohm-m (Traverse 1) and 146 – 368 (Traverse 2) signifying sandy clay and clayey sand with thickness in the range 1.3 – 4.3 m and 2.1 – 2.5 respectively. Although, the topsoil has no significant contribution to groundwater potential, water infiltrate through it into the subsurface (saturated zone). The variation in the thickness of this layer is as a result of weathering, extent of compaction and erosion. The resistivity and thickness of weathered bedrock are in the range 40 – 322 Ohm-m, 2.2 – 8.4 m and 125 - 420 Ohm-m, 6.9 – 13.4 m respectively. Water saturated clay is dominant in the weathered zone of Traverse 1 due to its low resistivity values ¡ 100 ohm-m. The low resistivity is as a result of higher degree of weathering, which makes it significant to groundwater development. Zones in the resistivity range of 125 – 420 Ohm-m are also paramount to groundwater accumulation with medium to high groundwater potential because of its high porosity and permeability. The variation in resistivity of these locations is due to porosity of the geologic unit, chemistry of saturating fluid and extent of weathering. Partially weathered/fractured layer, the third layer has resistivity in the range 507 – 852 Ohm-m and 475 – 621 Ohm-m beneath VES stations 1 – 4 and 5 – 8 respectively (Figures 16 and 17). This geologic layer within this range of resistivity implies prolific aquiferous zone beneath the subsurface which contributes appreciably to sustain groundwater potential of the area. Presence of this layer enhances and supports groundwater potential of high yield for massive groundwater development scheme due to comparatively high permeability of the zone. The last geoelectric substratum, the fresh bedrock has resistivity values in the range 954 - 4176 Ohm-m with uneven bedrock interface and depth to bedrock in the range 8.2 – 51.3 m (Figure 16) and 27.1 – 41.4 m (Figure 17). It is observed from the geoelectric/geologic sections (Figures 16 and 17) that the VES stations across these locations are generally characterized with thick overburden and bedrock depression that form groundwater collection centre at VES 4 and 7 suggesting groundwater potential of substantial yield. This is an indication that the aquiferous horizon across these locations is considerably thick enough to sustain prolific groundwater abstraction in the area with overburden thickness of over 25 m across these locations except beneath VES 1 with minimal overburden (Figures 16 and 17).

4.2.2.2 ***Traverses 3 and 4*** Four geologic units are identified across these traverses (Figures 18 and 19), resistivity of the top layer in the range 100 – 470 Ohm-m (Traverse 3) and 98 – 221 (Traverse 2) signifies clay, sandy clay and clayey sand units having thickness ranging 1.5 – 2.2 m and 1.5 – 9.0 respectively. This layer serves as operation layer through which water flows into the saturated zones. The weathered bedrock has resistivity and thickness values ranging from 80 – 214 Ohm-m and 5.4 – 7.4 m (Traverse 3) and 103 – 193 Ohm-m and 12.4 – 22.1 m (Traverse 4) which constitute

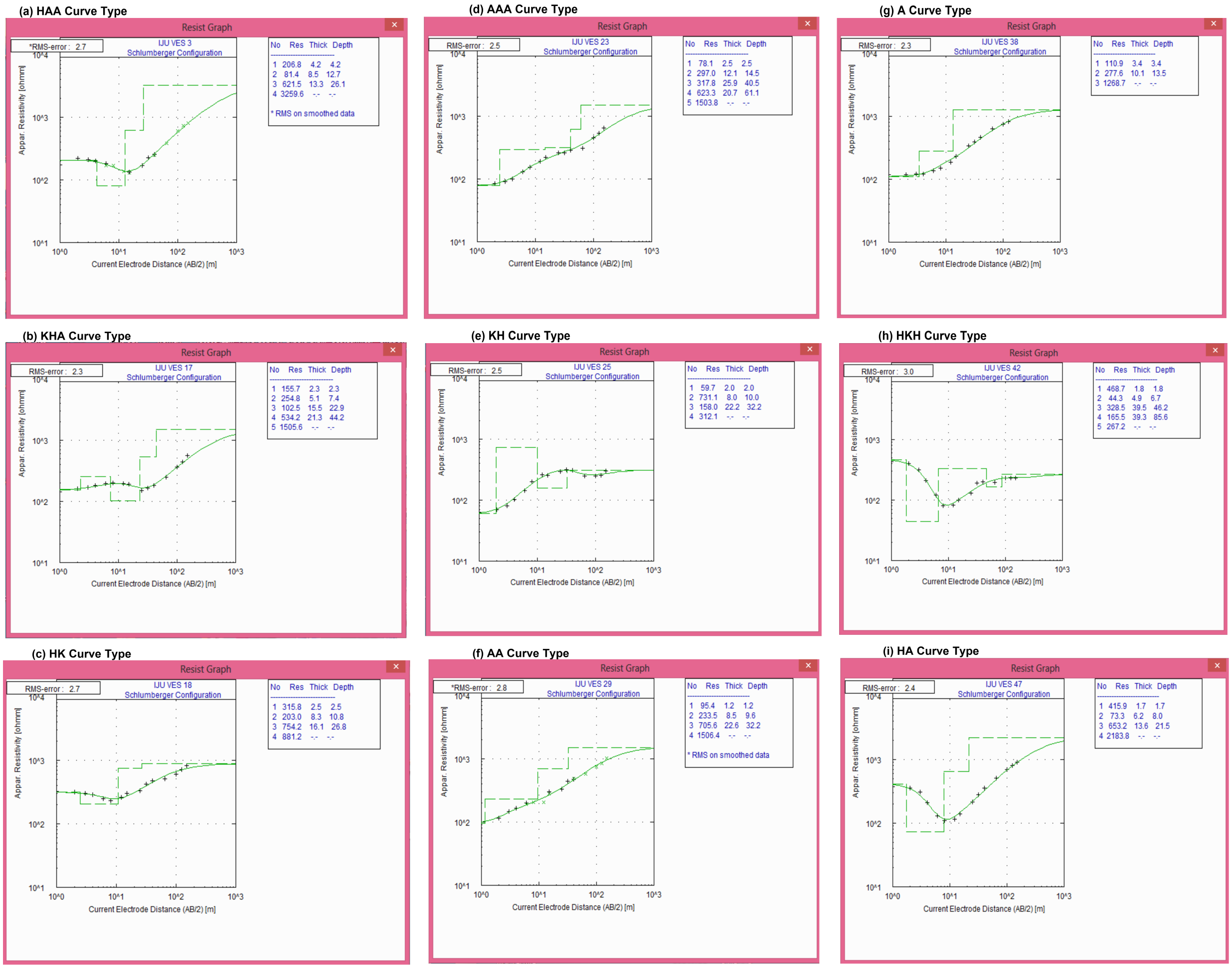

Figure 15. Representative curve types obtained from study

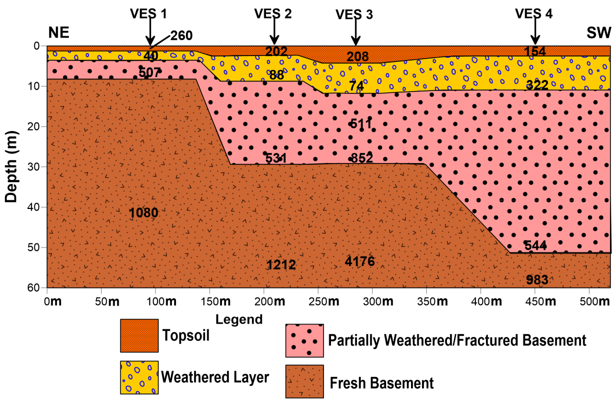

Figure 16. Geoelectrical section obtained from interpretation of VES curves 1 to 4 along Iju Traverse 1

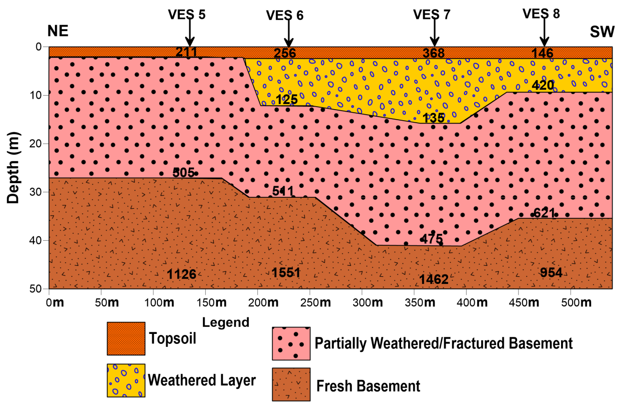

Figure 17. Geoelectrical section obtained from interpretation of VES curves 5 to 8 along Iju Traverse 2

highly productive zone due to its porosity having clay, sandy clay and clayey sand composition. Resistivity of the fractured layer/partially weathered bedrock are in the range 455 – 867 Ohm-m across the locations having thickness in the range 13.2 – 23.8 m (Traverse 3) and 17.5 – 26.6 m (Traverse 4) localized at all the VES points (Figures 18 and 19). The resistivity values indicate water saturated fractured aquifer that would sustain groundwater development scheme, the interconnectivity of pore spaces within the aquifer materials and the thickness is favourable to permit groundwater system to penetrate the fractured substratum and tap substantial quantity of water for maximum and continuous yields, for sustainable development and socio-advancement of the area. The resistivity and thickness of the fractured aquifer shows that it is a groundwater accumulation zone capable

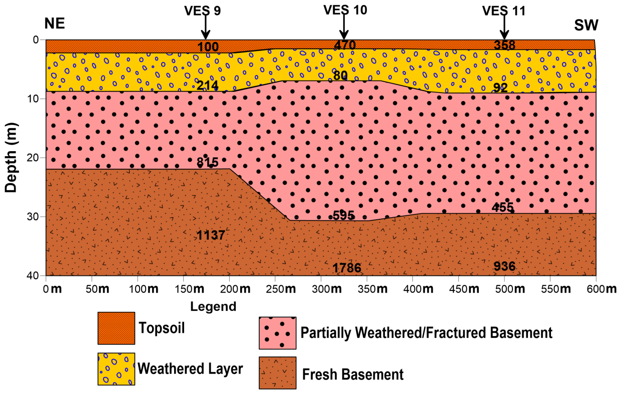

Figure 18. Geoelectrical section obtained from interpretation of VES curves 9 to 11 along Iju Traverse 3

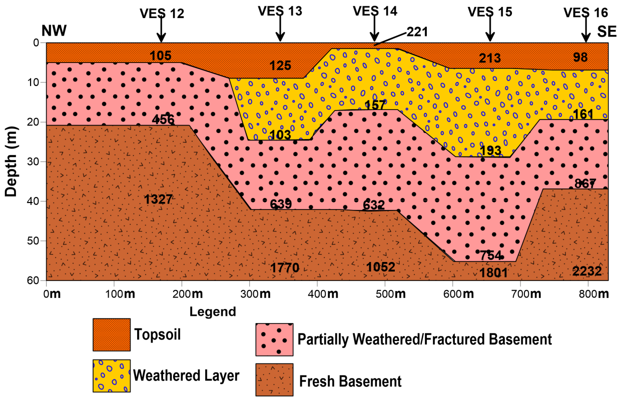

Figure 19. Geoelectrical section obtained from interpretation of VES curves 12 to 16 along Iju Traverse 4

of producing at substantial yield for community water supply. Also, groundwater in these locations exists under confined condition in the fractured bedrock beneath the weathered basement. This is because fractured layers are more porous and permeable than weathered basement. The resistivity values of the fresh bedrock are in the range 936 – 2232 Ohm-m with depth to bedrock from 20.8 (VES 12) – 55.3 m (VES 15). The bedrock topography is uneven with thickest overburden formation at VES 15 (Figure 19). Basement depressions observed at VES 10 and 15 is another factor responsible for high groundwater yield of the area.

4.2.2.3 ***Traverses 5, 6 and 7*** Four to five subsurface lithologic units are observed across the locations (Figures 20 - 22). The resistivity values of the topsoil vary from 78– 474 Ohm-m (Traverse 5), 43– 220 Ohm-m (Traverse 6) and 35–152 Ohm-m (Traverse 7) with layer thicknesses ranging 1.7 – 5.5 m, 2.0 – 2.9 m and 1.2 – 5.3 m respectively. The layer is characterized by clay, sandy clay and clayey sand but has no significant contribution to groundwater potential because of operation of human activities on the layer. There exist sandy layer beneath the topsoil having resistivity and thickness in the range 255 – 297 Ohm-m and 5.1 – 12.1 m respectively at VES 17 and 23. This layer plays vital role in groundwater production of the area because of its higher permeability, interconnectivity with the water-bearing unit, which guarantee greater well yield. The resistivity of the weathered

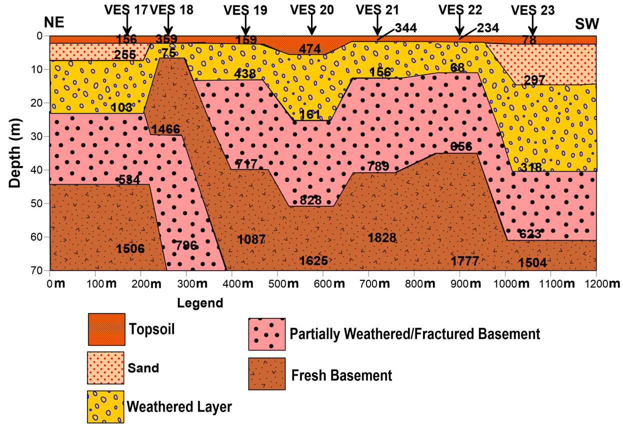

Figure 20. Geoelectrical section obtained from interpretation of VES curves 17 to 23 along Iju Traverse 5

bedrock of the locations varies from 68 – 438 Ohm-m (Traverse 5) (Figure 20), 74– 324 Ohm-m (Traverse 6) (Figure 21) and 234 Ohm-m (Traverse 7) (Figure 22) with thickness in the range 4.5 – 25.9 m, 7.4 – 22.2 m and 8.5 m respectively. This resistivity range signifies majorly sandy weathered profile in the area that would boost well yield than the clay-rich weathered profile which lowers well yield. Thus, the existence of this aquifer would provide sufficient and perennial yield. Resistivity values of the partially weathered/fractured layer are in the range 534 – 828 Ohm-m (Traverse 5), 312 – 817 Ohm-m (Traverse 6) and 403 – 706 Ohm-m (Traverse 7) with thickness in the range 20.7 – 28.1 m, 8.0 – 22.0 m and 6.0 – 22.6 m localized at all the VES points (Figures 20 - 22). The resistivity of the fractured bedrock in this range suggests sandy facies with adequate thickness to support massive groundwater scheme. The resistivity values indicate water saturated fractured layer of sand having higher permeability with potential high water yield that would enhance and sustainable groundwater development in the area. The presence of this water-bearing unit would aid the siting of groundwater prolific zones due to the vital role of fractured bedrock in/to groundwater yield in complex geological terrain. The resistivity values of the fresh bedrock are in the range 1087 – 7607 Ohm-m (Figures 20 - 22) with depth to bedrock from 29.7 (VES 18) – 61.1 (VES 23), 10.3 (VES 26) – 32.2 m (VES 25) and 11.3 (VES 30) – 32.2 (VES 29) along traverses 5, 6 and 7. The bedrock topography is uneven with the overburden formation thickest at VES 23 (Figure 20). The formation of basement depressions observed at VES 18, 20, 23, 24, 25, 27 and 29 is also another indicator that would aid the location of groundwater prolific zones, as they are groundwater accumulation zones.

4.2.2.4 ***Traverses 8, 9 and 10*** The top layers have resistivity values ranging from 80 – 280 Ohm-m (Traverse 8), 111 – 537 Ohm-m (Traverse 9) and 110 – 548 Ohm-m (Traverse 10) (Figures 23 – 25), majorly sandy clay, clayey sand and sand/lateritic sand with thickness in the range 1.3 – 3.0 m, 1.1 – 3.4 m and 0.7 – 4.6 m respectively. The weathered basement beneath the topsoil has resistivity values in the range 28 - 322 Ohm-m (Traverse 8), 18 – 278 Ohm-m (Traverse 9) and 49 – 305 Ohm-m (Traverse 10) and thickness in the range 2.3 – 7.9 m, 3.4 – 39.3 m and 4.1 – 7.7 m in

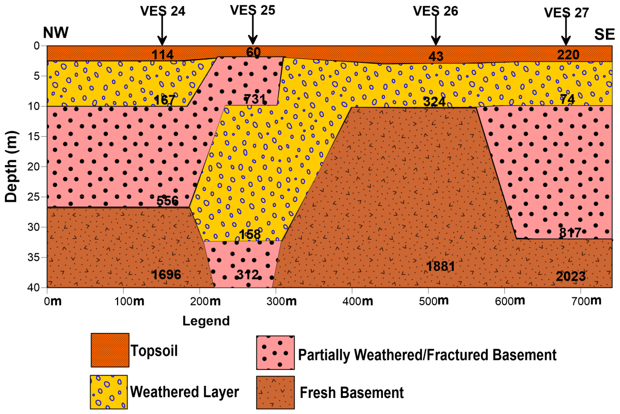

Figure 21. Geoelectrical section obtained from interpretation of VES curves 24 to 27 along Iju Traverse 6

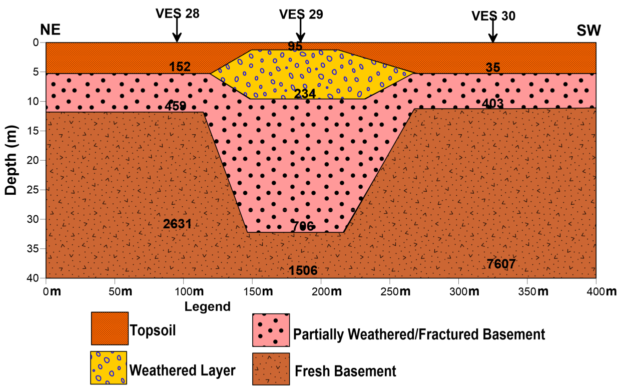

Figure 22. Geoelectrical section obtained from interpretation of VES curves 28 to 30 along Iju Traverse 7

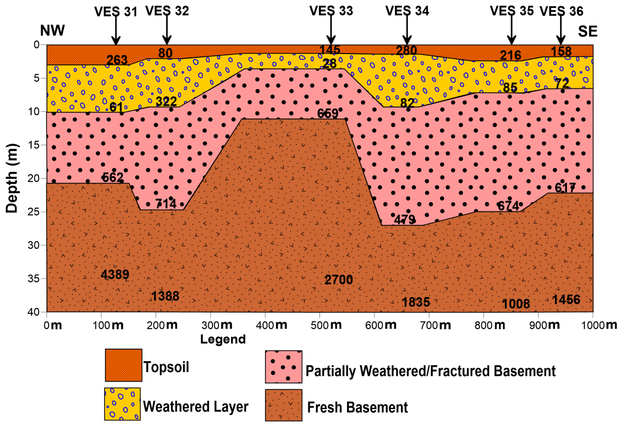

Figure 23. Geoelectrical section obtained from interpretation of VES curves 31 to 36 along Iju Traverse 8

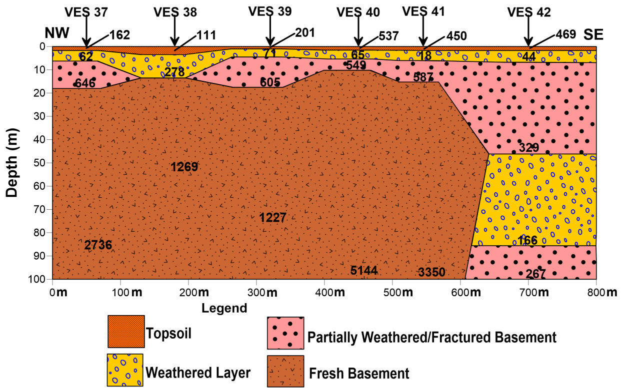

Figure 24. Geoelectrical section obtained from interpretation of VES curves 37 to 42 along Iju Traverse 9

that order (Figures 23 - 25). Resistivity values of this layer indicate high level of saturation corresponding to aquiferous zone in the area. The lithological unit of this layer signifies clay, sandy clay and clayey sand with predominant clay areas (¡ 100 Ohm-m) signifying low groundwater potential due to its low permeability with low well yield capacity. The resistivity values of partially weathered/fractured basement in the range 479 – 714 Ohm-m, 267 – 646 Ohm-m and 469 – 667 Ohm-m along traverses 8, 9 and 10 having thickness 7.5 – 17.7 m, 5.0 – 39.5 m and 9.2 – 25.2 m confined in all the VES stations of the area (Figures 23 - 25). Clayey sand and sandy composition of the fractured bedrock presented it as the major aquifer layer in the area with characteristics high permeability and greater groundwater yield capacity. The evidence of fractured bedrock in the area indicates saturated nature of sandy subsoil with high groundwater potential. The layer portrays aquiferous zone beneath the subsurface that can support immense groundwater development scheme in the area for substantial quality water supply. This layer also highlights bedrock depressions beneath VES 32, 34, 42 and 44 filled with sandy facies having high water content with significant thickness to sustain productive groundwater supply due to its high permeability. The resistivity values also indicate water saturated substratum suggesting buried stream channel beneath the subsurface of the area. Thus, it serves as appropriate sites for groundwater development scheme. Fractures in the area signify high groundwater storage and movement in the aquifers, hence, borehole sites on the fractured bedrock would permit penetration into the fractured zone to tap substantial quality water because of its high groundwater yielding ability. Also, the sandy soil profile of the zone would boost well production yield due to its higher permeability and greater yield capacity for successful and sustainable groundwater development. The resistivity of the fresh bedrock is in the range 1008 – 4389 Ohm-m, 1227 – 5144 Ohm-m and 1000 – 2585 Ohm-m across traverses 8, 9 and 10 respectively with uneven bedrock topography. However, the depth to bedrock varies from 11.1 – 27.0 m, 10.2 – 85.6 m and 17.2 – 36.9 m respectively (Figures 23 - 25). Overburden at some locations are appreciably thick thus, coupled with the overburden composition are favourable to sustaining massive groundwater development scheme in the area.

4.3 Hydrogeological characterization of the aquifer units in the area

Three distinct categories of aquiferous system are identified from the interpretation of the forty-seven resistivity sounding curves of the area. These are; weathered unconfined aquifer, weathered/fractured zone unconfined aquifer and weathered/fractured confined aquifer, each displaying

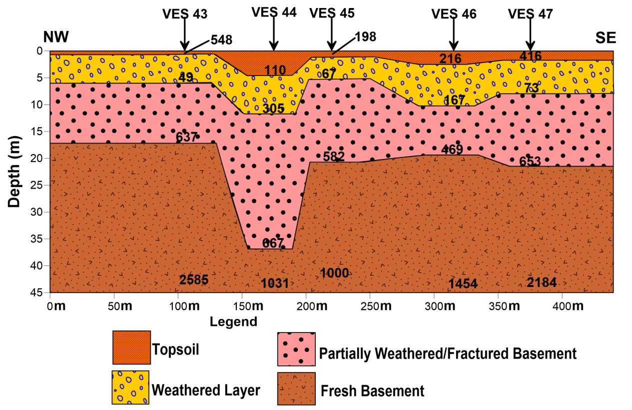

Figure 25. Geoelectrical section obtained from interpretation of VES curves 43 to 47 along Iju Traverse 10

unique geoelectric features with their characteristic hydrogeological significance

4.3.1 Weathered basement (unconfined) aquifer

Groundwater existence and flow within weathered rock unit is influenced by weathering and fracturing of the geological unit. Groundwater occurs in this zone in an unrestricted state. There is conspicuous change and difference between the weathered unit and fresh bedrock. In this kind of aquifer, groundwater yield is minimal especially when the weathered profile is rich in clay (¡ 100 Ohm-m), because of the low permeability of clay. Its low yielding and storage capacity dictates its production yield potential. The geologic representation is illustrated in HA resistivity sounding curve type of the area (Figure 15) (Table **??**. Lower clay contents of this aquifer would enhance higher yield. Thus, geological composition of the weathered profile determines its yield as sandy soil profile would offer greater groundwater yield due to its moderately high resistivity and high permeability.

4.3.2 Weathered/Fractured bedrock (unconfined) Aquifer

Groundwater occurs in this condition when a fractured rock unit is directly beneath the weathered bedrock. When the fractured bedrock underlies the weathered substratum and the resistivity contrast is low, then the fractured layer is illustrated by increase in resistivity from the topmost layer to the fresh bedrock as observed in some geoelectric curves of the area. Groundwater in this category also exists in semi-confined state in places of the study area where thick interbedded succession of sand serves as the aquifer unit and sandy clay/clayey sand act as aquicludes. The groundwater yield from this type of aquifer depends on fracture density. Geologic representations of the category of this aquifer in this study are: A, AA, AAA and HAA- type curves (Figure 15).

4.3.3 Weathered/Fractured unit (confined) Aquifer

This aquifer occurs when there is a mixed overlying weathered unit and closure of fractured zone within the fresh bedrock. The extent of confined fractured zone is revealed as shallow, thick or severe on the resistivity sounding curves. The geologic representation is an alternating sequence of low and high resistive layers as illustrated by KH, HK and HKH-type (5-layer geologic setting) (Table 11; and Figure 15). The geological setting of KH is where a high resistive geomaterial lies beneath low resistive topsoil (clayey) and another low resistive weathered body is below the high resistive layer, as identified in VES 25. The geologic replica of HK- curve type identified in VES 18 (Figure 15), where a low resistive clayey weathered unit underlies resistive lateritic topsoil and fresh bedrock encloses the fractured zone beneath it. The fresh bedrock overlies the fractured zone. Substantial and greater groundwater yield would be achieved when the fractured zone is thick and extremely fissured.

4.4 Geoelectric Characterization of the Major Aquifer System in the area

4.4.1 Resistivity of Aquifer Layer (weathered bedrock)

The weathered and fractured rock units constitute the water bearing formation in the area with significant groundwater yield. The resistivity of the weathered zone in the range 18 – 438 Ohm-m with a mean 147 ± 107 Ohm-m is characterized by clay, sandy clay, clayey sand and sand. The variation in resistivity of this location is due to porosity of the geologic unit, chemistry of saturating fluid and extent of weathering. The resistivity of the aquiferous zone reduces as the quantity of available water increases. Also, further reduction in the resistivity occurs by the development of joints and fractures in the geologic formation (Olayinka & Olorunfemi, 1992). This conductive weathered basement aquiferous unit is unevenly distributed and made up of diverse resistive geologic materials of different composition. Figure 26 displays the distribution of resistivity of the weathered basement aquiferous unit of the area. The low resistivity of this zone signifies decomposed bedrock having comparatively high water content significant to groundwater development. The low resistivity zones are zones of weakness suitable for productive groundwater development but incompetent for civil engineering construction works as it forms the deeply weathered bedrock. The higher the degree of weathering, the lower the resistivity of the basement rocks, this low resistive zone is due to the higher degree of weathering, forms significant layer for groundwater development. Resistivity classification of the weathered subsurface layer with respect to groundwater yield are as follows: ¡ 20 Ohm-m (clayey with limited/partial groundwater yield), 20 – 100 Ohm-m (significant for optimum groundwater yield), 101 – 150 Ohm-m (moderate groundwater yield), 151 – 300 Ohm-m (limited groundwater yield) and ¿ 300 Ohm-m is rated insignificant for groundwater potential (Omosuyi, Adeyemo, & Adegoke, 2007). Thus, the occurrence of low resistivity $\leq$ 100 Ohm-m towards the southwestern part of the area (Figure 26) is an indication of existence of water in the deeply weathered bedrock bordered by high resistive fractured geological unit (Figure 26) of significant groundwater potential which enhances water infiltration and accumulation. The occurrence of clay which has water absorption capacity within the saprolite will lower the resistivity of this weathered basement ¡ 100 Ohm-m and thus, reduces the permeability and groundwater yield of the aquiferous zone. Also, thick weath-

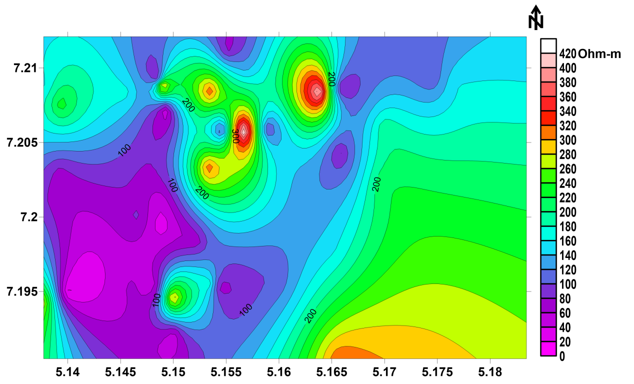

Figure 26. Weathered bedrock (aquiferous unit) resistivity map of Iju

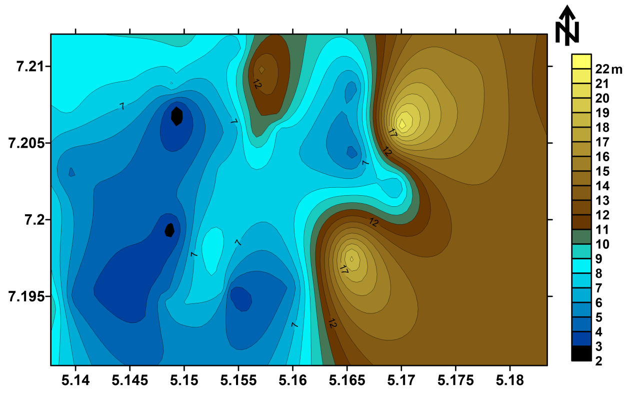

Figure 28. Weathered bedrock (aquiferous unit) thickness map of Iju

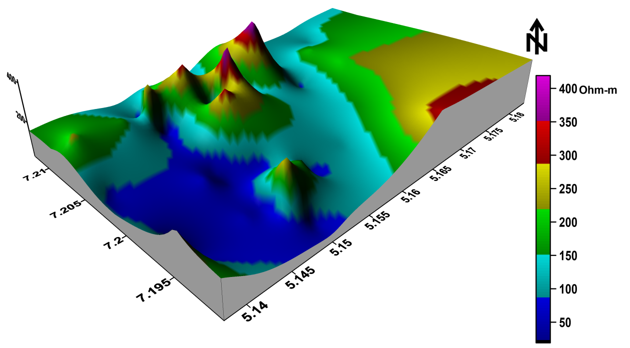

Figure 27. 3D perspective resistivity view of the weathered bedrock aquifer of Iju

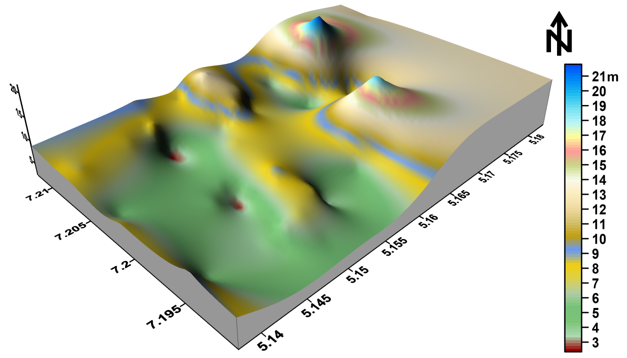

Figure 29. 3D perspective thickness view of the weathered bedrock aquifer of Iju

ered bedrock having less proportion of clay with resistivity ¿ 250 Ohm-m in the northeastern, southeastern and certain portion of the northwestern flank of the area is noted for significant groundwater yield because of the characteristic sandy formation of the zone, capable of storing and transmitting substantial quantity of water. As groundwater yield is a function of bedrock weathering and fracturing in a complex geological terrain, deductions from this aquiferous unit is that irrespective of the degree of weathering in the area, there is evidence of groundwater potential of this zone.

4.4.2 Thickness of the Weathered Bedrock Aquifer Layer

The thickness variation of the weathered layer aquifer unit in the range 2.2 – 39.3 m, having mean thickness 8.7 ± 6.3 m represents shallow to deep weathering, which is as a result of variation of rock resistance to physical and chemical weathering in the area. Thick weathered bedrock aquiferous unit is observed towards the northeastern and southeastern parts of the area, which almost divide the area into two equal halves (Figure 29), reflecting the influence of weathering on the parent rock of the area. The thickest weathered bedrock aquifer in this region is characterized by sandy materials of lower proportion of clay due to less activities of weathering. Sandy composition of this thick weathered aquifer above 15 m indicates high prospect of the area for substantial groundwater development. This is because sandy weathered rock aquifer would boost high productivity of borehole than the clay-rich weathered aquifer. The 3-D map of the weathered bedrock thickness (Figure 29) shows the variations of the layer thickness essential for assessing the groundwater potential of the area, while that of low thickness values correspond to low groundwater yield capacity of the region.

4.4.3 Resistivity of Fractured Bedrock Aquifer

The existence of fractured bedrock in complex geological terrain guarantees high groundwater productivity. The fractured aquifer has resistivity in the range 267 – 867 Ohm-m with a mean 602 ± 140 Ohm-m. It is characterized by sandy geologic formation with the range of resistivity depicting water saturated zone beneath subsurface. It is established that low resistivity (weathered regolith) thick overburden and fractured bedrock below the weathered layer constitute the aquifer units for groundwater development in the area (Oluwafemi & Oladunjoye, 2013). This geologic layer with this range of resistivity portrays prolific aquiferous zone beneath the subsurface that contribute appreciably to sustainable groundwater potential of the area. Presence of this layer supports and enhances groundwater potential of high yield for massive groundwater development due to its comparatively high permeability. Geologically, bedrock resistivity ¡ 1000 Ohm-m signifies fractured bedrock (Olayinka &

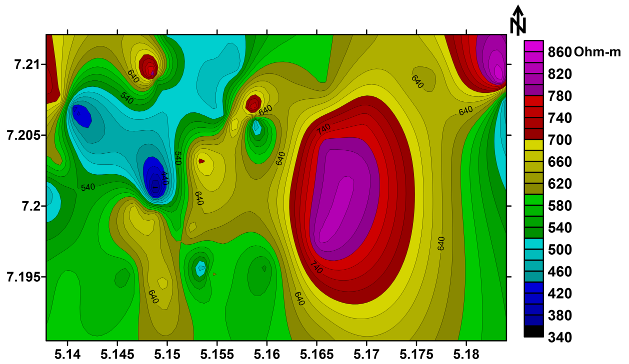

Figure 30. Fractured bedrock aquifer resistivity map of Iju

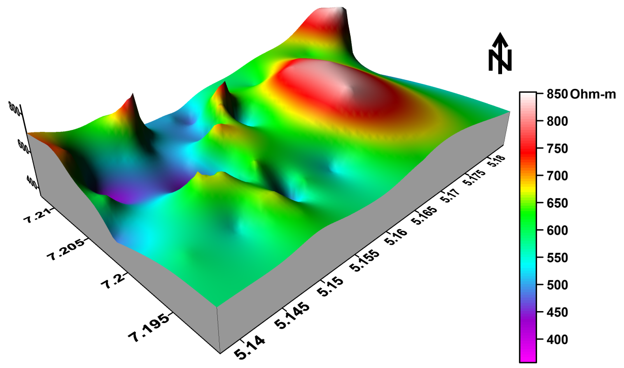

Figure 31. 3D view of the fractured aquifer of Iju

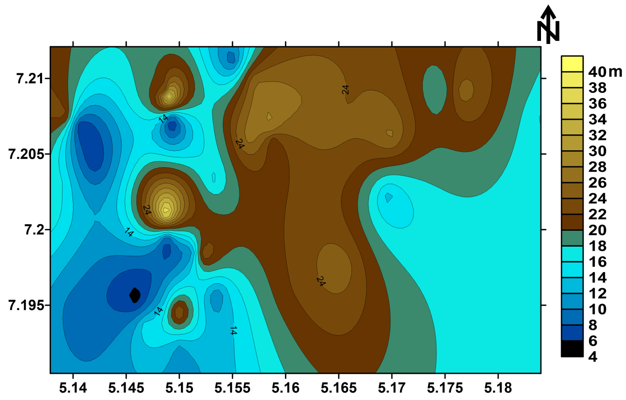

Figure 32. Fractured bedrock aquifer thickness map of Iju

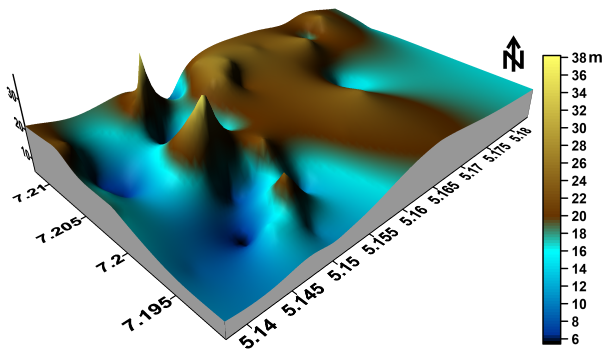

Figure 33. 3D perspective view of the thickness of fractured aquifer of Iju

Olorunfemi, 1992), which enhances high groundwater productivity of an area because it is more porous and permeable than other zones. The uneven resistivity distribution of the fractured bedrock aquifer in the area (Figure 30) is related to lithological variation, degree of weathering, fracturing and mineralogical composition of the layer. Characteristic high bedrock fracture of notable high porosity and permeability identified at the southwestern and northwestern parts with resistivity responses ¡ 650 Ohm-m (Figure 30) indicates high prolific aquifer. This fractured porous and permeable zone therefore represents the target aquifer for groundwater extraction in substantial quantity to address the hardship encountered by the people in the community on non-availability of water to improve their livelihoods and support the development of productive water scheme. Sandy facies of the aquifer would permit groundwater flow and accumulation within the aquifer. Thus, boreholes sited on this zone would tap sufficient water from the fractured zone to boost substantial and perennial groundwater yield because of the excellent fractured network of the aquifer.

4.4.4 Thickness of Fractured Bedrock Aquifer

The thickness of the fractured aquifer in the range 4.7 – 40.4 m with mean thickness of 18.3 ± 8.2 m suggests that the zone is thick enough to sustain massive groundwater scheme in the area. Thick fractured aquifer at the northeastern, central and southern part above 20 m (Figure 32) signifies high potential zones for groundwater accumulation (storage) as bedrock fissures/fractures influence groundwater productivity more than other water-bearing unit (weathered aquifer) due to its high permeability. Water can be derived substantially from fractures in complex geological terrain. The northwestern, southwestern and southeastern regions characterized by thickness ¡ 20 m from the 3D view (Figure 33), are viable for extraction of groundwater but with low yield due to its thickness compared with thick aquifer zones of other parts of the study area (northeastern, central and southern parts). The fractured bedrock is not uniformly distributed, as its thickness varies within the subsurface. The variation in thickness of this zone is as a result of the level of resistant of the different existing parent rocks to weathering and fracturing. This determines the nature, potential and condition of aquifer system in an area which in turn dictates the groundwater yielding capacity of the aquiferous units. Thus, the thick aquifer units are considered as excellent aquiferous unit of high groundwater yield that can serve the community throughout the season due to the good bedrock fracture network with high storage and percolation capacity. The existence of thick fracture in over 50% of the area guarantee supports for high groundwater potential of the zones.

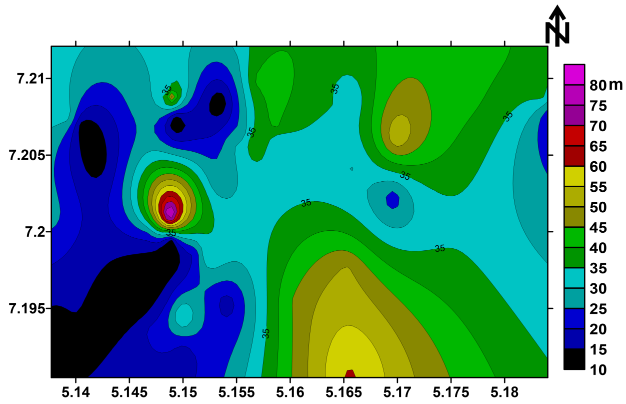

Figure 34. Overburden thickness map of Iju

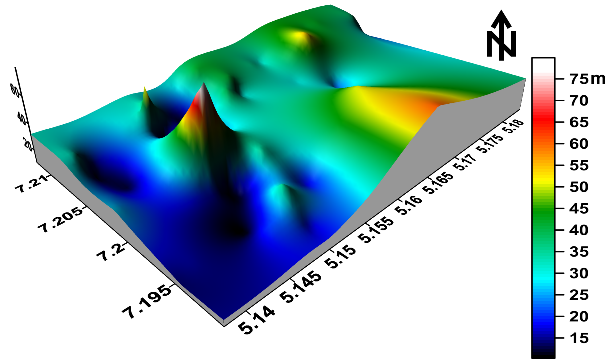

Figure 35. 3D view of overburden thickness of Iju

4.4.5 Overburden Thickness Distribution

Geologic material of any nature, consolidated or unconsolidated that lies above the bedrock is overburden. Groundwater drains through the overburden (unsaturated soil) into saturated unit where pores and fractures accumate water. The overburden thickness plays an important role in groundwater development of an area because aquifer is recharged from rainwater, surface water base flow (leakage from surface water), irrigation and run-off infiltration via the overburden. Thus, it determines the recharge, quantity of available groundwater and aquifer yield. The overburden thickness is in the range 8.2 – 85.6 m with mean 29.7 ± 15.1 m (Figure 34). Based on the classification of Olayinka, Akpan, and Magbagbeola (1997), overburden thickness of 20 – 30 m is considered satisfactory for high groundwater yield. The northeastern, central and southeastern flanks of the area having ¿ 25 m overburden thickness are viable groundwater potential zones for maximum productivity and sustainability to enhance groundwater development in the area. It can be deduced that 75% of the area have overburden thickness above 25 m specified, which is an indication of high groundwater prolific zone. The southwestern and northwestern zones are considered as low groundwater yield zone because of the overburden thickness ¡ 25 m (Figure 35). Groundwater extraction from the northeastern, central and southeastern flanks of the area is substantially possible from the fractured aquiferous units because of the thick overburden encountered in the subsurface geological formation of the area. The variation in overburden thickness is influenced by weathering, topography, fracturing and erosion. The bedrock depressions identified in the area are characterized by significantly thick overburden. The thick overburden implies the ability of the zone to hold and accumulate water from rainfall and permit its flow to the aquifer. The overburden in this area is highly porous because of the sandy facies originated from the erosion, weathered and fractured bedrock. The overburden thickness relates to groundwater storage capacity of the subsurface, thus, areas of thick overburden are capable of contributing significantly to groundwater development of high and perennial yield for sustainable groundwater accumulation, distribution and extraction.

4.5 Hydrogeological parameters of the aquifers

4.5.1 Porosity of the aquiferous zone

The porosity of the aquifer in the area was estimated to certify its characteristics, geological condition and describe the aquifer units. The degree of interconnection between the pore spaces of geo-material of the aquifer was related with the electrical/conductivity signatures of this study. Arrangement and homogeneity of grain-size materials of the subsoil determines its porosity. The porosity of the aquifers is within 0.20 – 1.05 (Figure 36) with average of 0.43 ± 0.18, which correlates with the characteristic range of granular aquifers (0.20 – 0.35) given by Todd (1980). Variation in porosity of the area (Figure 36) is due to the grain size distribution, size and extent of bedrock weathering and fissuring (fracturing). The southwestern flank of the area possesses high porosity values (Figure 36), thus classified as high porous zone. This is an indication of high interconnectivity network of the grain-size materials of aquifer units in the area. Other zones of low porosity serve as seal rock to trap the groundwater within the bedrock fractures and prevent its movement. This classification correlates with the weathered bedrock resistivity (Figure 26) as the occurrence of low resistivity ≤ 100 Ohm-m represents clay towards the southwestern part of the area (Figure 27), which portrays the existence of water in the deeply weathered bedrock bordered by fractured geological unit. From the porosity map (Figure 36), the relatively thin saprolite layer containing high proportion of clay (Figure 26) at the southwestern part of the area is highly porous. The major hydrogeological limit of the weathered bedrock aquifer is its unevenly distributed porosity. It also correlates with the fractured bedrock that forms the target zone for optimum groundwater yield due to its sandy composition across the zone (Figure 30). Groundwater development in the area should be sited on the fractured layers (target zone suitable for optimal groundwater yield) of resistivity responses ¡ 650 Ohm-m of the high porosity zone, for high and sustainable groundwater yield.

4.5.2 Geophysical Resistivity contrast and Reflection coefficient (Rc)

The resistivity contrast and reflection coefficient (Rc) of the lithologic units at the basement interface of the area gives

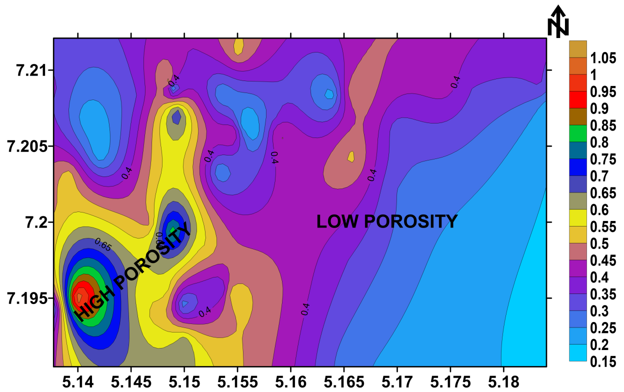

Figure 36. Porosity map of Iju

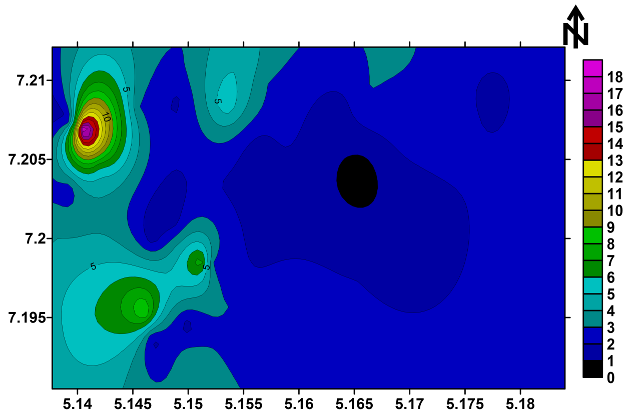

Figure 37. Map of geophysical resistivity contrast of Iju

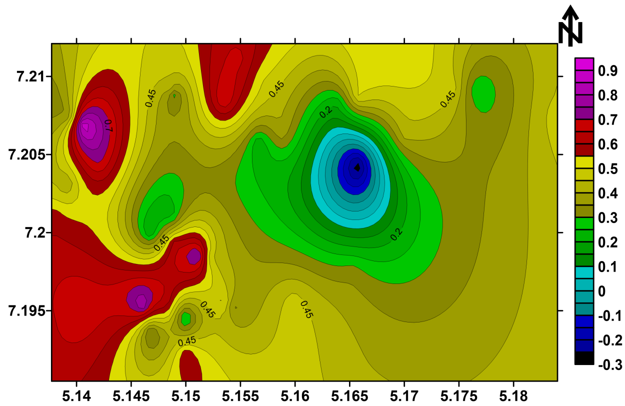

Figure 38. Map of reflection coefficient of Iju

insight to the extent of freshness or fissuring/fracturing of the bedrock. Highly resistive basement presents good geophysical resistivity contrast, while the reflection coefficient beneath the weathered basement approaches a value of 1.0 with resistivity contrast ¿ 19, then the bedrock is fresh devoid of any sign of weathering (Olayinka, 1996; Verma, Rao, & Rao, 1980). The resistivity of the fresh bedrock in the range 936 – 5144 Ohm-m (Table 1) has influence on groundwater yield and condition of the aquifer present in the area. The variation in the resistive bedrock in the area is due to the degree of weathering, varied mineralogical composition of the existing parent rocks and existence of different geological structures in the subsurface of the area. The resistivity contrast ranges 0.54 – 18.90 with mean 3.34 ± 2.87 (Figure 37), while the reflection coefficient (Rc) is in the range -0.30 – 0.90 with mean 0.44 ± 0.21 (Figure 38). The area under study is characterized by resistivity contrast ¡ 19 (Figure 37), the same for reflection coefficient (Rc) which is ¡ 0.75 across the area except some points towards the northwestern and southwestern flank with Rc ¿ 0.75. The result of the resistivity contrast and Rc correlates with the overburden thickness (Figure 34), where the southwestern and northwestern zones are considered as low groundwater yield zone because of the overburden thickness ¡ 25 m (Figure 35). The low range of Rc implies higher density of saturated fractures (water filled fractures). The zone where the Rc ¡ 0.75, resistivity contrast ¡ 19 and the thickness of overburden is ¿ 25 m, such zone is considered significant for groundwater exploration of maximum yield, whereas any location with resistivity contrast and Rc above 19 and 1 respectively have no hydrogeological significance, thus, unsuitable for groundwater development.

4.5.3 Longitudinal layer conductance (SL)

The longitudinal layer conductance (SL) is used to infer the conditions of aquifer in an area, from which protective capability of water bearing units are determined. The geoelectrical parameters (resistivity and thickness) of the subsurface layers were used in the estimation of the longitudinal layer conductance (SL) of the area (Equation 4). The SL is in the range 0.048811 – 0.472009 (Table 1) with mean 0.128679 ± 0.071055 mhos was used to produce the map of longitudinal layer conductance (SL) of Iju to categorize the protective ability of the subsoil profile of the area. The protective ability of the subsoil was deduced from the estimated SL using protective capability rating. According to Henriet, 1976, longitudinal layer conductance (SL) ¿ 10 mhos is rated excellent, between 5 and 10 mhos very good, 0.7 – 4.9 mhos (good), 0.2 – 0.69 mhos (moderate), 0.1 – 0.19 mhos (weak) and ¡ 0.1 mhos (poor). Based on this rating, the overburden of the area has poor to moderate protective ability. Only some parts around the southwestern, southern and northeastern flank of the area possess moderate protective ability, other parts are characterized by weak/poor protective materials (Figure 38). Over 87% of the area is within the weak/poor protective ability rating (Table 1 and Figure 39), which implies that the subsoil beneath the area is of weak/poor protective materials. This is an indication of low clay content in the area as longitudinal layer conductance (SL) is related to high water absorbing and retaining clay. It is an evidence of high groundwater potential yield of the aquifers in the area, though leads to reduction in the protective capacity of the overburden. Thus, actions should be taken to regulate groundwater extraction and prevent infiltration of pollutants into the aquiferous zones in the area.

4.5.4 Transverse layer resistance (RT)

Transverse layer resistance (RT) is related functionally to transmissivity (T) hydrogeologically. The RT is in the range 2522.3 – 34845.3 Ohm-m2 (Table 1 and Figure 40) with mean 13390 ± 7519 Ohm-m2. The transverse resistance of

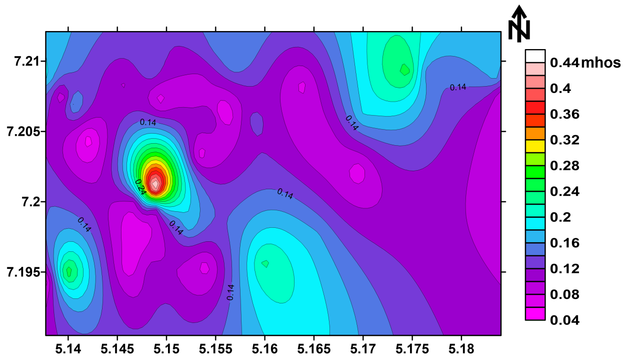

Figure 39. Longitudinal layer conductance (SL) map of Iju

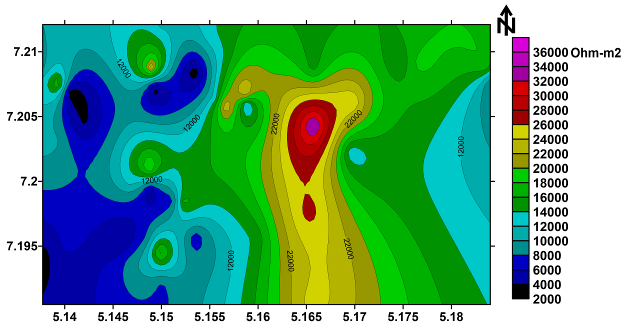

Figure 40. Transverse resistance (RT) map of Iju

the area above 2500 Ohm-m2 implies high transmissivity and potentiality of the aquifer with sufficient groundwater extraction capacity of the aquifer. The highest values of RT cluster around the central, northwestern and southeastern regions of the area in the range 14000 – 34845 Ohm-m2 (Figure 40). Thus, the study area reflects high prospects for viable groundwater development.

4.5.5 Coefficient of anisotropy/Electrical anisotropy (λ)

It is usually presumed that the existence of fluid-filled fissures/fractures in crystalline basement rocks causes anisotropy as a result of inhomogeneities in different resistive lithological units. It can also be caused by disseminated ore grains in the rocks and metamorphism (Watson & Barker, 1999). Olorunfemi et al. (1991) suggested that the average electrical anisotropy of metamorphic and igneous rocks are 1.56 and 2.12 respectively. The anisotropy coefficient of this area under study is in the range 1.03 –2.64 (Table 1 and Figure 41) with mean 1.39 ± 0.30. This range of value indicates that the underlying rocks of the area range from metamorphic to igneous rocks, with the evidence which corroborates with the geological map of the area produced from comprehensive geological field mapping. From the estimated coefficient of anisotropy (λ), the groundwater yield of the area could be reasonably predicted because the higher the coefficient of anisotropy/electrical anisotropy (λ), the higher the groundwater yields. It is observed from the map (Figure 41) that southwestern, central and parts of the northwestern area of study are characterized by high groundwater yield due to their high coefficient of anisotropy/electrical anisotropy (λ) possessed by these locations (Figure 41),

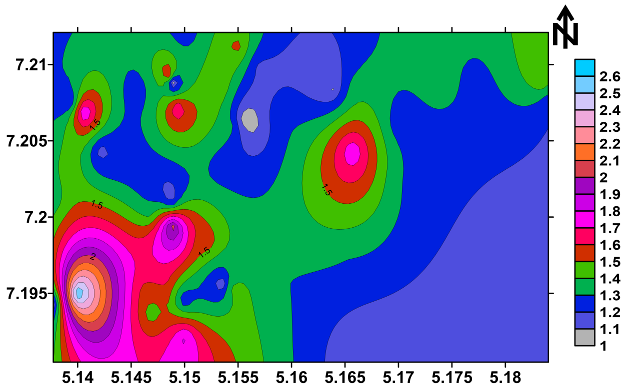

Figure 41. Coefficient of anisotropy/electrical anisotropy (λ) map of Iju.

while other parts have low coefficient of anisotropy/electrical anisotropy (λ). This variation in the distribution could be attributed to the geological variations, faulting and fissuring/fracturing system.

4.5.6 Hydraulic conductivity (K)

Hydraulic conductivity (K) is the easy flow of water in an aquifer, which expresses its vertical flow in the aquifer. It is derived from transmissivity (Tr) of the water bearing unit (aquifer) divided by its thickness. It indicates the recharge potential of the aquifer particularly in the absence of borehole pump test data (Sattar, Keramat, & Shahid, 2016). The calculated hydraulic conductivity (K) with characteristic range of 0.28 – 15.06 m/day (Table 1 and Figure 42) having average of 4.46 ± 4.10 m/day indicate moderate/high potential of aquifer recharge in the area with the highest values recorded towards north, northwestern, southeastern regions of the area (Figure 42). The southwestern and parts of the northeastern has characteristic low range of hydraulic conductivity, which could be ascribed to clay formation in the aquifer. Variation in hydraulic conductivity (K) of the aquiferous layer is attributed to the bedrock fractures. According to the classification of hydraulic conductivity (Vrbka, Ojo, & Gebhardt, 1999), the aquiferous zones of the area is within the range of permeable to high permeability (Figure 43), which confirm the high groundwater recharge potential of the aquiferous zones. The high permeability of the aquifer would enhance groundwater yield due to the presence of fractures within the bedrock.

4.5.7 Transmissivity (Tr)

Transmissivity (Tr) determines the aquifer capacity to transmit groundwater through its saturated thickness and the lateral flow of groundwater in an aquifer. It dictates the rate at which groundwater moves through an aquiferous unit width in a unit hydraulic gradient. Transmissivity (Tr) aids the development of groundwater resources as it indicates groundwater yield potential of an aquifer. The distribution of aquifer transmissivity (Tr) in the range 1 – 377 m2/day (Figure 44) confirms the presence of transmissive structures within the subsurface that aids accumulation and flow of groundwater. High aquifer transmissivity (Tr) values noted

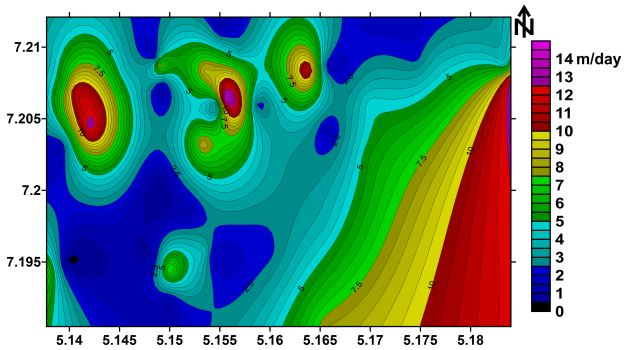

Figure 42. Iju hydraulic conductivity (K) map

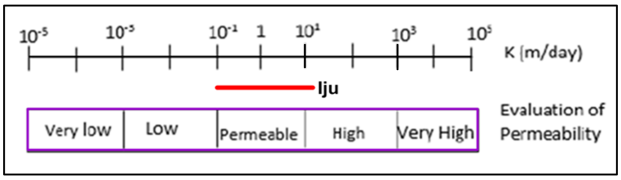

Figure 43. The classification of the hydraulic conductivity based on permeability (Vrbka et al., 1999)

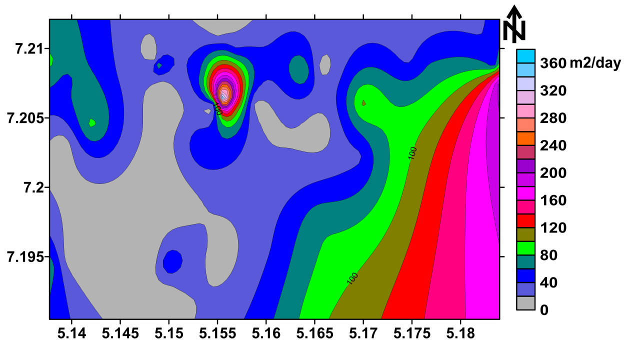

Figure 44. Iju transmissivity (Tr) map

in the southeastern and northcentral regions of the area signify that these parts of the area are more prolific for high groundwater extraction. Hydrogeologically, groundwater extraction potential of aquifer is related to its transmissivity (Tr) values, that is, aquifer potentiality corresponds to its transmissivity. According to the aquifer potentiality description stated by Krásnỳ (1993) based on its transmissivity (Tr), it can be inferred that the aquiferous units of the area under study are in the category of low-moderate-high potentiality. The transmissivity (Tr) distribution implies the condition of different water bearing units in the area (Ademila & Saloko, 2018). This implies that the aquifers in the area of low, moderate and high groundwater yield potential can be exploited for groundwater development based on magnitude/size of consumption and proposed area of need.

4.6 Groundwater potential of the area

This study assessed the groundwater yield potential of Iju by combining the results of VLF-EM, geoelectrical resistivity and hydrogeological parameters to produce groundwater/aquifer potential map of the area (Fig. 45). The groundwater/aquifer potential map of the area are classified into high, medium and low aquifer/groundwater potential zones (Fig. 4545) based on the summary of results of geoelectrical and hydrogeological parameters. High aquifer potential of the area is noted with overburden thickness ¿ 30m with evidences of fractures within the bedrock, which is with respect to the geoelectric parameters (resistivity and thickness) of weathered basement and fractured bedrock. The areas coincide with the groundwater converging centres as observed from the groundwater head map that reflects the groundwater flow pattern of the area (Figure 4) which form the discharge area for the groundwater. Few existing wells which fall within this zone encountered during geological field mapping were productive. Other hydrogeological parameters used in classifying the aquifer potential are porosity, reflection coefficient, resistivity contrast, coefficient of electrical anisotropy, transverse resistance, longitudinal resistance, hydraulic conductivity and transmissivity. The medium aquifer potential zones are areas with thickness of overburden in the range 10 - 30m. Also, the aforementioned parameters were used in the successful classification of the zone. The low aquifer potential zones are distinguished with low thickness of overburden (¡ 10m). Two failed boreholes were encountered in these zones. Also the groundwater head map (Figure 4) confirms that the zones are groundwater radiating zones. All the existing hand-dug wells visited in this region were not productive. Thus, detailed knowledge and understanding of the geological formation characteristics of the aquifers in the area would enhance the location of viable points for groundwater development for daily use of the citizens. The groundwater potential map would therefore assist in the groundwater development scheme of the area as it gives insight on the estimation and magnitude of the yield of different aquiferous zones in the area. Approximately 30% of the area towards the southeastern, northern and central southern regions is categorized as high aquifer potential zones, which are majorly underlain by coarse porphyritic granite and migmatite gneiss (Figure 2). The medium aquifer potential zones of the area which is approximately 40% characterized the northeastern, south and central through the northwestern regions, while the low aquifer potential parts of the area constitute 30% and spread through the southwestern, northwestern and central flanks of the area. This study has shown the different aquiferous zones in the area with their class of productivity for successful groundwater development scheme. This is based on the target of development for urbanization and socioeconomic advancement of the town through consumption of potable water and its supply for other uses. So, this study stands to recommend reliable information on geological formation characteristics of the area in terms of locating suitable sites for substantial groundwater yield development. This geological and geophysical subsurface characterization of the study area also provides detailed information on appropriate sites for waste disposal and dam structural development.

5 CONCLUSIONS AND RECOMMENDATION

Detailed groundwater exploration survey involving geological, hydrogeological and geophysical investigations were carried out to explore the geological condition of Iju, in order to

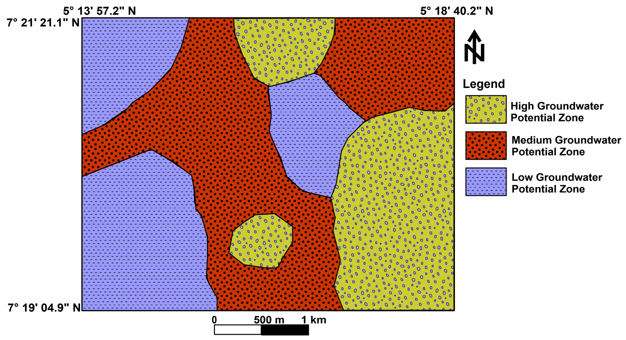

Figure 45. Groundwater/Aquifer potential map of Iju

understand the subsurface structural disposition and hydrogeological characteristics for appropriate siting of borehole locations for groundwater development scheme. This would bridge the gap between water supply and rising demand of people for urbarnization and socioeconomic advancement of the town. The field geological mapping resulted in production of the geological map of the area and most of the geological structural features observed are significant in groundwater exploration. Groundwater flows from eastern, northeastern and northern directions to the northwestern, central, southeastern, southern and western parts of the area. These converging zones enhance maximum groundwater potential for groundwater resource development. The anomalous points of conductive zones within the subsurface established by the VLF-EM survey were further investigated by vertical electrical resistivity sounding techniques. These conductive zones are relevant in groundwater development of the area as they serve as potential sites for groundwater supply. Nine different curve types were identified from the geoelectric investigation which represents three to five distinctive lithologic layers; topsoil, sand, weathered bedrock, partially weathered/fractured bedrock and fresh bedrock in the area. Suitability of the subsoil layers for groundwater development was assessed from the distributed layer resistivity and thickness (geoelectric parameters) to present favourable zones of maximum groundwater production yield. The inference from this is that the weathered and fractured bedrock form the aquiferous zones of the area with the fractured bedrock being the target aquifer unit. These major aquifer systems are characterized based on their geoelectric signatures for their hydrogeological conditions and significance. The generated series of relevant hydrogeological maps from the estimated hydrogeological parameters give detailed knowledge to the hydrogeological formation properties of the aquifer units. The reduced protective capacity of the overburden necessitates regulation of groundwater exploitation and prevents contamination of aquifers in the area. These series of hydrogeological maps were integrated to produce the groundwater/aquifer potential map of the area which categorizes the water bearing layers of the study area into different class of groundwater yield. High groundwater yield potential zones; southeastern, northern and central southern regions of the area can be harnessed for massive groundwater development scheme. Other zones can also be targeted for groundwater exploitation based on the magnitude of proposed area of need. This study has shown the class of aquifer productivity for successful groundwater development scheme based on the targeted purpose for the development, urbanization and socioeconomic advancement of the town through consumption of potable water and its supply for other uses to prevent water-borne diseases. This study recommends that waste disposal sites should be located far away from the groundwater potential zones to prevent groundwater contamination in the area and it is useful in other areas of environmental studies. This subsurface investigation has provided detailed information useful to characterize groundwater condition and geologic formation properties of subsoil for elaborate groundwater development. It is recommended that this study be carried out prior to the design and execution of any civil engineering construction work. It provides reliable background information for further geological/geophysical investigation in a complex geological terrain.

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Table 1. Summary of the hydrogeological parameters from VES curves of the study area

VES	Resistivity (Ohm-m)					Thickness (m)				Curve
sta	$\rho1$	$\rho2$	$\rho3$	$\rho4$	$\rho5$	h1	h2	h3	h4	type
1	260	40	507	1080		1.3	2.2	4.7		HA
2	202	88	531	1212		2.4	6.3	20.7		HA
3	208	74	511	852	4176	4.3	7.5	8.5	8.9	HAA
4	154	322	544	983		2.5	8.4	40.4		AA
5	211	505	1126			2.1	25			A
6	256	125	511	1551		2.5	9.6	18.9		HA
7	368	135	475	1462		2.4	13.4	25.5		HA
8	146	420	621	954		2.5	6.9	25.9		AA
9	100	214	815	1137		2.2	6.6	13.2		AA
10	470	80	595	1786		1.5	5.4	23.8		HA
11	358	92	455	936		1.6	7.4	20.4		HA
12	105	456	1327			5	15.8			A
13	125	103	639	1770		9	15.4	17.6		HA
14	221	157	632	1052		1.5	15.4	25.4		HA
15	213	193	754	1801		6.5	22.1	26.6		HA
16	98	161	867	2232		6.9	12.4	17.5		AA
17	156	255	103	534	1506	2.3	5.1	15.5	21.3	KHA
18	359	75	1466	796		2.2	4.5	23		HK
19	159	438	717	1087		2.4	10.8	26.6		AA
20	474	161	828	1625		5.5	19.6	25.6		HA
21	344	156	789	1828		1.7	11	28.1		HA
22	234	68	656	1777		1.9	9	24.1		HA
23	78	297	318	623	1504	2.5	12.1	25.9	20.7	AAA
24	114	167	556	1696		2.5	7.6	16.7		AA
25	60	731	158	312		2	8	22.2		KH
26	43	324	1881			2.9	7.4			A
27	220	74	817	2023		2.7	7.4	22		HA
28	152	459	2631			5.3	6.4			A
29	95	234	706	1506		1.2	8.5	22.6		AA
30	35	403	7607			5.3	6			A
31	263	61	562	4389		3	7.1	10.6		HA
32	80	322	714	1388		2.1	7.2	15.4		AA
33	145	28	659	2700		1.3	2.3	7.5		HA
34	280	82	479	1835		1.4	7.9	17.7		HA
35	216	85	674	1008		2.4	4.8	17.7		HA
36	158	72	617	1456		1.8	4.8	15.7		HA
37	162	62	646	2736		1.8	4.5	11.7		HA
38	111	278	1269			3.4	10.1			A
39	201	71	605	1227		1.1	3.4	13.1		HA
40	537	65	549	5144		1.6	3.6	5		HA
41	450	18	587	3350		1.8	4.3	9.2		HA
42	469	44	329	166	267	1.8	4.9	39.5	39.3	HKH
43	548	49	637	2585		0.7	5.3	11.2		HA
44	110	305	667	1031		4.6	7.1	25.2		AA
45	198	67	582	1000		1.2	4.1	15.3		HA
46	216	167	469	1454		2.5	7.7	9.2		HA
47	416	73	653	2184		1.7	6.2	13.6		HA

Table 2. Summary of the hydrogeological parameters from VES curves of the study area(continued)

VES sta	ϕ	Resistivity contrast	Rc	SL (mhos)	RT ($\omegam2̂$)	λ	K (m/day)	Tr ($\m2̂$/day)
1	0.7071	2.13	0.36	0.06927	2808.9	1.7	0.7277	1.601
2	0.4767	2.28	0.39	0.122455	12030.9	1.3	1.8671	11.7626
3	0.5199	4.9	0.66	0.149104	13375.7	1.5	1.5179	11.3841
4	0.2492	1.81	0.29	0.116585	25067.4	1.1	8.7982	73.9051
5	0.199	2.23	0.38	0.059458	13068.1	1	15.064	376.6001
6	0.4	3.04	0.5	0.123552	11497.9	1.2	2.84	27.2638
7	0.3849	3.08	0.51	0.159465	14804.7	1.2	3.1136	41.7216
8	0.2182	1.54	0.21	0.075259	19346.9	1.1	12.086	83.3949
9	0.3057	1.4	0.16	0.069037	12390.4	1.3	5.3995	35.6365
10	0.5	3	0.5	0.110691	15298	1.3	1.6661	8.9969
11	0.4663	2.06	0.35	0.129739	10535.6	1.3	1.9689	14.5702
12	0.2094	2.91	0.49	0.082268	7729.8	1.2	13.334	210.682
13	0.4407	2.77	0.47	0.249058	13957.6	1.4	2.2534	34.7031
14	0.3569	1.66	0.25	0.145066	18802.1	1.2	3.7291	57.4286
15	0.3219	2.39	0.41	0.180303	25706.2	1.2	4.7725	105.473
16	0.3525	2.57	0.44	0.167611	17845.1	1.5	3.8429	47.6525
17	0.4407	2.82	0.48	0.225117	14630	1.3	2.2534	34.9285
18	0.5164	0.54	-0.3	0.081817	34845.3	1.8	1.5424	6.9409
19	0.2137	1.52	0.21	0.076851	24184.2	1.1	12.708	137.244
20	0.3525	1.96	0.32	0.16426	26959.4	1.3	3.8429	75.3217
21	0.3581	2.32	0.4	0.111069	24471.7	1.3	3.7008	40.7084
22	0.5423	2.71	0.46	0.17721	16866.2	1.6	1.372	12.348
23	0.2595	2.41	0.41	0.187465	24921	1.1	7.9882	96.6577
24	0.3461	3.05	0.51	0.097475	10839.4	1.2	4.0147	30.5117
25	0.3558	1.97	0.33	0.184784	9475.6	1.3	3.7575	83.4172
26	0.2485	5.81	0.71	0.090281	2522.3	1.5	8.8636	65.5904
27	0.5199	2.48	0.42	0.139201	19115.6	1.6	1.5179	11.2324
28	0.2087	5.73	0.7	0.048812	3743.2	1.2	13.439	86.0109
29	0.2924	2.13	0.36	0.080968	18058.6	1.2	6.0079	51.0669
30	0.2228	18.9	0.9	0.166317	2603.5	1.8	11.504	69.0237
31	0.5726	7.81	0.77	0.146661	7179.3	1.6	1.205	8.5553
32	0.2492	1.94	0.32	0.070179	13482	1.2	8.7982	63.3472
33	0.8452	4.1	0.61	0.102489	5195.4	2.1	0.4752	1.0929
34	0.4939	3.83	0.59	0.138293	9518.1	1.3	1.716	13.5563
35	0.4851	1.5	0.2	0.093843	12856.2	1.4	1.7913	8.5981
36	0.527	2.36	0.4	0.103505	10316.9	1.5	1.469	7.0512
37	0.568	4.24	0.62	0.101803	8128.8	1.6	1.2286	5.5288
38	0.2682	4.56	0.64	0.066962	3185.2	1.1	7.3814	74.5525
39	0.5307	2.03	0.34	0.075013	8388	1.4	1.4446	4.9118
40	0.5547	9.37	0.81	0.067472	3838.2	1.6	1.3	4.68
41	1.0541	5.71	0.7	0.258562	6287.8	2.6	0.2803	1.2051
42	0.6742	1.61	0.23	0.472009	20579.1	1.2	0.8155	3.996
43	0.6389	4.06	0.6	0.127023	7777.7	1.8	0.9275	4.9155
44	0.2561	1.55	0.21	0.102878	19479.9	1.2	8.246	58.5469
45	0.5464	1.72	0.26	0.093543	9416.9	1.4	1.3479	5.5265
46	0.3461	3.1	0.51	0.077298	6140.7	1.1	4.0147	30.9132
47	0.5234	3.34	0.54	0.109845	10040.6	1.5	1.4934	9.2591