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INQUIRY FOR SUITABLE LOCATIONS FOR A DRILLING REGIME AT AN UPSLOPE ROCKY KNOLL OF LAWU ESTATE, WESTERN BYPASS, MINNA, NIGERIA

PROSPECÇÃO DE LOCAIS APROPRIADOS PARA PERFURAÇÃO EM ELEVAÇÃO ROCHOSA DA PROPRIEDADE LAWU, VIA DE CONTORNO OESTE, MINNA, NIGÉRIA

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ABSTRACT

Background: A client requested that the study group help determine suitable locations for a drilling regime on his lot, located on an upslope rocky knoll in Lawu Estate, Minna, Nigeria. There is no luxury of conducting an unimpeded wide-area survey for this housing Estate, as it is built up almost entirely. Therefore, the constrained area to be surveyed necessitated the adoption of the "electrical drilling," or vertical electrical sounding, mode of the geoelectrical method to satisfy the client's inquiry. **Aim**: To carry out a purpose-specific survey to pinpoint the best location in a built-up property at the upmarket Lawu Estate that would be suitable for a drilling regime targeted for household consumption. The specific objectives are to determine the subsurface layer structure, to identify fracture zones with potential for water accumulation, and to estimate the depths of potential aquifers. **Methods**: The survey crew reconnoitered the study area to georeference locations for the VES survey within the 30 m x 20 m lot. Owing to the extensive build-up at this lot, only a four-point traverse along the 30-metric dimension of the building's frontage was demarcated in the northeasterly direction, thereby limiting the survey crew's desire to define an appropriate survey grid. The VES data acquisition followed the "traditional" sequence of Schlumberger array layout measurements, in which the current and potential probes are maintained at the same relative spacing and the whole spread is progressively expanded about a fixed central point. **Results**: Log-log and pseudosection plots were generated from the acquired data, from which the conventional three-layer structure is deciphered, with a desired 193 Ωm for VES Station 4 at the third layer. **Discussion**: The acquired and processed data for this study were subjected to a suite of empirical rules-of-thumb procedures for interpreting VES data in the Nigerian Basement Complex geological province, with VES Station 4 showing the most encouraging 100% result. **Conclusion**: Drilling to a depth of 100 m at Station 4 is recommended based on the identified fractured basement at this depth.

Keywords: *Geoelectric; VES; traverse; groundwater; aquiferous*

RESUMO

Introdução: Um cliente solicitou ao grupo de estudo auxílio para determinar locais adequados para um regime de perfuração em seu lote localizado em uma elevação rochosa na encosta superior da Propriedade Lawu, Minna, Nigéria. Não há possibilidade de conduzir levantamento de área ampla sem impedimentos, pois esta propriedade residencial está quase totalmente edificada. Portanto, a área restrita a ser levantada necessitou a adoção da "perfuração elétrica", ou modo de sondagem elétrica vertical (SEV), do método geoelétrico para satisfazer a consulta solicitada pelo cliente. **Objetivo**: Realizar levantamento específico para identificar o melhor local em uma propriedade edificada na Propriedade Lawu adequado para regime de perfuração destinado ao

consumo doméstico. Os objetivos específicos incluem determinar a estrutura das camadas subsuperficiais, identificar zonas de fratura com potencial para acumulação de água e estimar as profundidades de aquíferos potenciais. **Métodos**: A área de estudo foi reconhecida pela equipe de levantamento para georreferenciar os locais a serem ocupados para levantamento SEV no lote de 30 m x 20 m. Devido à extensa edificação neste lote, apenas uma travessia de quatro pontos ao longo da dimensão de 30 metros da fachada do edifício foi demarcada na direção nordeste, limitando assim o desejo da equipe de levantamento de definir uma grade de levantamento apropriada. A aquisição de dados SEV seguiu a sequência "tradicional" de arranjo-medições Schlumberger, onde os eletrodos de corrente e potencial são mantidos no mesmo espaçamento relativo e todo o arranjo é progressivamente expandido em torno de um ponto central fixo. **Resultados**: Gráficos log-log e pseudosseção foram devidamente gerados a partir dos dados adquiridos, dos quais se decifrou a estrutura convencional de três camadas com desejável resistividade de 193 Ωm para a Estação SEV 4 na terceira camada. **Discussão**: Os dados adquiridos e processados para este estudo foram submetidos a um conjunto de procedimentos empíricos baseados em regras práticas para interpretação de dados SEV na província geológica do Complexo Basal Nigeriano, com a Estação SEV 4 apresentando o resultado mais encorajador de 100%. **Conclusão**: Recomenda-se perfuração até profundidade de 100 m na Estação 4 com base no embasamento fraturado identificado nesta profundidade.

Palavras-chave: *Geoelétrico; SEV; travessia; água subterrânea; aquíferoPalavras-chave: Geoelétrico; SEV; travessia; água subterrânea; aquífero*

1. INTRODUCTION

A client who owns a limited-extent real estate property at the upmarket Lawu Estate requires pinpoint information to determine the best location to drill a potable-water borehole, even after his lot has undergone extensive built-up development. The client's challenge becomes the heart of the problem the survey crew of this project must solve, given that, aside from the lot already being built-up, the property is located on an upslope rocky knoll within this Estate.

This study aims to conduct a purpose-specific survey to pinpoint the best location within the upmarket Lawu Estate that is suitable for a drilling regime targeted for household consumption.

The specific objectives herein are to determine the subsurface layer structure, to identify fracture zones with potential for water accumulation, and to estimate the depths of potential aquifers. The designated area of interest here, a 30 m x 20 m lot located on an upslope rocky knoll, was heavily built-up; thus, the survey crew designated a four-station traverse, segmented into 1 x 4 = 4 vertical electrical sounding (VES) survey stations at the frontage of the built-up compound. The VES survey regime was planned for a total depth of 100 m at each survey location. The wider study area of Lawu Estate is shown in the satellite imagery map of Figure 1. On this map, the built-up area forming the backdrop of the study area has been appropriated demarcated based on the georeferenced information of its edges: Point A at 09°39′50.6″;006°30′50.3″, Point B at 09°39′49.7″;006°30′49.0″, Point C 09°39′49.9″;006°30′49.8″, Point D at 09°39′50.7″;006°30′49.8″. Also indicated in Figure 1 are the four individual points along a linear stretch of the frontage earmarked for survey (alas, the plotted solid red triangles for the frontage-traverse are slightly skewed laterally in the northeasterly direction).

***Figure 1**. Satellite imagery map showing the under-construction and partially built-up Lawu Estate, with the core study area appropriately demarcated by solid red triangles*

According to Obaje (2009), the geology of Nigeria comprises three major litho-petrological components: the *Basement Complex*, *Younger Granites*, and *Sedimentary Basins*. The Basement Complex, which is Precambrian in age, comprises the Migmatite-Gneiss Complex, the Schist Belts, and the *Older Granites.* The Younger Granites comprise several Jurassic magmatic ring complexes centered on Jos and other parts of north-central Nigeria. They are structurally and

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petrologically distinct from the Older Granites. The Sedimentary Basins, containing sediment fill of Cretaceous to Tertiary ages, comprise the Niger Delta, the Anambra Basin, the Lower, Middle, and Upper Benue Trough, the Chad Basin, the Sokoto Basin, the Mid-Niger (Bida-Nupe) Basin, and the Dahomey Basin.

The Basement Complex forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons and south of the Tuareg Shield (Black, 1980). It is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments.

The Nigerian basement was affected by the 600 Ma Pan-African orogeny, and it occupies the reactivated region which resulted from plate collision between the passive continental margin of the West African Craton and the active Pharusian continental margin (Burke and Dewey, 1972; Dada, 2006). The basement rocks are believed to result from at least four major orogenic cycles of deformation, metamorphism, and remobilization, corresponding to the Liberian (2,700 Ma), Eburnean (2,000 Ma), Kibaran (1,100 Ma), and Pan-African (600 Ma) cycles. The first three cycles were characterized by intense deformation and isoclinal folding, accompanied by regional metamorphism, followed by extensive migmatization.

The Pan-African deformation was accompanied by regional metamorphism, migmatization, and extensive granitization and gneissification, which produced syntectonic granites and homogeneous gneisses (Abaa, 1983). Late tectonic emplacement of granites and granodiorites, along with associated contact metamorphism, accompanied the end stages of this last deformation. The end of the orogeny was marked by faulting and fracturing (Gandu *et al.*, 1986; Olayinka, 1992).

Jonah *et al.* (2013) were tasked with locating an aquifer at a lot on the Dan Zaria Academic Estate, opposite the Gidan Kwano Campus of the Federal University of Technology, Minna. The team members adopted a different approach from the conventional to conduct reconnaissance for the planned survey at this estate; a resistivity geoelectrical survey in the VES mode of the Schlumberger array was employed for the reconnaissance and final stages of this investigation. This “unconventional” approach was the acquisition of VES data at shallow depths (i.e. progressively down to 10m) over the area of study in order to determine the point of lowest resistivity, instead of the approach to determine the lateral variation of resistivity at these shallow depths using the constant separation traversing (CST) method. The point of lowest resistivity thus identified was surveyed to a final depth of 100m. The authors observed that the 30-40m depth interval at this point was the possible groundwater yield zone.

In fidelity to the “conventional” approach, Jonah *et al.* (2014[a]) prospected for an aquifer at a lot located on a granitic knoll in Minna. At the outset, the client’s property was visually reconnoitered; the extent and preferred traverse directions were noted. The survey crew proposed a north-south (i.e., longitudinal traverse, LT) profiling scheme with 10 m separation between survey stations and 10 m separation between profile lines for the constant-separation traversing reconnaissance phase to a depth of 15 m. Thence, detailed vertical electrical sounding surveys were conducted for locations of “low-ohmic interest” to a depth of 100 m. The result of the reconnaissance phase indicated the lowest resistance value of 1.6348 Ω at “LT4-1.” Upon final VES surveys, it was concluded that the prospect of aquifers of good yield in the area of study was very poor indeed; this conclusion corroborated the one drawn from the initial survey that the crew was unaware of.

A third approach in the series of surveys undertaken by Jonah *et al.* (2014[b]) was the “No CST” format, informally described as “not carrying out any reconnaissance survey in order to determine the lateral variation of resistivity.” For this field technique, a VES survey to a depth of 100 m is carried out at each selected location. The survey crew adopted this method to prospect for the suitable location for a desired borehole at a built-up compound of an enclosed bungalow with a self-contained sewage system; only the three corners of the brick fence away from the corner where the cesspool was situated defined in one north-south (longitudinal traverse, LT) and two east-west (transverse traverse, TT) modes were suitable for this survey. Since the client requested that a borehole be drilled on her property, the survey crew considered it inexpedient to conduct a CST survey; hence, the “No CST” format.

The derived continuous variation of resistivity with depth model indicated that a four-layer sequence was identified for VES TT1, a four-layer sequence for VES LT1, and a three-layer sequence for VES TT2. The authors based their interpretation of the aquifer prospect at the three VES locations on a combination of informal, but fairly successful, empirical rules to determine the

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likely presence of groundwater in the basement complex geological province. Based on these rules, TT1 indicates the best prospect for groundwater yield in the area of survey with good showings from the 30m-depth mark down to the 50 m-depth; LT1 could be discounted in water yield terms with respect to TT1, and TT2 satisfies the criteria at the 20m-depth mark and discontinuously still, at the 50 m-depth mark before a spike in "ohmic" values. Also, it was observed that the 50 m depth mark for TT1 and TT2 correlates very well with a prospective aquifer zone. If drilling must be done at all, then it was recommended that point TT1 be considered a good prospect for groundwater yield over the 20-m "yield window." Because of the smoothly changing continuum of resistivity values down to the 100 m-depth mark, it was recommended that drilling should be terminated at this maximum or total depth (TD) of survey in order to tap into the fractured basement at this TD. Incidentally, TT1 was upslope of the sewer pit, which was a plus for this VES station over the possible prospect of TT2.

In order to carry out a geoelectrical investigation for groundwater development at a wetland lot at the Bosso Estate, Minna, Nigeria, this location being some 350 m south of Lawu Estate, Jonah *et al.* (2014[c]) started off by visually reconnoitering the target objective (i.e. client's property); the extent, local geology, and preferred traverse directions of the area of survey were noted. The survey crew proposed a southwest-southeast profile as the longitudinal traverse (LT), with 10 m separation between survey stations and 10 m between profile lines, for the initial low-resistance reconnaissance scheme to a depth of 15m.

Thence, a detailed vertical electrical sounding (VES) survey was conducted for locations of "low-ohmic interest" to a depth of 70 m. In essence, the team treated this exercise as a blind geoelectrical prospecting, since the client had exclusive access to the results of an earlier, independent survey conducted for an aquifer prospect at this lot. On-the-field inspection of the CST dataset revealed that the lowest resistance value of 2.1919 Ω was obtained at "LT3-5" corresponding to the following geographic coordinate: $09^0$39'15.8", $006^0$30'46.6"; an arbitrary field benchmark of <3 Ω was selected for this fieldwork. The survey crew based their interpretation of the aquifer prospect at the VES locations on an informal, but fairly successful, empirical rule to determine the likely presence of groundwater in the basement complex geological province. Based on this standardization, the survey crew observed that the prospect for groundwater yield is encouraging at location "LT3-5." This location is actually approximately 5-6m displaced from the position of the initial survey carried out 2 years earlier, as verified by the client. The survey party recommended sinking a borehole to a depth of 50 m at this location.

In the desire to explore approaches that are not generally conventional, but ones that have a good foundational basis, Jonah *et al.* (2015) conducted a wet-season geoelectrical investigation for groundwater development at a built-up property at the Western Bypass, Minna, Nigeria, this location being *circa* 200 m away due southwest along the Western Bypass from Lawu Estate. The client had already commissioned a dry-season spell survey at the same built-up property, but the result was not known to the present survey crew beforehand. The result of the present endeavour would be essentially corroborative. The vertical electrical sounding (VES) mode of the resistivity-type geoelectrical survey employing the Schlumberger array was the preferred format for this exercise. The survey schedule called for VES to a total depth of 100 m, where possible. However, that depth was well beyond the effective water-bearing subsurface environment and into the local bedrock proper.

Nonetheless, the built-up nature of the neighbourhood around the survey locations precluded the 100 m target. In interpreting possible groundwater locations, two constraints are used: the "ideal" log-log plot and the "Olasehinde Protocol." Such a log-log plot must have almost all plotted points alternately "rising-and-falling" along the curve, and the Olasehinde Protocol states that resistivity values between 180 Ωm and 250 Ωm at the 20 m to 25 m depth mark is indicative of a possible groundwater prospect. Only the third and last survey location approximated these impositions at the 20 m–30 m depth range, with a smoothly varying resistivity profile extending to 40 m, and its corresponding plot indicated a three-layer sequence. Based on the imposed constraints, the survey crew concluded that the location at 09°39′36.2″ N and 006°30′30.2″ E was the best prospect identified in this survey. If drilling must be done at all, the survey crew recommended drilling this location to a total depth (TD) of 50 m.

According to Yaman *et al.* (2020), the Minna Area is mainly underlain by rocks of the Basement Complex. The authors observed that the main lithological unit underlying the area is granites (over 90%), which virtually cover the entire map, whilst the other lithological unit is

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schist, which occurs in the southeastern part of the area. The cross-section indicates a terrain that is not very rugged, but gentle, with schists forming the higher elevations. The elevation ranges from 240 m to 300 m, with the highest point near the Police Secondary School. The authors remarked that the granites are the youngest of the two rock types.

Ibeneme *et al.* (2014) remark that the different aquifer units within the Lower Orashi River Sub-Basin, Southeastern Nigeria, were delineated using the Vertical Electrical Sounding (VES) technique. The authors observe that twenty-two (22) VES soundings were carried out using the ABEM SAS 4000 Terrameter. The generated data were analyzed using the Zohdy software, which produced modeled curves for depth and resistivity. According to the authors, six profiles were collected in the northeast–southwest and northwest–southeast directions to cover the entire study area. Four to six geoelectric layers comprising the top soil, clayey sand, dry sandstone, saturated sandstone, shaley sand, and sandy shale were delineated, with the latter usually occurring as the last layer. The third and fourth layers underlying dry sandstone form the aquiferous unit. This unit was found to have an average resistivity of 10.7–6060 Ωm and an average thickness of 32 m. It was observed that most of the aquifer units in the area are unconfined, with static water levels ranging from 10.6 to 62.8 m. Some aquifer units are shallow, with static water levels below 40 m, while others are deeper, with static water levels above 60 m. It was advised that care should be taken when drilling and casing in shallow aquiferous areas to maintain proper sanitary conditions and reduce the risk of groundwater contamination.

Bahri *et al.* (2016) note that they endeavored to evaluate the quality of groundwater and the associated pollution of aquifers at Sukolilo, Surabaya, East Java, Indonesia. They pointed out that the vertical electrical sounding procedure is a geoelectric method for measuring rock resistivity, and the associated instrumentation is used to obtain subsurface information on aquifer depth. The authors used a water-quality tester to measure pH, conductivity, salinity, oxidation-reduction potential, and total dissolved solids. The authors reported that the prevailing aquifer thickness in the study area is in the region of 3.17 m, with a depth range of 0.45 m to 3.62 m. They also noted that the local lithology is alluvial and changes toward the north, as indicated by the varying depths of the observed rock layers. The authors note that seawater has intruded into the groundwater in the Sukolilo area, a finding corroborated by high salinity and total dissolved solids readings. Thus, the authors concluded that water from the unconfined Sukolilo aquifer was polluted and unsuitable for consumption.

Asta and Prasetia (2020), in MATEC Web of Conferences 331, discussed the application of vertical electrical sounding with a resistivity meter powered by a boost converter to estimate groundwater potential in Karang Anyar, Tarakan City, Indonesia. The authors noted that the vertical electrical sounding method can be used to predict geological and hydrogeological conditions. The authors observed that, as a result of the investigation using a resistivity meter powered by a boost converter, their results indicated the presence of groundwater at depths of 7.91m to 44.33 m, with a characteristic resistance of 27.22 Ωm, consistent with an estimated lithology of sand.

Pacheco *et al.* (2023) explained that, in recent years, the occurrence of unexpected meteorological events during the dry season and population growth have led to shortages in the city of Pampas, Peru, in the supply of drinking water. This situation prompted the authors to look for new search strategies for natural water sources, including underground sources. The authors observed that faced with this problem, the possibility of detecting and parameterizing these sources was raised, while the design of a tubular well that allows the economic extraction of water from the aquifer was also raised studied; both of these objectives were achieved through the use of geophysical techniques, generating profile images of geological maps of the strata and the location of the possible water table of the study area.

The authors noted that preferred locations for groundwater collection are alluvial fans and fractured valley bottoms. Using the Schlumberger array, eleven (11) vertical electrical soundings were completed up to a depth of 150 m. The acquired resistivity values range from 6.32 Ωm to 125.23 Ωm. The PQWTS-150-Water Detector equipment was also used to measure the depth of the semi-confined aquifer and to know its groundwater flow. The authors further noted that the geological map was described, and that in this profile, clayey, silty, sandy, and gravelly soils, and combinations of them, were found. Of particular interest, according to the authors, was VES Point 11, which was surveyed at the nursery of Daniel Hernández district, an area that is flat and humid. The authors noted that the aquifer at VES Point 11 has good hydrogeological conditions, enabling surface recharge. The water table was also determined to be between 4 m and 8 m.

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Subsequently, the tubular well was designed. The authors concluded that the well was designed for a total depth of 115 m.

At the upmarket Lawu Estate in Minna, there is no luxury of conducting an unimpeded wide-area survey, as the Estate is built up almost in its entirety. Therefore, the constrained area required to be surveyed necessitated the adoption of the “electrical drilling,” or the vertical electrical sounding mode, of the geoelectrical method in order to make the inquiry requested by the client.

In general, the Bosso Estate-Lawu Estate-Western Bypass triangulate tranche of the larger Minna Area has not been an encouraging neighborhood for sustained large-scale groundwater exploitation from boreholes drilled into its near-surface, solid-rock substratum. Thus, as a result of lessons learnt from previous observations, a survey regime of the kind herein is more formally structured to gather relevant information from greater depths, which could be encouraging.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Hand-Held Global Positioning System (GPS) Unit

The hand-held Garmin GPSmap78® global positioning system unit, shown in Figure 2, was employed to georeference the four corners of the lot to be surveyed, as well as the individual locations selected for occupation for the VES data acquisition scheme. The GPSmap78® is a high-sensitivity GPS with proprietary HotFix® coordinate-fixing software, featuring an in-built 3-axis compass and barometric altimeter. This GPS unit also features 1.7 GB of internal memory and up to 20 hours of battery life (dual AA batteries, that is).

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***Figure 2**. Hand-held Garmin GPSmap78® global positioning system unit*

2.1.2 Resistivity Meter

The resistivity meter employed for the survey herein, the locally built Vineyard Geological Survey brand, is shown in Figure 3. This terrameter brand is based on the generic design of PIOS Hydrogeophysical Services (PHG), with its head office in Ilorin, Nigeria. The PIOS suite of locally-built geophysical equipment is managed by PHG, a company founded by the late Prof. P. I. Olasehinde. Thus, the locally built vineyard geological survey brand employs a highly durable multi-conductor field cable set with strong electrodes and provisions to measure current, I, and voltages V1 and V2 separately. Resistance, R, is thus calculated by dividing the potential difference ΔV by the observed current I. An in-built 12V Ni-Cd battery pack powers the equipment. It can also run from an external 12V DC source (e.g., a lead-acid car battery) via an external battery port. If fully charged, it can provide one working day of electrical soundings, provided it is turned off between soundings.

***Figure 3**. Resistivity meter employed for survey*

2.2 Methods

2.2.1 Survey Design

Owing to extensive build-up in the study area, only a four-point traverse along the 30-meter dimension of the building's frontage was demarcated in a northwesterly direction, thereby limiting the survey crew's ability to define an appropriate survey grid.

2.2.2 Field Procedures

At the outset, the survey crew reconnoitered the study area to georeference the locations to be occupied for the VES survey within the 30 m x 20 m lot. Unable to define a preferred grid pattern, the four-point traverse along the 30-

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meter dimension of the building's frontage was duly identified by its latitude and longitude coordinates. Such a survey-design procedure has precedents from the works of Jonah *et al.* (2014[a]), Jonah *et al.* (2014[b]), and Jonah *et al.* (2015).

2.2.3 Data Acquisition Parameters

The VES data acquisition procedure adopted for this study, in the Schlumberger array mode, is the “electrical drilling” or “expanding probe” technique, used mainly to study horizontal or near-horizontal interfaces, which is the assumed geological character of the local basement region of the study area. The current and potential probes were maintained at the same relative spacing and the whole spread was progressively expanded about a fixed central point (Koefoed, 1979; Kearey and Brooks, 1984; Parasnis, 1986).

The initial potential electrode separation was 0.5 m whilst the initial current electrode separation was 1 m. The 0.5 m potential electrode separation was maintained for the next five measurement sequences, with the current electrode separation progressively increased by 1 m after each sequence. At the 6th meter current separation spread, the VES measurement was repeated as the potential probe distance was increased from 0.5 m to 1 m to ensure that these metallic probe-electrodes could detect a sufficiently measurable potential difference, ΔV.

This format was repeated until a second repeated measurement for current electrode separation of 10 m was obtained, by which time the potential probe separation was increased to 2.5 m. Another repeat measurement was at a 40 m current electrode separation, by which time the potential probe separation had increased to 7.5 m. The final repeat measurement was at a current electrode separation of 80 m, by which time the potential probe separation had been increased to 15 m. The final measurement for a survey point was 100 m with the current electrode separation.

The accompanying tables during the measurement sequences at the four survey points record information regarding “AB/2” (that is, half current electrode separation), “MN/2” (that is, half potential electrode separation), geometrical factor for the Schlumberger array, the first and second potential readings and their computed differences, the amount of current sent into the ground for each measurement, the computed resistance and thence the resistivity values.

2.2.4 Data Processing Method

The conversion of each computed resistance value into its corresponding resistivity value is achieved by simply multiplying the resistance value by the corresponding geometrical factor.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Generation of Log-Log Plots

Usually, after determining the resistivity values from the field resistance values, it is desirable to generate curves, commonly log-log plots, showing the variation of resistivity values with the total depth surveyed at that particular sequence for each VES station. It is recognised that the effective depth of penetration is equal to half the current electrode spacing (i.e., AB/2, where AB separates the current electrodes). According to Zohdy (1989), a continuous variation of resistivity with depth curve can be easily derived from a multilayer step-function curve by drawing a curve that passes through the logarithmic midpoint of each vertical and horizontal line on the multilayer step-function model. Given that the layer depths are logarithmically spaced, the derived continuous variation of resistivity with depth model is equivalent to the original model. This approach makes it easy to construct maps of contoured resistivity values at different depths and to construct contoured geoelectric sections.

The field resistivity values were initially subjected to the log-log plot routine in the Windows-compatible WinResist® software, from which corresponding field curves for all occupied stations were produced. The initial outputs were the “default” graphs. These were further smoothed through layer-by-layer iterations, resulting in final “modelled” outputs. The smoothed graphs connect all the plotted points and are presented in Figures 4-7. The log-log plots of VES Stations 1, 2, 3, and 4, presented in Figures 4, 5, 6, and 7, have been conveniently (though erroneously) labelled as those of VES Stations 13, 14, 15, and 16, which do not exist in the archive. Each WinResist® log-log plot provides information on the number of layers, the average resistivity of each layer, the depth of each layer, and its approximate thickness.

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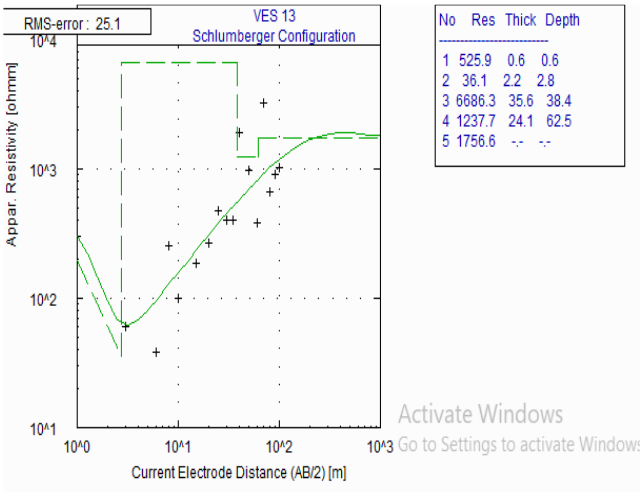

***Figure 4**. Log-log plot of Station 1*

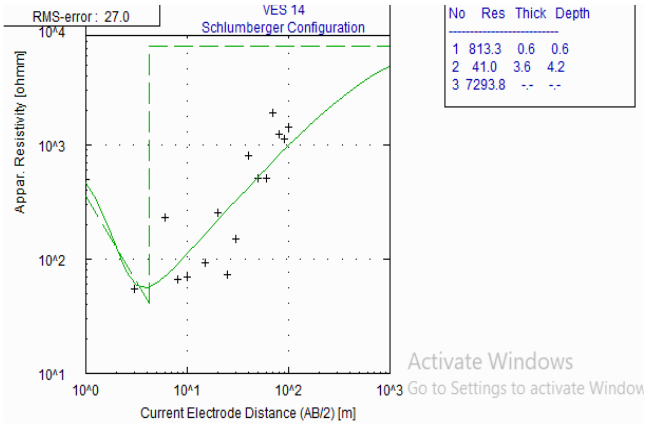

***Figure 5**. Log-log plot of Station 2*

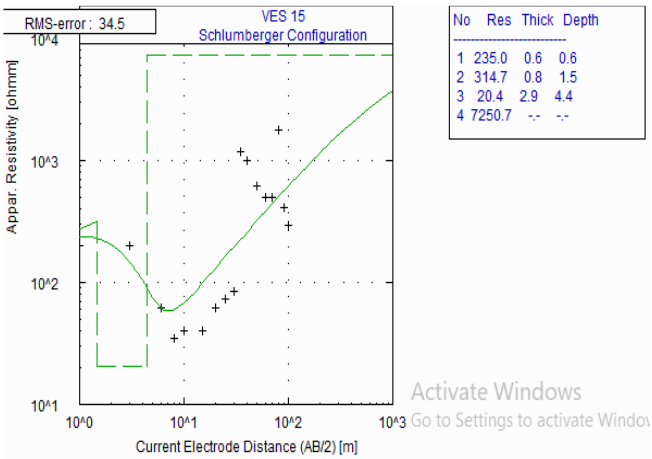

***Figure 6**. Log-log plot of Station 3*

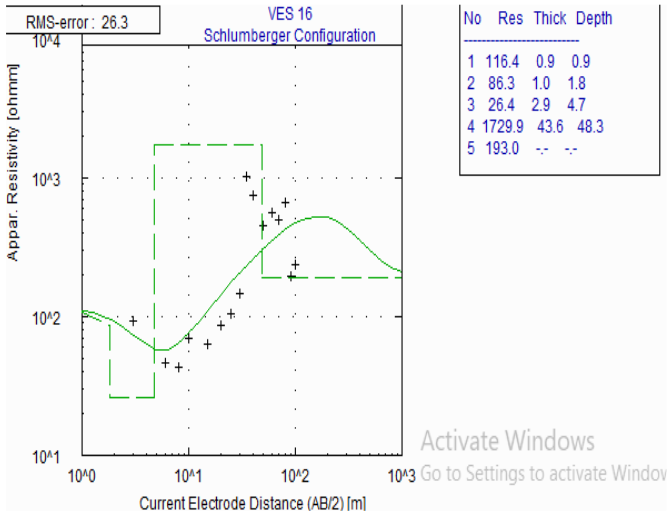

***Figure 7**. Log-log plot of Station 4*

3.1.2 Production of Pseudosection Plot

To show the resistivity cross-section along the survey traverse line in the study area, a pseudosection plot was generated and is shown in Figure 8.

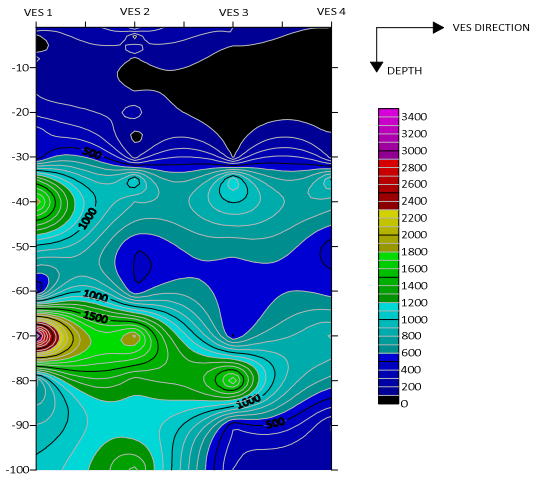

***Figure 8**. Pseudosection plot of study area*

3.2 Discussions

3.2.1 "Tricks" for Groundwater Search at the Nigerian Basement Complex

For the Nigerian Basement Complex, empirical rules (as complements to the "traditional" interpretation sequences taught in schools) exist by which workers can reliably make deductions regarding the presence of sustainable groundwater at VES survey points along a line or across an area of study. Loke (2001) quoted Acworth (1981) as stating that, "the weathered layer is thicker in areas with fractures in the

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bedrock." Jonah and Jimoh (2016) examined the validity of an empirical rule for delineating aquifer prospects at the Gidan Kwano Campus Development Phase II, Federal University of Technology, Minna, and this reliable route has been christened "Geoexplore Empirical Standardisation for Minna Area;" The Geoexplore Empirical Standardisation for Minna Area states that resistivity values between 200 Ωm and 300 Ωm at the 20 m depth and less than 200 Ωm at depths greater than 20 m are indicative of possible groundwater prospects. These recognised empirical rules, the veritable "tricks" for groundwater search in the Nigerian Basement Complex, are at the core of the rules-of-thumb employed to determine the location of groundwater in the first and fourth-stage interpretation instances, according to Jonah (2024).

3.2.2 The Log-Log Plots

The log-log plots indicate that, along the four stations of the traverse-line of survey, only one station is designated as a three-layer location, only one as a four-layer location, whilst two stations are designated as five-layer locations. According to Olasehinde (personal communication), the three-layer structure is the expected norm at the local basement geological province. Whereas, too, the norm is to have a comparatively high resistivity value for the third layer of a discerned three-layer geological structure in a general survey area of the local basement complex geological province, in ordinal format; this condition is satisfied for VES Station 2, albeit not in ordinal format. The mid-section layers of the inferred four-layer locations of Figure 6 corresponding to VES Station 3 could be "compressed" into a single layer in order to achieve fidelity to the three-layer specification at the local geological province. In a similar vein, the mid-section layers of the inferred five-layer locations of Figure 4 and Figure 7, corresponding to VES Station 1 and VES Station 4 could be "compressed" into a single layer.

3.2.3 Fidelity to the Log-Log Plots of the First Rule-of-Thumb Schedule to Determine a Groundwater Location

The first rule-of-thumb is recognised herein to be the "traditional" or the "desired outcome" interpretation schedule whence the resistivity of the third layer in a three-layer geological sequence suddenly drops to the below-1000 Ωm values that indicates presence of fracture for where the prevailing resistivity values of the second layer in this sequence are greater than the 1000 Ωm values that correspond to those for fresh basement.

3.2.4 Fidelity to the Log-Log Plots of the Second Rule-of-Thumb Schedule to Determine a Groundwater Location

The second rule-of-thumb is recognised herein as the Acworth Protocol (1981), henceforth called the Acworth Protocol.

3.2.5 Fidelity to the Log-Log Plots of the Third Rule-of-Thumb Schedule to Determine a Groundwater Location

The third rule-of-thumb is recognised herein to be the Geoexplore Empirical Standardisation for the Minna Area.

3.2.6 The Pseudosection Plot

The pseudosection plot of the four-station traverse-line study area shows discernible three-resistivity layers, with a predominantly low-resistivity trend generally occurring at depths shallower than 30 m but also discernible at greater depths, especially at the fourth VES station. However, a low-resistivity zone of interest is present at depth beneath the first VES station. The next high-resistivity trend predominates across the traverse line from the 30 m depth downwards, whilst the highest-resistivity trend of unmistakable fresh basement character seems to "juts" from VES Station 1 at the 70 m to 80 m depth, seemingly terminating at VES Station 3.

4. CONCLUSIONS

4.1 The Log-Log Plots

4.1.1 Fidelity to the Log-Log Plots of the First Rule-of-Thumb Schedule to Determine a Groundwater Location

As per the constraint of the first rule-of-thumb schedule to determine a groundwater location, VES Station 1 is not in fidelity to the first rule-of-thumb schedule and it is therefore designated as not "hydro-centric." The term "hydro-centric" is used herein to indicate "water-bearing." Based on the same argument, VES Station 2 and VES Station 3 are also not "hydro-centric." However, VES Station 4 is tagged "hydro-centric" based on its conformity to the first rule-of-thumb schedule.

4.1.2 Fidelity to the Log-Log Plots of the Second Rule-of-Thumb Schedule to Determine a Groundwater Location

With respect to the second rule-of-thumb schedule, VES Station 1, VES Station 2, and VES Station 3 are not "hydro-centric." VES Station 4 meets the "hydro-centric" classification under the

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"relaxed" condition of assuming that a 4.7 m thickness regime of the assumed second layer is relatively "thick." Moreover, the "hydro-centric" nature and designation of VES Station 4 is assured from fidelity to the first rule-of-thumb schedule.

4.1.3 Fidelity to the Log-Log Plots of the Third Rule-of-Thumb Schedule to Determine a Groundwater Location

VES Station 1, VES Station 2, and VES Station 3 are not "hydro-centric" under this scheme. VES Station 4 is tagged "hydro-centric" based on its conformity to the third rule-of-thumb schedule. VES Station 4 compliance with this schedule, by and large, occurs at the depth regimes of 20–30 m mark and at the greater depth of 90 m and beyond.

4.1.4 Percentage Fidelity of VES Stations to the Three Rules-of-Thumb

Table 1 presents the percentage weights for the four stations based on their fidelity to the three rules of thumb.

Table 1. *Percentage weighting with respect to fidelity to the three rules of thumb*

VES Station	Percentage
Station 1	0%
Station 2	0%
Station 3	0%
Station 4	100%

4.1.5. Deductive Inference Regarding VES Stations

Based on percentage fidelity to the three rules-of-thumb, VES Station 1, VES Station 2, and VES Station 3 are not groundwater locations.. However, VES Station 4 is an "assured" groundwater location or a "strongly aquiferous" location, "aquiferous" being a term coined by S.A. Jonah to indicate association with the likelihood of an aquifer in the subsurface.

4.2. The Pseudosection Plot

The pseudosection plot validates the "assured" groundwater and "strongly aquiferous" location inferences for VES Station 4. The reason for not designating VES Stations 1, 2, and 3 as "aquiferous" locations is obvious from the pseudosection plot. A 75% "fail" margin for this survey does not come across as a surprise because of the location of the traverse line of the survey in an area of prominent and profuse granitic outcrop showings. In spite of the high 75% "fail" margin for this survey, VES Station 4 "checks off" all the constraints of the groundwater-determination rules-of-thumb for 100% assurance. Thus, it is strongly recommended that VES Station 4 be used in the client's planned drilling programme. Drilling to a depth of 100 m at Station 4 is recommended based on the identified fractured basement at this depth.

5. DECLARATIONS

5.1. Study Limitations

This study presents several limitations that should be considered when interpreting the results. The extensive build-up at the surveyed lot severely constrained the survey design, limiting data acquisition to only four VES stations along a single traverse direction (northeasterly) at the building frontage. This constraint prevented the establishment of an appropriate two-dimensional survey grid that would have enabled more comprehensive lateral mapping of subsurface resistivity variations across the entire 30 m × 20 m lot. The absence of perpendicular or oblique traverses limits the three-dimensional understanding of subsurface geological structures and the potential extent of aquifers.

The study relied exclusively on the VES geoelectrical method without complementary geophysical techniques such as seismic refraction, ground-penetrating radar, or electromagnetic surveys. Multi-method approaches typically provide more robust subsurface characterization and reduce interpretation ambiguities inherent in single-method investigations. Additionally, the interpretation of VES data was based primarily on empirical rules-of-thumb developed for the Nigerian Basement Complex geological province, which, while proven useful, may not capture site-specific geological complexities at this upslope rocky knoll location.

The investigation depth was limited to 100 meters, which may not fully characterize deeper aquifer systems if present. Furthermore, no borehole drilling or pumping tests were conducted to validate the geophysical interpretations, verify the presence and productivity of the identified fractured basement aquifer at VES Station 4, or determine actual groundwater quality and sustainable yield rates. The study also did not include hydrochemical analysis, seasonal water

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level monitoring, or assessment of recharge mechanisms, all of which are essential for comprehensive groundwater resource evaluation and sustainable exploitation planning.

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The authors confirm that no commercial interests, external funding bodies, or third-party organizations influenced the design, execution, or interpretation of this research. This independence ensures that all findings and conclusions presented herein reflect solely the scientific evidence gathered and analyzed by the research team, maintaining complete integrity in the research process and data interpretation.

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5.4. Competing Interests

The authors declare that there exists no conflict of interest whatsoever arising from the preparation of this manuscript for publication with any other competing interests, whether they be of the authors' or of second parties and third parties thereof. The data employed in the enunciation of the textual material herein are original, having been duly acquired by the authors as part of the annual undergraduate schedule of project supervision here at the Federal University of Technology, Minna, Nigeria. This body of data field, duly archived for validation and reference purposes, is available for integrity checks anytime.

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5.6. Author Contributions

S.A.J. conceived the study design, supervised fieldwork, and wrote the manuscript. O.A. and S.G.A. conducted VES measurements and data collection. F.O.O. and V.C.O. assisted with field surveys and GPS measurements. J.A.A. and M.A. contributed to data processing and analysis. E.E.E. assisted with equipment setup and calibration. S.S. provided geographical expertise and site reconnaissance. All authors contributed to the manuscript review and approved the final version.

6. HUMAN AND ANIMAL-RELATED STUDIES

6.1. Ethical Approval

Not applicable.

6.2. Informed Consent

Not applicable.

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