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CHARACTERIZATION OF SUBSURFACE LITHOLOGICAL UNITS AND AQUIFEROUS FORMATIONS USING INTEGRATED VLF AND VES TECHNIQUES IN OWO, ONDO STATE

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Abstract

This study applies integrated Very Low Frequency (VLF) electromagnetic profiling and Vertical Electrical Sounding (VES) to delineate groundwater potential zones in Owo, Ondo State, Nigeria. Utilizing the Schlumberger array configuration, subsurface resistivity variations revealed lithological units and aquiferous formations. VES results indicate an overburden depth of 24 metres – 27 metres with resistivity values between 43 Ωm and 50 Ωm, suggesting moderate hydrogeologic significance for groundwater development. The VLF pseudo section identifies conductive zones associated with groundwater-bearing structures, with isoline conductivity values ranging from 0.02 S/m in fractured zones to 0.26 S/m in fresh basement rock. The survey highlights a thick overburden (0–25 metres), underlain by a weathered basement (25 metres – 50 metres), a wet basement at 50 metres, and a thin fractured basement (80 metres – 90 metres). This research aims to optimise drilling site selection and enhance sustainable groundwater resource management in erosion-prone terrains. Aligned with Sustainable Development Goal (SDG) 6.2, which targets universal access to safe water, sanitation, and hygiene, the study underscores the critical role of geophysical methods in advancing water security, resilience, and equitable resource distribution in regions vulnerable to water scarcity.

Keywords: Aquiferous formations, Electromagnetic profiling, (VES), Groundwater, Resistivity, Vertical Electrical Sounding.

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1.0 INTRODUCTION

Groundwater plays a vital role as a primary source of water for drinking, agriculture, and industry worldwide (Kresse et al., 2022). In many regions, it serves as the most dependable source of freshwater, particularly where surface water is either insufficient or severely contaminated. This underground resource is stored in aquifers—geological formations that are permeable enough to allow water transmission and storage (Olayinka et al., 2022). As urbanization and industrial activities expand, the pressure on groundwater resources increases, highlighting the need for effective management and sustainable use to ensure its availability for future generations (Kresse et al., 2022).

In Nigeria, groundwater is a crucial part of the water supply, especially in areas where surface water sources are either polluted or depleted. In Owo, Ondo State, groundwater is particularly essential due to the challenges of poor surface water quality and availability. Effective geophysical techniques are required to accurately identify and characterize the aquifer systems in such regions to manage this critical resource.

Electromagnetic (EM) prospecting methods are commonly employed in hydrogeophysical studies because of their ability to detect subsurface structures and variations in electrical properties effectively. These methods operate on the principle of electromagnetic induction, where an alternating current (AC) is introduced through a coil to create a primary electromagnetic field. This field induces eddy currents in the subsurface materials, and the secondary electromagnetic field generated is measured to determine the electrical properties of the subsurface (McNeill, 1980; Lee et al., 2021). EM methods include Time Domain Electromagnetic (TDEM), Frequency Domain Electromagnetic (FDEM), and Ground Penetrating Radar (GPR), all of which offer unique advantages in groundwater exploration (Daniels, 2004; Lee et al., 2021; Zhang et al., 2023).

TDEM and FDEM are particularly advantageous for groundwater exploration as they can penetrate significant depths and provide crucial information about subsurface conductivity, which helps in identifying water-bearing formations (Stolz et al., 2023). TDEM involves measuring the decay of the secondary electromagnetic field over time after switching off the primary field, while FDEM measures the response of the secondary field to a continuous primary field. Recent advancements, such as high-resolution TDEM systems, have improved depth penetration and resolution, enhancing aquifer characterization (Liu et al., 2022; Stolz et al., 2023). Similarly, modern FDEM systems provide improved spatial resolution and accuracy, detecting subtle variations in subsurface conductivity (Zhang et al., 2023).

Vertical Electrical Sounding (VES) is another valuable geophysical technique for groundwater exploration. VES involves measuring electrical resistivity variations with depth by using a vertical electrode arrangement. This technique provides essential data about the vertical distribution of resistivity, which helps in determining the presence and characteristics of aquifers (Olayinka et al., 2022; Koefoed, 1979). In VES, an electrical current is introduced into the ground through current electrodes, and the resulting voltage difference is measured using potential electrodes. The resistivity of the subsurface is calculated from these measurements. By adjusting the distance between the electrodes, VES can probe different depths and produce a resistivity profile with depth (Hann et al., 2023).

Recent improvements in VES technology have enhanced its accuracy and efficiency. Innovations in electrode design and data acquisition techniques have improved the spatial resolution and depth penetration of VES surveys. Additionally, advancements in data processing software enable more precise interpretation of VES results, which aids in determining aquifer parameters and groundwater quality (Siddiqui et al., 2024; Cheng & Hou, 1990). Combining electromagnetic profiling and VES methods provides a comprehensive approach to groundwater exploration. This integration allows for detailed spatial and vertical subsurface information. Electromagnetic profiling offers broad coverage and identifies conductive anomalies indicative of potential aquifer zones, while VES provides vertical resistivity profiles to delineate the depth and thickness of these zones (Keller & Frischknecht, 1966; Asher et al., 2023).

In Owo, Ondo State, integrating EM and VES methods can significantly enhance groundwater delineation and drilling site selection. EM profiling can reveal areas with high conductivity that may indicate potential aquifers, while VES can deliver detailed vertical profiles to evaluate the depth and quality of these aquifers. This integrated approach ensures a more precise characterization of groundwater resources, aiding in the identification of optimal drilling sites and promoting sustainable water supply (Asher et al., 2023; Ayolabi et al., 2013).

Recent research underscores the effectiveness of combining EM and VES methods for groundwater exploration. Liu et al. (2022) demonstrated the successful application of integrated TDEM and VES techniques in mapping aquifer systems in arid regions, highlighting their capability to provide detailed subsurface information. Similarly, Zhang et al. (2023) explored the use of FDEM and VES for groundwater characterization in urban settings, showing the advantages of this combined approach for accurate aquifer delineation. These findings emphasize the potential of integrating EM and VES methods to enhance groundwater management and ensure sustainable water resources.

Groundwater serves as an essential resource for drinking, agriculture, and industrial purposes, especially in areas where surface water sources are scarce or polluted. In southwestern Nigeria, finding dependable groundwater sources is complicated by the region's intricate geology. This area, situated within the Precambrian Basement Complex, is primarily composed of igneous and metamorphic rocks. The geological framework here features undifferentiated gneiss and other metamorphic formations, frequently obscured by an overlying regolith of loose, unconsolidated material (Rahaman, 1976).

The main challenge in this region is accurately identifying and characterizing potential aquifers due to the depth and geological complexity of the basement rocks, as well as the obscuring effect of the regolith. The problem is further exacerbated by the indistinct nature of the lithological units, which makes it difficult to differentiate between water-bearing formations and non-aquiferous rock types (Al-Amri, 1998; Mohamed et al., 2017). As a result, pinpointing suitable drilling locations that can ensure a reliable and sustainable groundwater supply presents a significant challenge.

To tackle these challenges, a holistic approach that combines advanced geophysical methods with thorough geological analysis is required. This project seeks to utilize electromagnetic profiling and vertical electrical sounding techniques to navigate the obstacles presented by the regolith and improve the understanding of aquifer distribution and quality within the Precambrian Basement Complex of southwestern Nigeria. This integrated approach will aid in identifying the most suitable drilling locations and support the effective management of groundwater resources in the region.

Geology of the Study Area

The Precambrian Basement Complex rocks (igneous and metamorphic) of southwestern Nigeria (Rahaman, 1976) underlie the study area. The lithological units identified to be undifferentiated gneiss/metamorphic rock are mostly concealed by the unconsolidated basement regolith in the area. The area falls within the basement complex zone in Southwestern Nigeria. The study area is flat terrain with a topographic elevation between 300m and 335m above sea level, located within the rainforest belt of Nigeria with a climate of long wet seasons (April to October) and short dry seasons (November to March). Groundwater recharge is mostly through meteoric precipitation (rainfall) and lateral base flow.

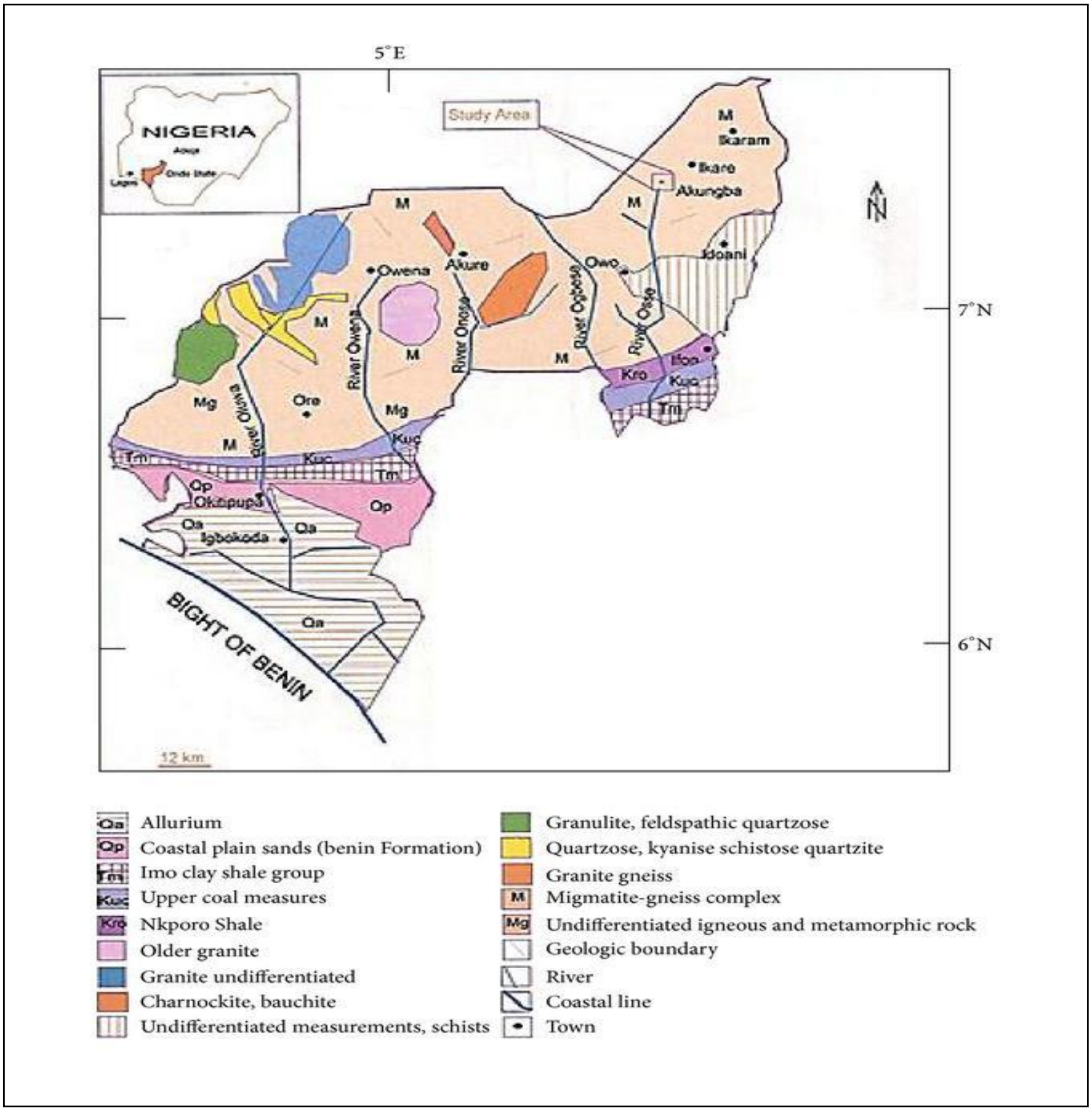

Figure 1: Geological map of the study area (Source: Rahaman, 1976)

2.0 MATERIAL AND METHODS

The survey was conducted near the Anatomy Laboratory of Achievers University, Owo, Ondo State, as shown in Figure 2. In the Basement Complex area, the location of a borehole is a critical determinant of its performance efficiency. Therefore, before initiating any drilling operation, a comprehensive evaluation of the focus area is essential to identify the most suitable drilling site.

To achieve this, a water detector was initially employed to identify the groundwater flow pattern and pinpoint areas with significant groundwater storage. This preliminary screening narrowed down the search area, reducing the need for extensive and costly geophysical surveys in less promising regions.

Subsequently, Vertical Electromagnetic Sounding (VEMS) data was collected along a profile perpendicular to the laboratory, covering a distance of 7 m. Vertical Electrical Sounding (VES) data was then collected along a 100 m survey line parallel to the VEMS profile. This configuration was designed to provide a more accurate, reliable, and comprehensive interpretation of the subsurface features by integrating lateral and vertical variations in subsurface conductivity and resistivity.

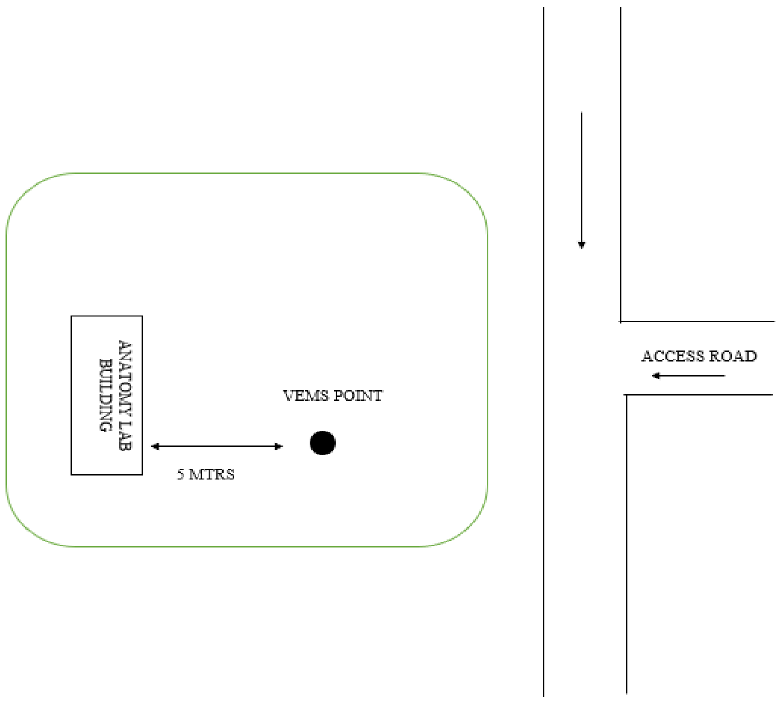

Figure 2: Site Description (Not to Scale)

Field Methodology

Vertical Electrical Sounding (VES); a geophysical method was used to investigate the subsurface resistivity variations with depth. The Schlumberger array configuration technique was used due to its sensitivity to vertical changes in resistivity.

The Schlumberger array uses four electrodes: two current electrodes (A and B) and two potential electrodes (M and N). Initially, the potential electrodes (M and N) were placed relatively close together at the mid-point of the survey line, and the current electrodes (A and B) farther apart as shown in Figure 3.

The current electrodes (A and B) were positioned symmetrically around the potential electrodes (M and N). The electrodes were connected to the resistivity meter using insulated wires. A direct current (I) of the order of 200nA was passed through the ground using the current electrodes (A and B). The resulting potential difference (ΔV) between the potential electrodes (M and N) was measured and recorded. The apparent resistivity (ρ_a) was then evaluated.

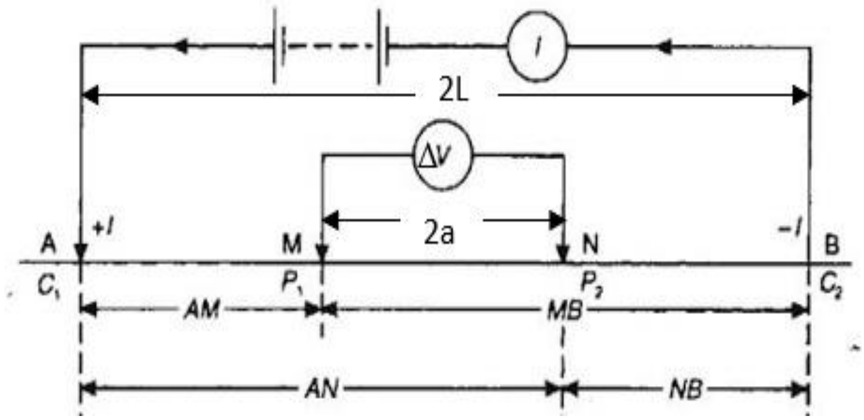

Figure 3: Geometry of current and potential electrodes for Schlumberger

$$\Delta V = \frac{\rho_a I}{2\pi}\left[\left(\frac{1}{AM} - \frac{1}{MB}\right) - \left(\frac{1}{AN} - \frac{1}{NB}\right)\right] \qquad 1$$

AM = L – a; MB = L + a; AN = L + a; NB = L – a

$$\Delta V = \frac{\rho_a I}{2\pi}\left[\left(\frac{1}{L-a} - \frac{1}{L+a}\right) - \left(\frac{1}{L+a} - \frac{1}{L-a}\right)\right] \qquad 2$$

$$\Delta V = \frac{\rho_a I}{2\pi}\left[\frac{2a}{L^2 - a^2} - \frac{-2a}{L^2 - a^2}\right]$$

$$\Delta V = \frac{\rho_a I}{2\pi}\left[\frac{4a}{L^2 - a^2}\right]$$

$$\rho_a = \frac{\pi \Delta V}{I}\left[\frac{L^2 - a^2}{2a}\right] \qquad 3$$

$$L = \frac{AB}{2} \;\; and \; a = \frac{MN}{2}$$

$$\rho_a = \frac{\pi \Delta V}{I}\left[\frac{\left({}^{AB}/_{2}\right)^2 - \left({}^{MN}/_{2}\right)^2}{MN}\right] \qquad 4$$

$$k = \frac{\pi (AB/2)^2 - (MN/2)^2}{MN} \qquad 5$$

K is called the geometric factor

To probe deeper, the spacing between the current electrodes (A and B) was increase incrementally while keeping the potential electrodes (M and N) at the centre. For each new spacing, repeat the measurement of the potential difference (ΔV) and calculate the apparent resistivity. The maximum depth of investigation is usually roughly one-third of the maximum spacing between the current electrodes (AB/2).

The Very Low Frequency (VLF) method is a passive electromagnetic technique used to detect subsurface conductive structures such as faults, fractures, and groundwater-bearing zones. The ADMT series instruments which uses natural electromagnetic field of the earth as the working field source to study the electrical structure inside the earth was deployed for this study. According to the principle that different frequencies of electromagnetic waves have different skin depths in the conductive coal, the surface is measured from high frequency to the low-frequency earth variation of geological bodies at different depths in the subsurface and determines the occurrence of underground geological bodies.

Electromagnetic prospecting relies on the principle of electromagnetic induction. When an alternating current (AC) flows through a coil, it generates a primary electromagnetic field (Figure 4). This field induces eddy currents in the subsurface materials, which in turn produce a secondary electromagnetic field. By measuring this secondary field, geophysicists can infer the electrical properties of the subsurface (McNeill, 1980).

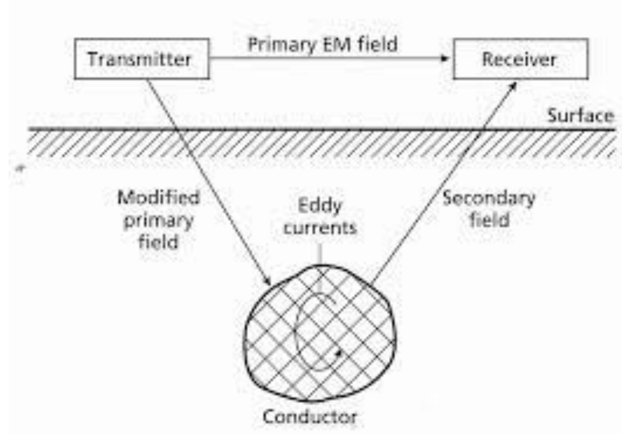

Figure 4: Principles behind electromagnetic survey instruments and their detection of buried objects (Source: Kearey et al., 2002)

Electromagnetic wave propagation theory, Helmholtz equation, ground electromagnetic waves are sent to the ground, and the propagation of electromagnetic waves in the earth and soil follows the Maxwell equation. If it is assumed that the most of the subterranean geotechnical soil is non-magnetic and is uniformly conductive macroscopically, there is no charge accumulation, then the Maxwell equation can be simplified to:

$$\nabla^2 H + k^2 H = 0 \quad 6$$

$$\nabla^2 E + k^2 E = 0 \quad 7$$

Where k is called the wave number (or propagation coefficient)

$$K = (\omega 2\ \mu\varepsilon - i\omega\sigma\mu)1/2 \quad 8$$

Considering that the propagation coefficient k is a complex number, let k= b+ ia, where: a is the phase coefficient and b is called the absorption coefficient.

In the electromagnetic frequency range measured by the ADMT series of natural field geophysical instruments (0.1 Hz to 5kHz), the displacement current can usually be ignored, k is further simplified as:

K = $-\,i\omega\sigma\mu$ 9

3.0 RESULTS AND DISCUSSIONS

Field Results

The resistivity curve (Figure 5) decreases as AB/2 increases, indicating a typical decreasing trend in resistivity with depth. This can suggest a transition from resistive to more conductive layers with depth. RMS-error is about 0.051549. This shows that the difference between the measured and computed resistivity values is very low, thus, suggesting a good fit.

The first layer has a resistivity value of 238.8 Ωm with thickness of about 0.71 m to a vertical depth of about 0.71 m. The second layer has resistivity value of about 553.0 Ωm with a total thickness of 3.54 m to a depth of 4.25 m. The third layer has resistivity of 50.3 Ωm with thickness of about 21.50 m to a vertical depth of 25.75 m. The fourth layer has resistivity value of 1781 Ωm, with a total thickness of about 34.49 m to a vertical depth of 60.24 m. The fifth layer has a resistivity value of about 119.5 Ωm.

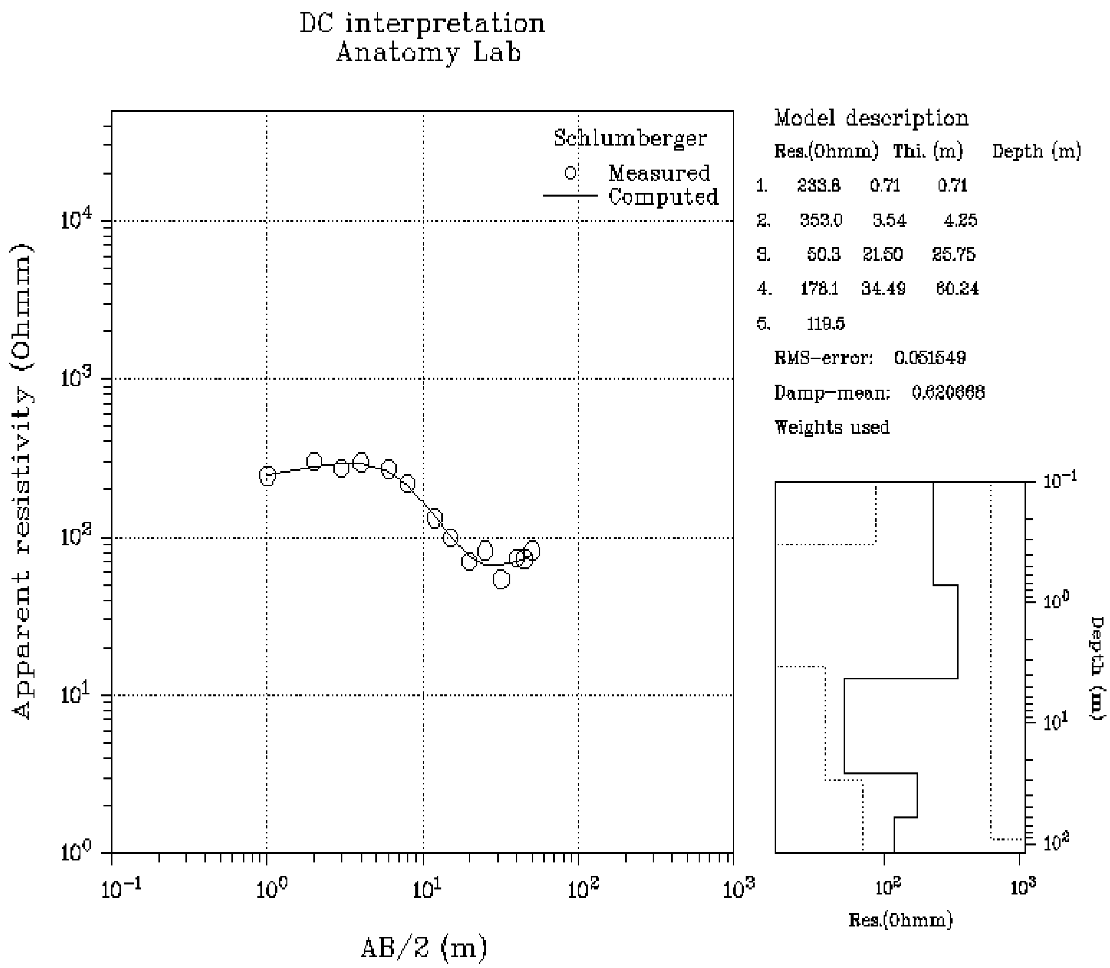

Figure 5: Vertical Electrical Sounding Curve

From the pseudo section in Figure 6, the Shallow layer of between 0.00 m to 30.00 m has conductivity values of between 0.08 S/m and 0.12 S/m. The intermediate layer which is at a depth of between 30.00 m to 70.00 m has conductivity that varies more significantly, with pockets of higher conductivity (0.14 S/m to 0.26 S/m) interspersed with lower conductivity zones (0.08 S/m to 0.12 S/m). The high conductivity zones are found around positions 1.5m to 2.5m, 3.0m to 3.5m, and 4.5m to 6.0m along the profile. The low conductivity zones are found around positions 0.5m to 1.5m and 4.0m to 4.5m. The deep layer is between the depths of 70.00 m to 150.00 m. This zone is characterized by low conductivity values of between 0.08 S/m to 0.14 S/m, with some high conductivity pockets up to 0.24 S/m. High resistivity zones are noticeable at positions 2.0m to 4.0m and 5.0m to 6.5m along the profile.

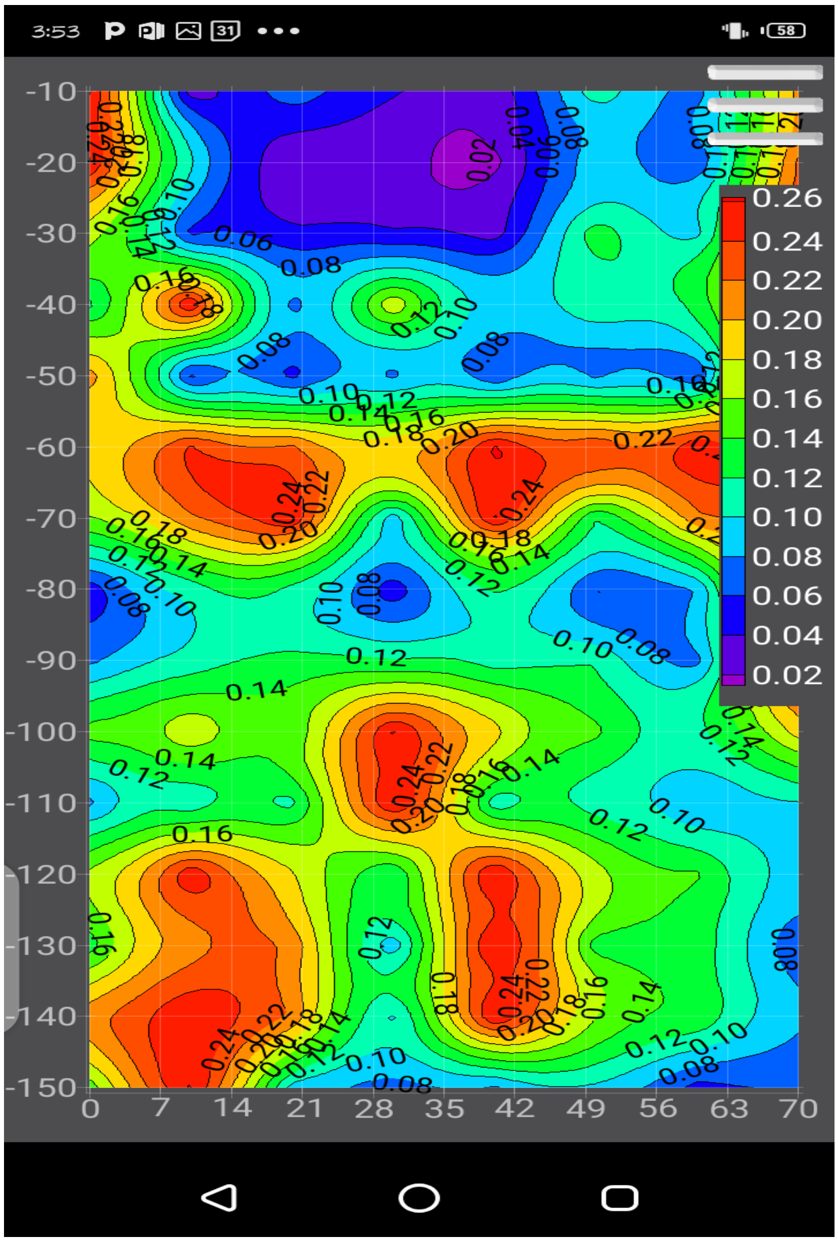

Figure 6: Pseudo section of the Electromagnetic Survey

Discussion of Results

From the geophysical interpretation using the ADMT equipment, the shallow layer of between 0.00 m to 30.00 m has conductivity values of between 0.08 S/m and 0.12 S/m. This upper layer shows moderate conductivity, indicating the presence of weathered regolith or topsoil mixed with some clay or silt. It may also include moisture from recent rainfall. The intermediate layer which is at a depth of between 30.00 m to 70.00 m has conductivity that varies more significantly, with pockets of higher conductivity (0.14 S/m to 0.26 S/m) interspersed with lower conductivity zones (0.08 S/m to 0.12 S/m). The high conductivity zones are found around positions 1.5m to 2.5m, 3.0m to 3.5m, and 4.5m to 6.0m along the profile. These zones likely indicate areas with higher moisture content or more permeable materials such as fractured rock or saturated sands and gravels. The low conductivity zones are found around positions 0.5m to 1.5m and 4.0m to 4.5m. These areas suggest less permeable or more resistive materials, possibly indicating more solid bedrock or dry, compacted materials.

The deep layer is between the depths of 70.00 m to 150.00 m. This zone is characterized by low conductivity values of between 0.08 S/m to 0.14 S/m, with some high conductivity pockets up to 0.24S/m. High resistivity zones are noticeable at positions 2.0m to 4.0m and 5.0m to 6.5m along the profile. These pockets suggest significant water-bearing formations within deeper fractured rock or deep weathered zones. The low conductivity zones are found in the central part around positions 3.5m to 5.0m along the profile. This indicates more resistive, likely less fractured and more intact bedrock, potentially gneiss or other metamorphic rocks. The optimal zones are around 2.0m to 3.5m distance with depths between 50m and 100m. And also, around 5.0m to 6.5m distance with depths between 70m and 150m. These areas have higher conductivity values, suggesting the presence of water-bearing formations within the fractured rock or permeable materials.

The electrical resistivity results in Table 1 of the VES indicate that the overburden is 24–27 metres thick and is characterised by resistivity values ranging from 43 Ωm to 50 Ωm. Therefore, the overburden has moderate hydrogeological significance for groundwater development.

Table 1: Summaries of Geoeletric Parameters Of Location

VES No	No of Layers	Layer Resistivity (Ωm)	Layer Thickness	Depth (m)	Curve	Interpreted Lithology
1	5	234	0.71	0.71	KHK	Topsoil
		353	3.54	4.25		Lateritic clay layer
		50	21.50	25.75		Clayey layer
		178	34.49	60.24		weathered Basement
		120	+	+		Fractured basement

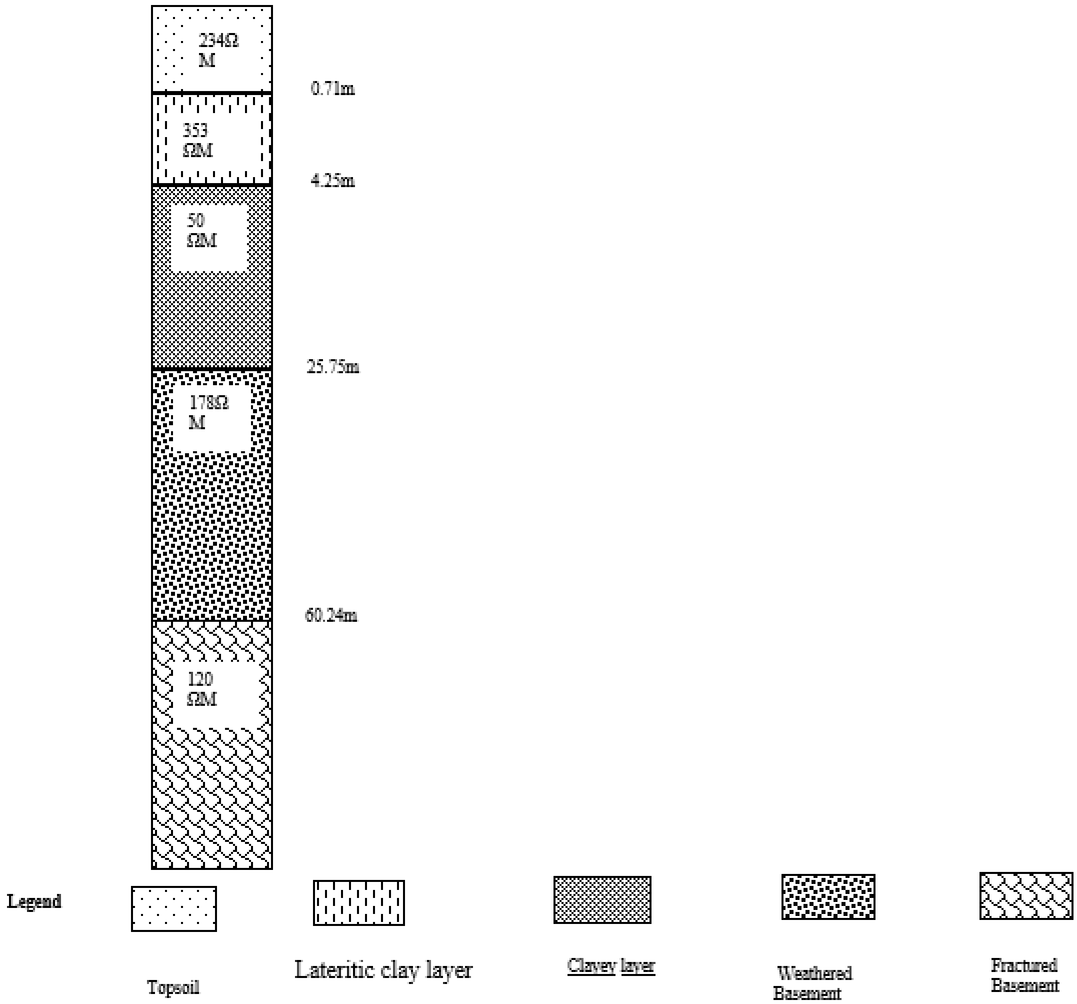

Figure 7: Probable lithology of the study location

The pseudo section reveals a complex subsurface with varying conductivity, indicating different geological formations and potential water-bearing zones. The highest potential for successful borehole drilling exists in the high conductivity zones identified within the intermediate and deep layers. Specifically, targeting the regions around 2.0m to 3.5m and 5.0m to 6.5m horizontally and between 50m to 150m in depth is recommended based on the observed conductivity values, which likely indicate significant groundwater presence. Groundwater potential at site located at Achiever University, Owo in Owo local government of Ondo State is feasible for underground water development. The survey in the area delineates five subsurface geoelectric layers; Topsoil, Lateritic clay, clayey layer, weathered basement and fractured basement.

4.0 CONCLUSION

The EM and VES methods show high resistivity near the surface, decreasing with depth, typical of dry, compact surface materials transitioning to more conductive layers. The second and third layers of VES (up to 25.75 m depth) correspond well with the low conductivity (high resistivity) zones in the shallow layer of the electromagnetic survey. At depths of 30 m to 70 m, both methods show variability. The high resistivity layer in the VES (fourth layer) matches the pockets of higher resistivity in the intermediate layer of the electromagnetic survey. The deep layers (>70 m) show a mix of resistivity and conductivity values in both methods. The VES indicates a conductive groundwater-bearing formation, which aligns with the low resistivity zones in the electromagnetic survey, suggesting significant groundwater presence.

REFERENCES

Al-Amri, A. M. (1998). Application of vertical electrical sounding (VES) in hydrostratigraphy delineation of the southern Red Sea coastal area, Saudi Arabia. Arabian Journal of Geosciences, 1(1), 45-54.

Asher, T., Smith, J., & Patel, R. (2023). Groundwater resource characterization in Owo: An integrated approach. Water Resources Management, 37(3), 895-912. DOI: [10.1007/s11269-023-03427-x](https://doi.org/10.1007/s11269-023-03427-x).

Asher, Y., Farquharson, C. G., & Oldenburg, D. W. (2023). Integrating TDEM and FDEM with VES for improved groundwater exploration. Geophysics, 88(2), 95-109.

Ayolabi, E. A., Olayinka, A. I., & Afolabi, O. (2013). Mapping aquifer systems in southwestern Nigeria using VES. Journal of Hydrology, 487, 1-11.

Cheng, C. H., & Hou, T. H. (1990). Influence of the resistances between subsurface and current electrodes on potential difference measurements. Geophysics, 55(5), 663-672.

Daniels, D. J. (2004). Ground Penetrating Radar (2nd ed.). IET.

Hann, H., Lee, J., Patel, R., & Brown, A. (2023). Recent advances in vertical electrical sounding technology. Geophysical Research Letters, 50(5), e2022GL100100. DOI: [10.1029/2022GL100100](https://doi.org/10.1029/2022GL100100).

Keller, G. V., & Frischknecht, F. C. (1966). Electrical Methods in Geophysical Prospecting. Pergamon Press.

Koefoed, O. (1979). Geosounding Principles 1: Resistivity Sounding Measurements. Elsevier.

Kresse, D., Smith, J., Brown, A., & Zhang, L. (2022). Groundwater resource management: A global overview. Journal of Hydrology, 604, 127046. DOI: https://doi.org/10.1016/j.jhydrol.2021.127046).

Lee, K. H., Wilt, M. J., & Newman, G. A. (2021). Advances in frequency domain electromagnetic methods for subsurface exploration. Geophysics, 86(1), 25-36.

Lee, S., Smith, J., & Brown, A. (2021). Advances in electromagnetic methods for subsurface exploration. Geophysical Prospecting, 69(2), 232-250. DOI: https://doi.org/10.1111/1365-2478.12918.

Liu, G., Xia, J., & Huang, Q. (2022). High-resolution TDEM systems for identifying water-bearing formations in arid regions. Journal of Applied Geophysics, 196, 104432.

Liu, Y., Zhang, Q., & Lee, S. (2022). High-resolution TDEM systems for aquifer characterization: Recent developments. Journal of Applied Geophysics, 208, 104939. DOI: https://doi.org/10.1016/j.jappgeo.2022.104939.

Liu, Y., Zhao, L., & Wang, X. (2022). Integrated TDEM and VES techniques in arid regions. Journal of Hydrological Engineering, 27(6), 118–135. DOI: https://doi.org/10.1061/(ASCE)HE.1943-5584.0002073).

McNeill, J. D. (1980). Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6, Geonics Limited.

McNeill, J. D. (1980). Electromagnetic Terrain Conductivity Measurement: A Review. Geophysics, 45(3), 529-541. DOI: https://doi.org/10.1190/1.1441070.

Mohamed, M., Abdalla, O. A., & Yousif, A. (2017). Application of VES in desert environments for groundwater exploration in Sudan. Groundwater, 55(4), 467-477.

Olayinka, A. I., Adewale, T. A., & Akinmoladun, A. F. (2022). VES and EM methods for aquifer delineation in Nigeria. Nigerian Journal of Science, 62(1), 97–110. DOI: https://doi.org/10.4314/njs.v62i1.9.

Olayinka, A. I., Adediji, T. A., & Bakare, A. O. (2022). Application of VES and EM techniques in Southwestern Nigeria. Environmental Geology, 62(4), 789-800. DOI: https://doi.org/10.1007/s00254-022-06024-7.

Rahaman, M. A. (1976). Review of the Basement Geology of Southwestern Nigeria. In: C.A. Kogbe (Ed.), Geology of Nigeria. Elizabethan Publishing Co., Lagos, pp. 41-58.

Siddiqui, S., Khan, M.A., & Ahmed, N. (2024). Innovations in data processing for vertical electrical sounding. Journal of Geophysical Research: Solid Earth, 129(2), e2023JB027890. DOI: https://doi.org/10.1029/2023JB027890.

Stolz, E., Xu, T., & Alumbaugh, D. L. (2023). Enhancing depth penetration and resolution in TDEM systems for aquifer characterization. Geophysics, 88(2), 175-189.

Stolz, M., Müller, M., & Keller, G.V. (2023). Comparative study of TDEM and FDEM methods for groundwater exploration. Hydrogeology Journal, 31(4), 957-975. DOI: https://doi.org/10.1007/s10040-023-02890-w).

Zhang, Q., Chen, L., & Wu, X. (2023). FDEM and VES for urban groundwater characterization. Urban Water Journal, 20(1), 34–49. DOI: https://doi.org/10.1080/1573062X.2023.2160425.

Zhang, Q., Li, J., Wang, X., & Liu, Y. (2023). Modern FDEM techniques for enhanced groundwater mapping. Geophysical Journal International, 224(2), 1211-1225. DOI: https://doi.org/10.1093/gji/ggac434.

Zhang, X., Wang, Y., & Liu, Z. (2023). Advances in FDEM systems for subsurface exploration and groundwater mapping. Journal of Applied Geophysics, 200, 104572.