

Geoelectric Assessment of Groundwater Potential in Erin-Ile Basement Region Complex of Southwestern Nigeria

N.K. Olasunkanmi^{*1}, J.A. Babawale², G.B. Egbeyale¹, H.T. Oladunjoye³, U.Z. Magawata⁴,
Y. A. Jimoh⁵ and M.K Fatola¹.

¹Department of Physics and Materials Science, Kwara State University Malete Nigeria

²Department of Science Laboratory Technology, Federal Polytechnic Offa, Kwara State Nigeria

³Department of Physics, Olabisi Onabanjo University, Ago Iwoye Ogun State

⁴Department of Physics, Abdullahi Fodio University of Science and Technology, Aliero, Nigeria

⁵Department of Geology and Minerals Science, Kwara State University Malete Nigeria

Date Received: 05-09-2024

Date Accepted: 27-03-2025

DOI: <https://doi.org/10.48198/NJPAS/24.B20>

ABSTRACT

This study presents a geoelectric evaluation of groundwater potential in Erin-Ile, situated in the basement complex terrain, utilizing Vertical Electrical Sounding (VES) to delineate lithological layers and assess aquifer characteristics. The study area relies entirely on groundwater for daily water supply, leading to challenges such as low borehole yields and increased water demand due to population growth and infrastructure development. The resistivity and thickness parameters analyzed to understand the subsurface hydrogeological structure. Notably, the study employs H-Type and KH-type curves to categorize lithological layers as lateritic soil, weathered basement, and fractured/fresh basement. Groundwater potential analyses consider aquifer resistivity, thickness, hydraulic conductivity, and transmissivity. The results indicate varying groundwater potential across the 50 VES points, with transmissivity ranging from -931.6 to 474.37 m²/day. Of these points, 74% are classified as having moderate potential, 24% as having low potential, and 2% as having negligible potential. No locations were identified with high or good groundwater potential. The southwestern part of the study area is predominantly characterized by moderate groundwater potential. This research contributes valuable insights into the hydrogeology of Erin-Ile, offering a foundation for sustainable groundwater resource management. This study provides valuable insights into the hydrogeology of Erin-Ile, emphasizing the importance of geoelectric methods in assessing groundwater potential. The findings highlight opportunities for improving groundwater resource management and optimizing water supply infrastructure.

Keywords: Geoelectric Assessment; Groundwater Potential; Aquifer Characterization; Hydrogeological Exploartion; Water Resources Management.

Introduction

The exploration and assessment of underground water resources are vital endeavour for sustaining

communities, agriculture, and industries worldwide (Sunday and Usman, 2021). However, groundwater, found in saturated regions beneath

Corresponding Author: N.K. Olasunkanmi

Department of Physics and Materials Science, Kwara State University Malete Nigeria

Email: nurudeen.olasunkanmi@kwasu.edu.ng; +2348034370033



the Earth's surface, flows through geological formations such as porous aquifers and impermeable aquicludes (Nwachukwu et al., 2022). Although surface water is more accessible, it is often contaminated, making groundwater a better option for high-quality water needs (Wattanasen and Elming, 2008; Anomohanran, 2015; Al-Hashimi et al., 2021). Various geophysical techniques, including magnetic resonance sounding, remote sensing, GIS, gravity, seismic methods, and electrical resistivity, have been employed in groundwater exploration globally (Schirov et al., 1991; Wattanasen and Elming, 2008; Mohamed et al., 2022). The electrical resistivity survey method, one of the oldest and most widely used geophysical exploration techniques, has applications in environmental, engineering, hydrological, archaeological, and mineral exploration surveys (Jones et al., 2011; Loke et al., 2013; Alao et al., 2024). Vertical Electrical Sounding (VES) is particularly popular for investigating subsurface structures and lithology at moderate depths, offering insights into aquifer structures and groundwater quality (Araffa et al., 2015; Mendoza et al., 2019; Alghamdi et al., 2021). By analyzing variations in electrical resistivity within the subsurface, researchers can understand geological formations and hydrological processes influencing groundwater distribution (Singha and Gorelick, 2006; Minsley et al., 2022). Electrical resistivity imaging techniques enhance the understanding and management of underground water resources, contributing significantly to sustainable water management and environmental conservation efforts (Binley et al., 2015; Black et al., 2023). VES is effective in investigating the vertical sequence of conducting zones and delineating subsurface stratigraphy based on resistivity differences (Hassan et al., 2017).

The exploration of groundwater has become a major concern due to diminishing resources and irregular rainfall patterns in semiarid regions (Nagaiah et al., 2022). Recent research has

focused on evaluating, exploiting, and assessing groundwater quality in Nigeria's basement complex, especially in the southwestern region (Afolabi et al., 2018). Groundwater reservoirs in basement complex terrains are typically found in weathered or fractured bedrock zones, which enhance permeability and porosity, facilitating groundwater accumulation and exploitation (Ajayi et al., 2019). Numerous studies worldwide have evaluated groundwater potential and lithological layers in Basement Complex and Sedimentary basins using geophysical techniques. The studied area, Erin-Ile in Southwestern Nigeria, is a community that relies entirely on groundwater for their daily needs. This reliance is compounded by the low yield of existing boreholes and rapid population growth, which has led to severe water scarcity. This research provides a detailed assessment of groundwater potential in Erin-Ile, a semi-arid region, contributing to a deeper understanding of groundwater availability in Basement Complex terrains.

Materials and Methods

Location and Geology of the Study Area

The study is situated in Erin-Ile, Oyun Local Government Area, Kwara State, Nigeria, bounded by latitude 8.096019 N and longitude 4.697189 E. The state lies in Southwestern Nigeria and falls within the Basement Complex of Nigeria. The area is underlain by granite, augen gneiss and migmatite. Erin-Ile is the largest community in Oyun Local Government Area, covering a landmass of about 700 km², and serves as the gateway between Northern and Southern Nigeria. Its geographical coordinates are 8°7'0" North and 4°42'0" East. The climate of the area is characterized by wet and dry seasons. The rainy season typically begins towards the end of April and lasts until October, while the dry season starts in November and ends in April. The temperature ranges between 33°C to 35°C from November to

January, and it range between 34°C to 37°C from February to April.

5275

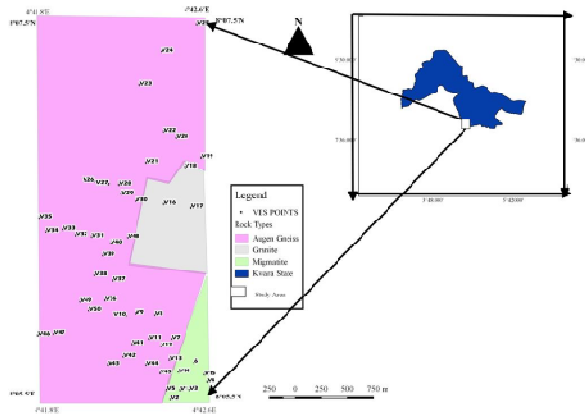


Figure 1: Geological Map of the Study Area

The geophysical survey was conducted with the approval of local authorities, adhering to environmental regulations and ethical guidelines.

The survey was conducted during the dry season using the SAS 1000 electrical resistivity meter along ten traverses. Fifty Vertical Electrical Soundings with Schlumberger electrode configuration were performed, with a maximum current electrode spacing of 100 m. The method involved passing electric current into the subsurface via two electrodes, creating a potential difference measured by another pair of electrodes. The instrument measures vertical changes in ground resistivity with depth, helping to identify vertical layers and aquifer thicknesses, with resistance values recorded directly from the Terrameter.

These resistance values were then converted to apparent resistivity values using Equation 1.

$$\rho_a = KR$$

(1)

$$K = \frac{\pi \left(\frac{a^2 - a^2}{4} \right)}{a}$$

(2)

Where, ρ_a is the apparent resistivity (Ωm) and K is the geometry factor.

The apparent resistivity values were plotted against current electrode spacing, initially interpreted manually using log-log graph paper, and then refined through computer-based iterative interpretations using WINRESIST Software. This process included generating sounding curves and interpreting them to determine geo-electric parameters such as resistivity values and layer thicknesses. The coordinates of each VES station were recorded using GPS. Hydraulic conductivity and aquifer transmissivity at each station were evaluated using the method of Todd (1980), Offodile (1983), Obiora et al. (2016), Raji and Abdulkadir (2020), and Venkateswara et al. (2022). Hydraulic conductivity was determined using the (Equ 3):

$$K = 386.40\rho^{-0.93283}$$

(3)

While the transmissivity was given in (Equ 4).

$$T = Kh$$

(4)

Where, K is the hydraulic conductivity (md^{-1}), ρ is the aquifer resistivity (Ωm), T is the aquifer transmissivity (m^2d^{-1}) and h is the aquifer thickness (m) as stated by Offodile, (1983) and Venkateswara et al., (2022).

The statistical analysis involved applying descriptive statistics (mean, standard deviation, and range) to summarize key hydrogeological parameters, including resistivity, layer thickness, and aquifer properties. To explore relationships between variables, correlation analysis was conducted, particularly assessing the association between aquifer resistivity and hydraulic conductivity, offering insights into subsurface material properties. Additionally, regression analysis was employed to model the relationship

between transmissivity and aquifer thickness, aiding in the prediction of groundwater potential. Normality tests were performed to evaluate data distribution, while outlier detection and treatment were implemented to improve data integrity. This statistical framework provided a rigorous and systematic approach to analyzing groundwater characteristics, enhancing the accuracy and reliability of interpretations.

Results and Discussion

The summary of the geo-electric parameters and inferred lithologies in the study area is presented in Table 1. Three-four geo-electric layers are identified, namely: topsoil, lateritic soil, weathered basement and fractured/fresh basement. The forms of these curves are H, KH and A types with 54%, 44%, 2% occurrences respectively (Figure 2). Most of the sounding curves obtained were of the H- type ($\rho_1 > \rho_2 < \rho_3$).

Lithological mapping

The geoelectric survey across the study area reveals a complex subsurface stratigraphy, with distinct lithological variations influencing groundwater potential. VES points 1–6 are located within the migmatite, VES points 16–18 within the granite, and VES points 7–13 and 19–50 within the augen gneiss. These lithological variations influence groundwater potential, with migmatite and granite generally exhibiting lower permeability, except where fractures or foliation enhance water percolation. The VES results delineate four primary layers: topsoil, lateritic layer, weathered basement, and fractured/fresh basement, each contributing differently to groundwater dynamics (Figure 3). Figure 3a reveals the presence of three to four distinct lithologic layers. At VES 3, the topsoil exhibits a resistivity of 9.1 Ωm with a thickness of 0.4 m. In contrast, lateritic soil is observed at VES 1, VES 2, VES 4, and VES 5, with resistivity values ranging from 85.9 Ωm to 485.9 Ωm and thicknesses between 0.8 m and 1.5 m. Beneath this, a

weathered basement layer is identified with resistivity values between 15.1 Ωm and 98.9 Ωm and thicknesses from 2.2 m to 19.0 m. Underlying this layer is a fractured/fresh basement with resistivity values ranging from 177.2 Ωm to 1078.2 Ωm . Additionally, a fourth layer with infinite thickness and a resistivity of 1531.3 Ωm is detected at VES 3, suggesting the presence of deep bedrock formations.

Figure 3b illustrates three to four geoelectric layers, including topsoil, lateritic soil, weathered basement, and fractured/fresh basement. Lateritic soil, characteristic of tropical weathering, dominates the uppermost layer at VES 6, VES 7, and VES 8, with resistivity values ranging from 107.5 Ωm to 124.7 Ωm and thicknesses between 0.4 m and 1.0 m. The weathered basement layer varies significantly, displaying resistivity values between 21.6 Ωm and 96.5 Ωm and thicknesses from 4.8 m to 10.4 m, indicating differences in weathering intensity. The underlying fractured/fresh basement layer shows resistivity values ranging from 206.7 Ωm to 1623.7 Ωm . Profile 3 (Figure 3c) presents variations in resistivity and thickness across the subsurface layers. The topsoil exhibits resistivity values from 16.7 Ωm to 88.9 Ωm , with thicknesses between 0.2 m and 1.5 m. The lateritic soil layer displays resistivity values ranging from 72.6 Ωm to 447.3 Ωm and thicknesses of 0.7 m to 3.0 m. A weathered basement layer, present across all VES stations, has resistivity values between 16.9 Ωm and 96.5 Ωm , with thicknesses ranging from 2.4 m to 16.5 m, indicative of significant weathering. Beneath this, the fractured/fresh basement layer exhibits higher resistivity values between 307.9 Ωm and 3128.2 Ωm , suggesting less alteration and the presence of deeper bedrock.

Profile 4 (Figure 3d) follows a similar stratigraphic sequence. The topsoil shows resistivity values between 60.3 Ωm and 87.1 Ωm with thicknesses ranging from 0.4 m to 0.7 m. The lateritic soil layer has resistivity values of 94.9

Ωm to 236.3 Ωm and thicknesses of 1.0 m to 3.1 m. The weathered basement layer exhibits resistivity values between 24.2 Ωm and 89.9 Ωm , with thicknesses from 2.1 m to 11.5 m, suggesting uniform weathering. The fractured/fresh basement layer presents higher resistivity values of 190.7 Ωm to 892.7 Ωm , indicative of deeper, less weathered bedrock. Profiles across Figures 3e to 3m show consistent stratigraphy with minor variations. The topsoil exhibits resistivity values ranging from 33.1 Ωm to 103.3 Ωm , with thicknesses between 0.2 m and 1.3 m. The lateritic soil is present at all VES stations, with resistivity values ranging from 51.6 Ωm to 308.7 Ωm and thicknesses varying from 0.5 m to 3.0 m. The weathered basement layer shows varying degrees of weathering, with resistivity values between 20.3 Ωm and 98.6 Ωm and thicknesses ranging from 1.7 m to 19.2 m. Below this, the fractured/fresh basement layer exhibits decreasing weathering with depth, with resistivity values ranging from 159.4 Ωm to 3128.2 Ωm , indicating the presence of fresher bedrock formations.

Generally, the topsoil resistivity ranges from 9.1 Ωm to 103.3 Ωm , with thicknesses between 0.2 m and 1.5 m. Lower resistivity values (e.g., VES 3) indicate higher moisture or clay content, enhancing surface water retention, while higher resistivity values suggest drier, more compacted soil, potentially limiting infiltration. The lateritic layer, present across all VES points, exhibits resistivity values between 51.6 Ωm and 485.9 Ωm and thicknesses from 0.4 m to 3.1 m. Higher resistivity zones (e.g., VES 1 and VES 5) may correspond to well-drained, mineral-rich laterite, while lower-resistivity areas may indicate enhanced weathering or groundwater saturation, contributing to localized recharge zones. The

weathered basement shows resistivity values ranging from 15.1 Ωm to 98.9 Ωm , with thicknesses varying between 1.7 m and 19.2 m. Thicker weathered zones (e.g., VES 3, VES 21, and VES 41) act as significant groundwater reservoirs due to their higher porosity and water retention capacity. Conversely, thinner or higher-resistivity sections (e.g., VES 6) suggest reduced porosity and limited groundwater potential. Notably, the weathered layer constitutes the primary aquifer unit, with groundwater potential directly influenced by its thickness and resistivity characteristics. Beneath the weathered layer lies the fractured/fresh basement, with resistivity values ranging from 159.4 Ωm to 3128.2 Ωm . High-resistivity anomalies (e.g., VES 3 and VES 11) likely indicate deep, unweathered bedrock with minimal water storage capacity, though they may have mineralization potential. In contrast, intermediate resistivity values suggest fracture networks that could facilitate groundwater movement, especially in areas with structural discontinuities or foliation planes.

Structurally, the variability in resistivity and layer thickness, coupled with sharp resistivity contrasts, suggests possible faulting or structural controls that influence fluid migration and groundwater distribution. For instance, the substantial weathered basement thickness at VES 3, VES 21, and VES 41 makes these locations prime targets for groundwater exploration, as they may support sustainable water supply systems. Meanwhile, fractured zones with intermediate basement resistivity could enhance groundwater recharge and flow, even in areas where the overlying weathered layer is thin.

5278

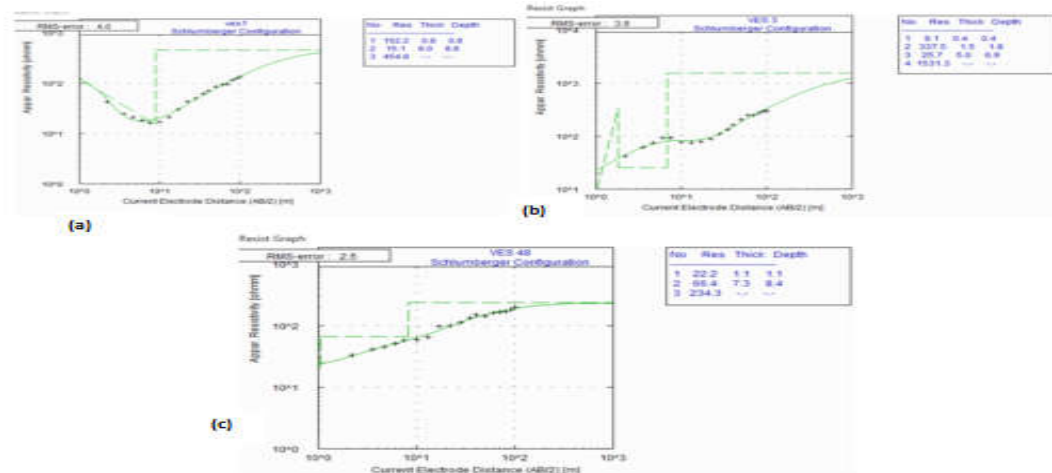


Figure 2: (a) H-type (b) KH-type and (c) A-type resistivity curve.

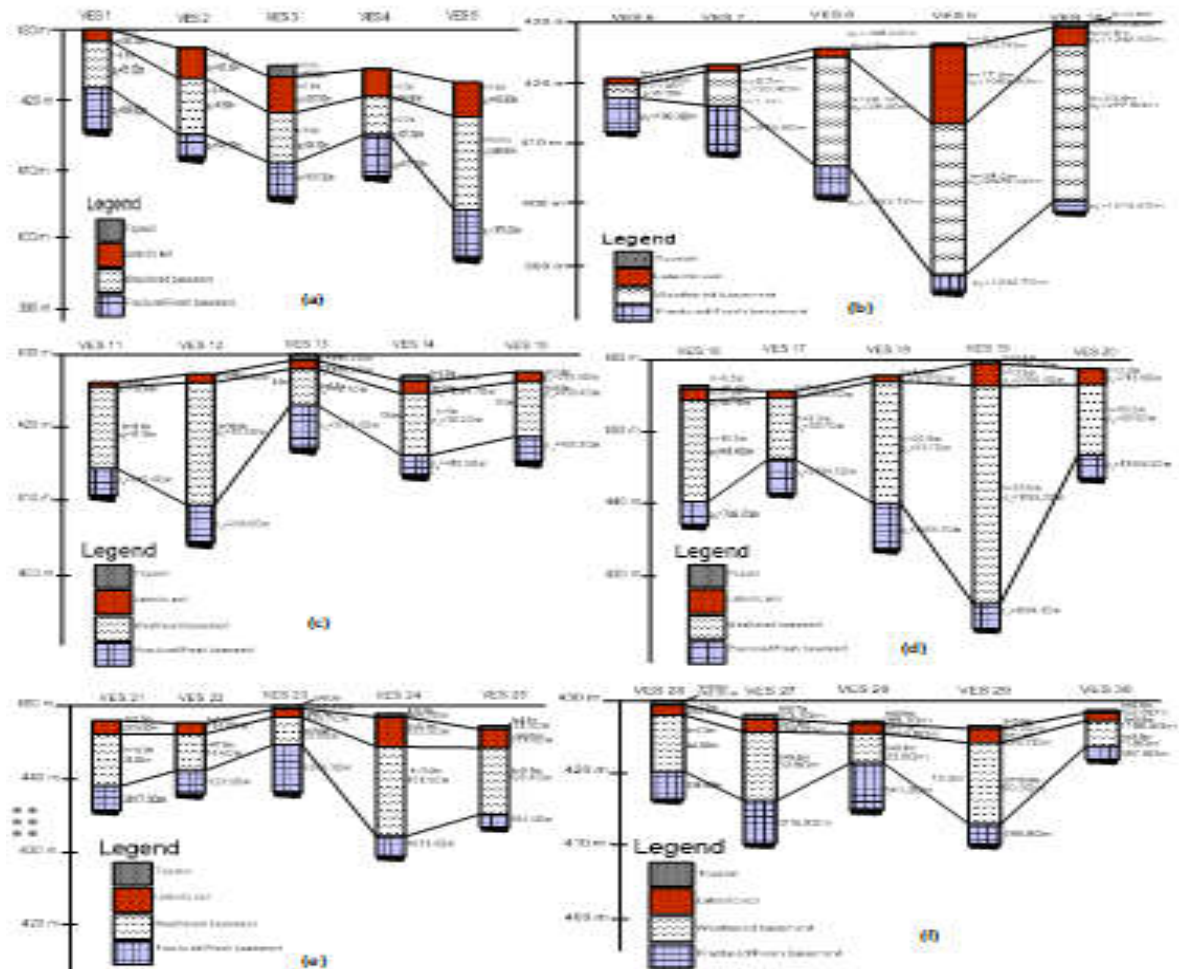


Figure 3a: Geo-electric section along profile 3a; 3b; 3c; 3d; 3e; 3f.

5279

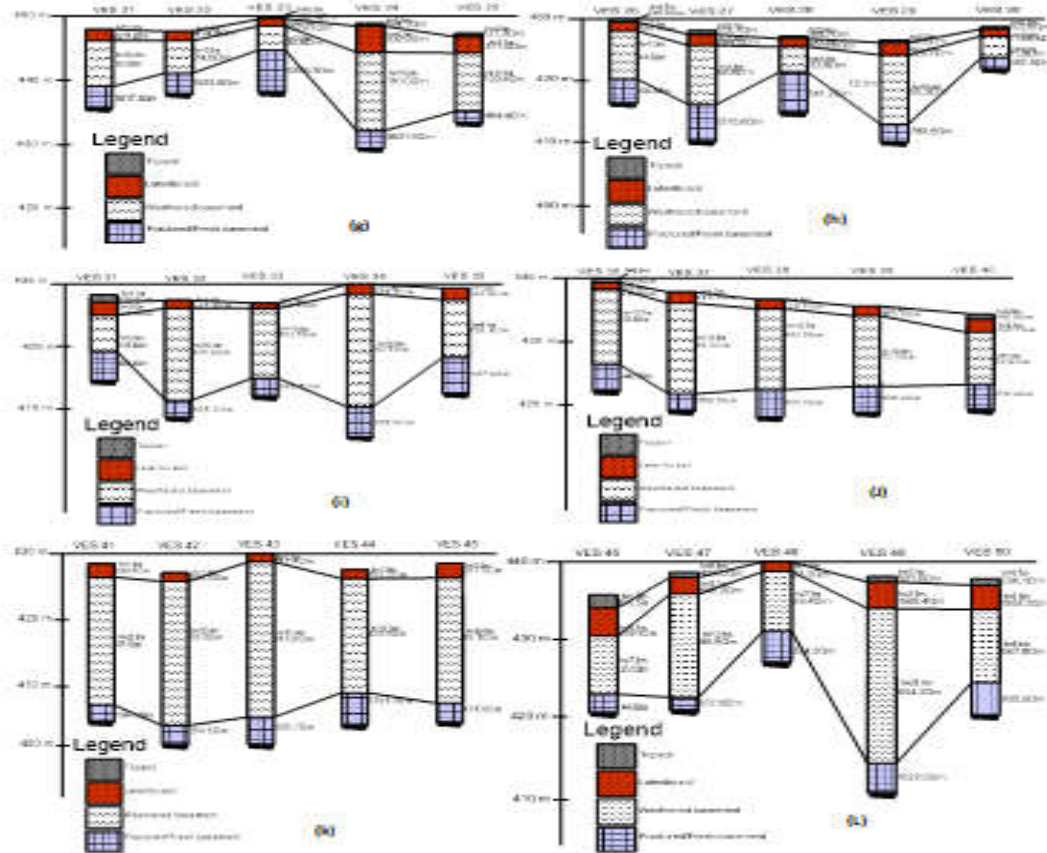


Figure 3b: Geo-electric section along profile 3g; 3h; 3i; 3j; 3k; 3l.

Table 1: Geo-electric parameters and lithology delineation of the study area

VES points	Layer	Resistivity	Thickne ss	Depth	Lithology	Curve type
VES 1,2,4,5,6,7,8,11,12,15,17,18,20,21,22,32,33,34,35,37,38,39,41,42,43,44,45	1	70.7– 2219.2	0.3 – 2.6	0.3 – 2.6	Topsoil	H
	2	8.7 – 450.4	1.6– 31.4	2.7– 32.7	Weathered Basement	
	3	106.3– 201815.6	-	-	Fracture/Fresh Basement	
VES 3,9,10,13,14,16,19,23,24,25,26,27,28,29,30,31,36,40,46,47,49,50	1	9.1 – 821.6	0.3 – 1.9	0.3 – 1.9	Topsoil	KH
	2	226.7 – 579.7	0.7– 17.6	1.1-17.9	Lateritic Soil	
	3	21.8 – 2978.0	3.0– 33.6	4.2-37.3	Weathered Basement	
	4	334.8-9289.3	-	-	Fracture/fresh Basement	
VES 48	1	22.2	1.1	1.1	Lateritic/ Topsoil	A
	2	66.4	7.3	8.4	Weathered Basement	
	3	234.3	-	-	Fracture/fresh Basement	

5280

Table 2 shows the summary of groundwater potential of the study area. In assessing the groundwater potential of the study area, some parameters such as the aquifer's resistivity, thickness, hydraulic conductivity and aquifer transmissivity obtained from VES interpretation result are considered. The aquifer transmissivity of the study area varies from -931.6 m²/day to 474.37 m²/day and the prospect of groundwater is categorized into high, medium and low potentials. In this study, areas with high transmissivity values above 500 m²/day typically have a great potential for holding water. Out of the 50 groundwater locations,

37 (74%) were classified as having moderate potential, 12 (24%) as having low potential, 1 (2%) as having negligible potential and no locations have high/good potential for groundwater (Figure 4a). Overall, the combined influence of lithology, weathering intensity, and structural factors defines the groundwater potential across the study area. The prevalence of moderately thick weathered layers and fracture networks suggests viable groundwater prospects, particularly in the southwestern region where moderate potential zones dominate.

Table 2: Groundwater potential of the study area

VES	Aquifer Resistivity (ρ) Ω m	Aquifer Thickness (h) m	Hydraulic Conductivity (K) m/day	Aquifer Transmissivity (T) m ² /day	Groundwater Potential
VES1,2,5,6,7,8,11,12,13,14,16,17,18,20,21,23,24,26,27,28,29,30,32,33,34,36,37,39,40,41,42,43,44,45,46,47,48	8.5 – 151	1.6 - 28	3.584-52.486	51.32-493.4	Moderate
VES4,9,10,15,19,22,25,31,35,38,49,50	37.3-2978	2.2-26.8	0.222-13.210	5.329-48.44	Low
VES 3	25.7	5	-18.699	-93.49	Negligible

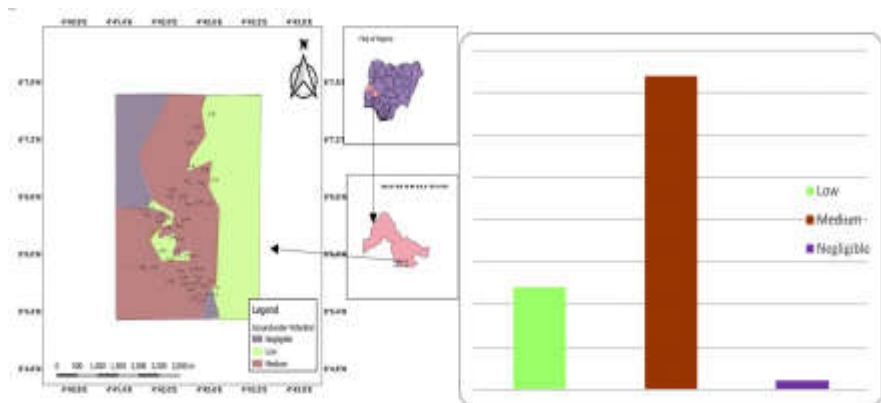


Figure 4: a) Groundwater potential map, b) Bar Chart showing the Groundwater potential of VES points.

Summary of Statistical Analysis

Descriptive statistics were applied to summarize resistivity, aquifer thickness, and transmissivity data across all VES points (Table 3). The negative transmissivity values (e.g., -93.49 m²/day) indicate highly impermeable layers that restrict groundwater flow, leading to negligible groundwater potential. The Correlation analysis was conducted to assess the relationship between

aquifer resistivity and hydraulic conductivity, helping to determine material properties influencing water movement. Also, regression analysis modeled the relationship between transmissivity and aquifer thickness, allowing for groundwater potential predictions. However, the confidence intervals were calculated to evaluate the reliability of the measured values across different VES points.

Table 3: Statistical summary including aquifer resistivity, thickness, hydraulic conductivity, and transmissivity.

Parameter	Mean	Standard Deviation	Min	Max	Confidence Interval
Aquifer Resistivity (Ωm)	1064.2	High Variability	8.5	2978	Calculated for each VES point
Aquifer Thickness (m)	13.7	Moderate Deviation	1.6	28	Calculated for each VES point
Hydraulic Conductivity (m/day)	5.23	Moderate Deviation	-18.699	52.486	Calculated for each VES point
Aquifer Transmissivity (m ² /day)	70.2	High Variability	-93.49	493.4	Calculated for each VES point

Conclusion

The study has demonstrated the effectiveness of the Vertical Electrical Sounding (VES) method in groundwater exploration within the basement complex of Nigeria. The VES curves obtained revealed three to four geoelectric layers: the topsoil, lateritic layer, weathered layer, and fractured/fresh basement. These curves exhibited various types, including H, KH, and A, with the H-type being the most prominent in the study area. In assessing the groundwater potential, parameters such as aquifer resistivity, thickness, hydraulic conductivity, and aquifer transmissivity obtained

from VES interpretation were considered. The aquifer transmissivity of the study area ranges from -931.6 m²/day to 474.37 m²/day, with groundwater potential categorized into high, moderate, and low zones. Generally, areas with transmissivity values above 500 m²/day are considered to have high groundwater potential, though no locations in this study met that threshold. Out of the 50 VES points, 37 locations (74%) exhibited moderate groundwater potential, 12 locations (24%) showed low potential, and 1 location (2%) had negligible potential (VES 3). The southwestern part of the study area was

5282

predominantly characterized by moderate groundwater potential. The weathered layer was identified as the primary aquifer unit, characterized by low resistivity values indicative of groundwater-bearing zones. Geoelectric parameters, including the thickness of the aquifer units and conductivity, were used to further delineate groundwater potential zones. VES points 4, 9, 10, 15, 19, 22, 25, 31, 35, 38, 49, and 50 were associated with low groundwater potential zones. The findings align with the varying permeability of the lithologies in the area: migmatite exhibits moderate permeability, granite shows low permeability due to its dense and crystalline structure, and Augen Gneiss demonstrates moderate to high permeability, particularly in fractured or foliated sections, which facilitate groundwater movement through fractures. Overall, while no high-potential zones were identified, the prevalence of moderate groundwater potential, particularly in the southwestern region, suggests viable groundwater

resources, especially in areas where aquifer thickness and transmissivity are relatively higher.

Based on the study's findings, it is recommended that groundwater development focus on the southwestern region, which shows moderate groundwater potential, particularly in areas with thicker and more conductive aquifer units. Additional aquifer testing and hydrogeological modeling should be conducted to refine groundwater characterization and ensure sustainable management, especially in areas with varying lithologies like migmatite, granite, and Augen Gneiss. For low-potential zones, alternative water supply solutions such as rainwater harvesting or surface water collection should be explored. Additionally, the results should be integrated into regional water resource planning to optimize groundwater use and support sustainable water supply strategies in the area.

Conflict of Interest

None

References

- Anomohanran, O. (2015). Hydrogeophysical and hydrogeological investigations of groundwater resources in Delta Central, Nigeria. *Journal of Taibah University for Science*, 9(1), 57-68.
- Alghamdi, A.F., Atekwana, E.A., Almalki, K.A., Rezanezhad, F., and Revil, A. (2021). Integrated geophysical and geochemical investigation of the vadose zone structure and hydrological processes in arid regions. *Water Resources Research*, 57(6), e2021WR029916. <https://doi.org/10.1029/2021WR029916>.
- Al-Hashimi, O., Hashim, K., Loffill, E., Marolt Čebašek, T., Nakouti, I., Faisal, A. A. H., & Al-Ansari, N. (2021). A Comprehensive Review for Groundwater Contamination and Remediation: Occurrence, Migration and Adsorption Modelling. *Molecules*, 26(19),

5913.

<https://doi.org/10.3390/molecules26195913>.

- Alao, J.O., Lawal, K.M., Dewu, B.B.M. (2024). The evolving roles of geophysical test sites in engineering, science and technology. *Acta Geophys.* **72**, 161–176 (2024). <https://doi.org/10.1007/s11600-023-01096-3>.
- Araffa, S.A.S., El Shayeb, H.M., Abu Hashesh, M.F. and Hassan, N.M. (2015). Delineating subsurface structures and assessment of groundwater aquifer using integrated geophysical interpretation at the central part of Sinai, Egypt. *Arabian Journal of Geosciences*, 8, 7993–8007.
- Afolabi O.O., Olutomilola O.O. and Ishaki J.D. (2018). Assessment of Groundwater System Characteristics in Ilorin Metropolis, South-Western Nigeria. *American Journal of Water Science and Engineering*; vol. 4:pp. 1-8.
- Ajayi, T., Bola, A., and Rereloluwa B. (2019). Geoelectric Assessment of Groundwater

- potential in Supare Akoko, Southwestern, Nigeria. *Environmental and Earth Sciences Research Journal*, vol. 6, No. 2, pp. 59-70.
- Baker, C., Jones, S. and Patel, K. (2016). Application of electrical resistivity method in delineating aquifer structures and detecting groundwater contamination. *Water Resources Research*, 31(2), 78-94.
- Black, J.B., Karaoulis, M., Schilling, O.S., Pidlisecky, A. and Blasingame, T. (2023). A review of electrical resistivity imaging techniques for characterizing subsurface hydrologic processes. *Water Resources Research*, 59(1), e2022WR030824. <https://doi.org/10.1029/2022WR030824>.
- Binley, A., Hubbard, S.S., Huisman, J.A., Revil, A., and Robinson, D.A. (2015). Enhancing our understanding of underground water resources through electrical resistivity imaging techniques. *Reviews of Geophysics*, 53(2), 384-406.
- Hassan, L., Abdellatif M., and Moutmaz, R. (2017). Modeling of transient two dimensional flow in saturated porous media. *European Scientific Journal* vol. 13(12), pp 1857 – 7881.
- Jullian, D.M., Melchizedek, A., Phoebe J.G., Ronnie, C. RyanRhyay, V., Argel, B., Elmer, R. (2022). A Review of Electrical Resistivity Tomography Applications in Underground Imaging and Object Detection. *Displays*, 73,102208, <https://doi.org/10.1016/j.displa.2022.102208>
- Kasidi, S. (2017). Groundwater Exploration Using Electrical Resistivity Method A case study In Federal Capital Territory (FCT) Abuja, Nigeria. *International Journal of Engineering and Applied Sciences (IJEAS)*, Vol. 4, ISSN: 2394-3661.
- Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O., and Wilkinson, P.B. (2013). Recent developments in the direct-current geoelectrical imaging method. *Journal of applied geophysics*, 95, 135-156.
- Mohammed, A., Al Deep, M., Othman, A., Taha, A.I., Alshehri, F., and Abdelrady, A. (2022). Integrated Geophysical Assessment of Groundwater Potential in Southwestern Saudi Arabia. *Front. Earth Sci.* 10:937402. doi: 10.3389/feart.2022.937402.
- Nagaiah, E., Sonkamble, S., and Chandra, S. (2022). Electrical geophysical techniques pin-pointing the bedrock fractures for groundwater in granitic hard rocks in Southern India. *Journal of Applied geophysics*, vol. 199, pp. 35-39.
- Nwachukwu, C.C., Ugbor, C.C., and Ogboke, O.J. (2022). Electrical Resistivity Sounding for Groundwater Investigation around Enugu Metropolis and the Environs, Southeast Nigeria. *International Journal of Geosciences*, vol. 13, pp. 54-70.
- Minsley, B.J., Oldenburg, D.W., Atekwana, E.A., Barrash, W., Day-Lewis, F.D., Lévy, M. and Revil, A. (2022). Advances in hydrogeophysics for the characterization of subsurface properties and processes. *Reviews of Geophysics*, 60(1), e2021RG000751. <https://doi.org/10.1029/2021RG000751>.
- Mendoza, J., Smith, R., and Johnson, A. (2019). The role of electrical resistivity method in exploring and assessing underground water resources. *Journal of Hydrogeology*, 24(3), 145 162.
- Offodile, M.I. (1983). The occurrence and exploitation of groundwater in Nigeria basement complex. *Journal of Mining Geology*, 20(3), pp. 131–146.
- Jones, E.H., Reynolds, D.A., Wood, A.L., and Thomas, D.G. (2011). Use of electrophoresis for transporting nano-iron in porous media. *Groundwater*, 49(2), 172-183.
- Singha, K., and Gorelick, S.M. (2006). Analyzing variations in electrical resistivity for insights into geological formations and hydrological processes. *Hydrogeology Journal*, 14(5), 672-685.
- Schirov, M., Legchenko, A., and Creer, G. (1991). A new direct non-invasive groundwater detection technology for Australia. *Exploration geophysics*, 22(2), 333-338.
- Sunday, A., and Usman, A. (2021). Delineating groundwater potential using electrical

- resistivity method in Adamawa State University permanent site, Mubi North-Eastern Nigeria. *International Research Journal of Natural Sciences*, vol. 9, No. 1, pp. 47-60.
- Sunkari, E.D., Zango, M.S., and Korboe, H.M. (2018). Comparative analysis of fluoride concentrations in ground waters in Northern and Southern Ghana: implications for the contaminant sources. *Earth Syst. Environ.* Vol.2 (1), pp. 103–117.
- Sunkari, E.D., Abu, M., Bayowobie, P.S., and Dokuz, U.E. (2019). Hydro geochemical appraisal of groundwater quality in the Ga West municipality, Ghana: implication for domestic and irrigation purposes. *Groundwater Sustain. Dev.* Vol. 8, pp. 501–511.
- Venkateswara, R.P., Mangalampalli S., and Bakuru, A.R. (2022). Investigation of groundwater potential zones in hard rock terrains along EGMB, India, using remote sensing, geoelectrical and hydrological parameters. *Acta Geophysica*, <https://doi.org/10.1007/s11600-022-00916-2>.
- Wattanasen, K., and Elming, S.A. (2008). Direct and indirect methods for groundwater investigations: a case-study of MRS and VES in the southern part of Sweden. *Journal of Applied Geophysics*, 66(3-4), 104-117.
- Zhang, Y., Singha, K., Day-Lewis, F.D., Zhou, Q., Revil, A., and Johnson, T.C. (2020). Electrical resistivity signature of pore-scale processes during drying and drainage in sand. *Water Resources Research*, 56(7), e2019WR026654. <https://doi.org/10.1029/2019WR026654>.