



Integrated Hydrogeophysical Characterization and Quantitative Groundwater Potential Modelling Using Vertical Electrical Sounding in a Basement Complex Terrain: Gaba Community, Abuja, Nigeria

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ABSTRACT

Groundwater exploration in crystalline basement terrains is highly uncertain due to pronounced lithological heterogeneity, variable weathering profiles, and discontinuous fracture systems, often leading to poorly sited boreholes and low drilling success rates. This study presents an integrated hydrogeophysical assessment of groundwater potential and aquifer protective capacity in Gaba Community, Bwari Area Council, Abuja, Nigeria, using Vertical Electrical Sounding (VES) with the Schlumberger configuration. Five VES stations were occupied with a maximum half-current electrode spacing (AB/2) of 200 m, corresponding to an investigation depth of approximately 60–100 m. Apparent resistivity data were inverted using WinResist iterative modelling, yielding root mean square (RMS) errors between 2.9% and 13.4%, indicating acceptable model convergence. Four geoelectric layers were delineated: topsoil (75–538 Ωm), weathered basement (35–785 Ωm), fractured basement (795–1009 Ωm), and highly resistive fresh basement. An anomalously high resistivity value of 40460 Ωm at VES 2 is interpreted as an inversion equivalence artefact rather than a true subsurface condition. Aquifer thickness ranges from 1.3 m to 9.7 m, while aquifer resistivity varies between 35 Ωm and 785 Ωm . Longitudinal conductance values (0.012–0.063 mhos) indicate generally weak aquifer protective capacity. A weighted Groundwater Potential Index (GPI), integrating aquifer thickness, resistivity, transverse resistance, longitudinal conductance, and overburden thickness, produced values between 0.223 and 0.609. VES 3 (0.609) and VES 1 (0.558) are identified as the most promising groundwater targets. The integration of Dar-Zarrouk parameters with quantitative index modelling provides a reliable framework for improved borehole siting in basement complex terrains.

Keywords:

Aquifer,
Dar-Zarrouk parameters,
Potential index.

INTRODUCTION

Groundwater remains a vital component of global freshwater resources, particularly in developing regions where surface water is seasonal, spatially uneven, or vulnerable to contamination (Suleman, Ibrahim & Ahmed, 2023). Rapid population growth, urban expansion, and climate variability have intensified pressure on existing water resources, increasing dependence on subsurface water supplies (Kasidi & Victor, 2019). In peri-urban settlements such as Gaba Community within the Bwari Area Council of the Federal Capital Territory (FCT), Nigeria, this dependence has been accentuated by recent institutional development, including nearby Veritas University and the Nigerian Law School, which have amplified local water demand.

Crystalline basement terrains pose significant hydrogeological challenges for groundwater exploration due to their negligible primary porosity and reliance on secondary porosity generated through weathering and fracturing (Wright, 1992). Accordingly, aquifers in such environments are commonly confined to weathered overburden and fracture networks within the bedrock, exhibiting marked spatial variability in thickness, continuity, and hydraulic properties (Olorunfemi & Fasuyi, 1993; Olorunfemi, Ojo & Akintunde, 1999). This heterogeneity often results in unpredictable borehole performance, including low yields and early failure, where prior subsurface characterization is inadequate. Numerous geophysical techniques have proved effective in delineating subsurface heterogeneity and informing

borehole siting decisions. Among these, electrical resistivity methods are widely adopted due to their sensitivity to lithological contrasts, moisture saturation, pore geometry, and clay content (Keller & Frischknecht, 1966; Telford, Geldart & Sheriff, 1990). In crystalline terrains, the vertical electrical sounding (VES) approach, particularly with Schlumberger electrode configuration, has demonstrated effectiveness in resolving vertical geoelectric layering and estimating aquifer depth and thickness (Zohdy et al., 1974). Lower resistivity values generally correspond to saturated weathered materials or fracture zones, whereas high resistivity delineates fresh, relatively impermeable bedrock.

Recent investigations underscore the continued relevance and adaptability of resistivity-based hydrogeophysical methods in basement settings. For instance, Ebele et al. (2024) applied integrated geophysical techniques to delineate groundwater zones in the crystalline terrain of Abuja, demonstrating significant improvements in target delineation when structural lineaments and resistivity contrasts were incorporated. Likewise, Osumeje et al. (2024) combined remote sensing and electrical resistivity data to map groundwater potential zones in northwestern Nigeria, reinforcing the utility of integrated approaches in complex subsurface environments. Other recent work in basement contexts highlights the effectiveness of resistivity methods in both delineating aquifer geometry and supporting vulnerability assessment (Ezeamaka, Onyekuru & Nwankwo, 2022; Sunkari, Kabo-Bah & Osae, 2021).

Despite these advances, many hydrogeophysical investigations within the FCT remain regional in scope, with limited high-resolution mapping of aquifer geometry, protective capacity, and vulnerability at the community level. Particularly in the Gaba Community, few studies have quantitatively integrated derived geoelectric parameters — such as longitudinal conductance and transverse resistance — with lithological interpretation and curve-type classification to assess aquifer protective capacity and vulnerability. This gap constrains the effectiveness of groundwater targeting and increases the risk of poorly performing wells.

Aquifer vulnerability evaluation using Dar-Zarrouk parameters (e.g., longitudinal conductance, transverse resistance) provides a quantitative framework for assessing the protective capacity of overburden materials against contamination — a factor of growing importance in urbanizing regions (Henriet, 1976; Oladapo & Akintorinwa, 2007). Such parameters, when combined with resistivity layering and curve-type patterns, enhance the understanding of subsurface conditions and support more reliable borehole siting decisions.

The Federal Capital Territory is predominantly underlain by Precambrian igneous and metamorphic rocks of the Northern Nigerian Basement Complex, with only minor Cretaceous sedimentary outcrops in the southwestern

quadrant (Sunkari et al., 2021). Within this geological framework, groundwater is primarily found in weathered regolith and structurally controlled fracture networks, resulting in significant spatial variability in aquifer distribution and productivity. Communities in the Bwari Area Council, including Igu, Kawu, and Gaba, continue to experience intermittent potable water shortages, often attributed to poorly sited or low-yield boreholes.

Addressing these challenges, this study applies the Vertical Electrical Sounding method using the Schlumberger array to evaluate groundwater potential in the Gaba Community. Specifically, the study delineates the subsurface geoelectric layers in the Gaba community and quantifies their resistivity characteristics and thicknesses. It also identifies the likely aquifer zones and computes the derived geoelectric parameters, including longitudinal conductance and transverse resistance, to assess aquifer protective capacity and vulnerability. It finally develops a Groundwater Potential Index (GPI) model for borehole sites. Through integration of lithological interpretation, geoelectric curve-type classification, and quantitative parameter analysis, the study develops a groundwater potential ranking framework designed to improve borehole success rates and inform sustainable groundwater resource management in crystalline basement environments of north-central Nigeria.

Study Area and Geological Setting

The study area is situated in Gaba Community, Bwari Area Council, Abuja, Nigeria (Figure 1), within the geographical coordinates of 9°25'–9°28'N and 7°19'–7°42'E. The terrain exhibits moderate elevation, ranging between 435 and 642 m above mean sea level, reflecting a gently undulating topography typical of the region.

The climate of the study area is characterized by a tropical wet-and-dry regime with two distinct seasons: the dry and rainy seasons. The dry season typically extends from November to February and is often influenced by the Harmattan, a dry and dust-laden northeasterly wind that significantly reduces atmospheric humidity and visibility. In contrast, the rainy season spans from April to October, with peak precipitation occurring between July and September. This seasonal rainfall pattern plays a critical role in groundwater dynamics within the area.

Groundwater recharge occurs predominantly through direct infiltration of rainfall during the peak rainy months (July–September). The efficiency of this recharge process is largely controlled by several interrelated factors, including soil permeability, the thickness and hydraulic properties of the weathered regolith, and the presence of structural discontinuities such as fractures and joints within the underlying basement rocks. These features enhance infiltration and facilitate the movement and storage of groundwater within the subsurface.

Geologically, the area forms part of the Precambrian Basement Complex of north-central Nigeria, predominantly composed of crystalline rocks such as granites, gneisses, and schists (Wright, 1992; Sunkari et al., 2021). These lithological units are inherently characterized by negligible primary porosity; consequently, groundwater occurrence is largely restricted to secondary porosity zones, particularly within the weathered overburden and fractured bedrock.

As a result, aquifer development within the study area is structurally controlled and exhibits considerable spatial heterogeneity. The hydrogeological characteristics are therefore strongly governed by the thickness and lateral continuity of the weathered layer, the degree of fracturing and connectivity within the basement rocks, and the level of groundwater saturation within the regolith. Collectively, these factors determine the storage capacity, transmissivity, and overall productivity of the aquifer systems in the area.

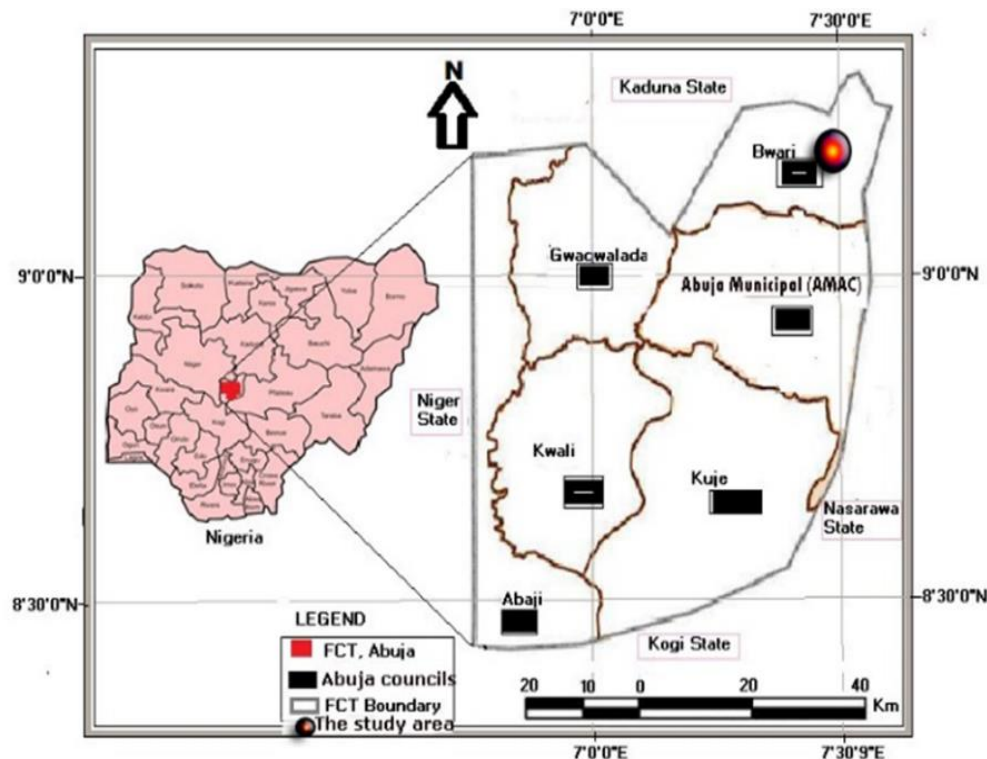


Figure 1: Modified Location Map of the Federal Capital Territory (FCT), Abuja, Showing the Study Area (Adapted from Ojiego et al., 2023)

MATERIALS AND METHODS

The electrical resistivity survey was conducted using the Allied Ohmega SAS 300B Terrameter, supported by stainless steel electrodes, insulated electrode cables, measuring tapes for electrode spacing, a Global Positioning System (GPS) receiver for geo-referencing, a hammer for electrode installation, and a laptop computer for data storage and processing.

The Schlumberger electrode configuration was employed for data acquisition due to its ability to achieve greater depth penetration with minimal electrode movement. (Keller & Frischknecht, 1966; Telford et al., 1990). Five VES stations were established across the study area with a maximum half-current electrode spacing (AB/2) of 200

m, providing an estimated investigation depth of 60–100 m.

The measured resistance values were converted to apparent resistivity ρ_a (Ωm) (Usman, 2019) using the Schlumberger.

$$\rho_a = \frac{K\Delta V}{I} = KR \quad (1)$$

Where ρ_a = apparent resistivity (Ωm), K = geometric factor, V = measured potential difference (V), I = injected current (A), and R = measured resistance (Ω). The Schlumberger configuration deployed to obtain the apparent resistivity of the present study is shown in Figure 2 (Idris et al., 2018).

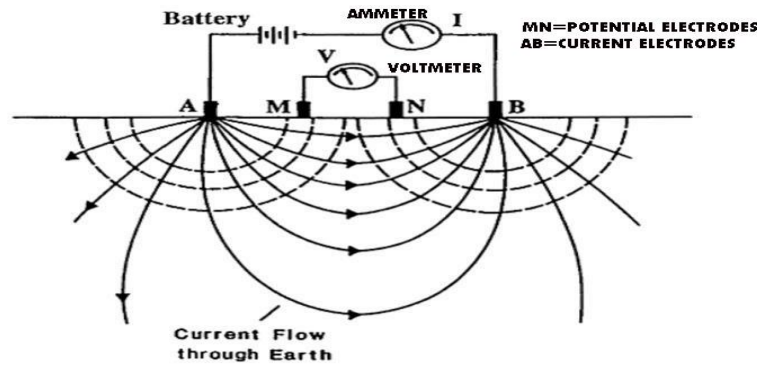


Figure 2: Modified Schlumberger Array Diagram

Figure 2 illustrates the electrode configuration used to obtain the parameters required for calculating the geometric factor K . The geometric factor employed in Equation (1) is given as (Fawale & Oladipo, 2020):

$$K = \frac{\pi}{2} \left[\left(\frac{AB}{2} \right)^2 - \left(\frac{MN}{2} \right)^2 \right] \quad (2)$$

Where AB represents the current electrode separation, and MN denotes the potential electrode separation. The apparent resistivity is a weighted average of subsurface resistivity variations and serves as the fundamental parameter for geoelectric.

Data Processing

Field data were interpreted through Partial curve matching and a computerized inversion using WinResist (Vander Velpen, 2004). In some cases, measurements were repeated at identical electrode spacings to improve data reliability and reduce field noise. The averaged values were subsequently used for interpretation. The inversion process iteratively adjusted layer parameters until the calculated curves matched the observed field data. To further evaluate aquifer characteristics and protective capacity, the Dar-Zarrouk parameters were computed from interpreted layer resistivities and thicknesses (Henriet, 1976). The longitudinal conductance (S) was evaluated using the expression (Henriet, 1976),

$$S = \sum_{i=1}^n \left(\frac{h_i}{\rho_i} \right) \quad (3)$$

Where h_i is the thickness of the i -th layer (m), and ρ_i is the resistivity of the i -th layer (Ωm). Longitudinal conductance is measured in mhos (Siemens). Longitudinal conductance (S) is expressed in Siemens (mhos) and serves as an indicator of aquifer protective capacity. Higher S values generally correspond to thicker or more conductive overburden, implying better protection against surface contamination.

Another Dar-Zarrouk parameter of significance in the present study was the transverse resistance (T). The transverse resistance is given by ((Henriet, 1976)):

$$T = \sum_{i=1}^n (h_i \rho_i) \quad (4)$$

Transverse resistance (T) reflects the transmissive properties of aquifer units, and it is commonly used to assess groundwater potential. Higher T values often indicate greater aquifer thickness and/or moderate resistivity conducive to groundwater storage.

The conceptual basis of the Groundwater Potential Index (GPI) in basement terrains is founded on key hydrogeophysical parameters—including aquifer thickness (h), aquifer resistivity (ρ), transverse resistance ($T = \rho h$), longitudinal conductance ($S = h/\rho$), and overburden thickness (OB)—which collectively control aquifer storage capacity, degree of saturation, hydraulic transmissivity, protective capacity, and overall groundwater recharge potential. To ensure dimensional consistency and eliminate scale bias, each parameter was normalized using the min-max scaling technique. For beneficial parameters, the normalized rating is expressed as:

$$R_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (5)$$

Where X_i is the observed value of the parameter at the i th location, X_{\min} is the minimum value of the parameter within the dataset, X_{\max} is the maximum value of the parameter within the dataset, and R_i is the normalized rating ranging between 0 and 1.

For inverse parameters (e.g., resistivity), where lower values indicate better groundwater potential, and the normalization is given as:

For inverse parameters (resistivity):

$$R_p = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}} \quad (6)$$

Where R_p is the normalized rating for resistivity on a scale of 0 to 1, with higher values representing more favourable conditions. Therefore, the Groundwater Potential Index (GPI) was computed using:

$$GPI = \sum (W_i R_i) \quad (7)$$

Where W_i is the weight assigned to the i th parameter (e.g., aquifer thickness, resistivity, longitudinal conductance, and transverse resistance), and R_i is the corresponding normalized rating.

Methodological Implications for Groundwater Exploration in Basement Terrains

The approach adopted in this study demonstrates the value of integrating conventional electrical resistivity interpretation with quantitative hydrogeophysical parameter analysis for groundwater exploration in crystalline basement environments. While traditional VES interpretation primarily focuses on identifying resistivity contrasts associated with weathered and fractured zones, the incorporation of derived parameters such as longitudinal conductance and transverse resistance provides additional insight into aquifer transmissivity and protective capacity. Furthermore, the

development of a normalized Groundwater Potential Index (GPI) allows multiple hydrogeophysical indicators to be systematically combined into a single evaluative framework for ranking potential drilling sites. Such an integrated methodology reduces subjectivity in interpretation and improves the reliability of groundwater targeting in geologically heterogeneous basement terrains where aquifer occurrence is highly localized.

RESULTS AND DISCUSSION

The results of the present study were obtained and are presented in this section. In Table 1, the coordinates of the location of the VES stations are presented.

Table 1: Coordinates of the location of the VES stations

VES	Latitude	Longitude	Elevation (m)
1	9.286765	7.421591	637
2	9.287172	7.422139	637
3	9.286244	7.422693	628
4	9.285166	7.421616	642
5	9.284956	7.421006	642

Table 2: Vertical Electrical Sounding (VES) Field Data at Gaba Community, F.C.T., Abuja

AB/2 (m)	VES 1 (Ωm)	VES 2 (Ωm)	VES 3 (Ωm)	VES 4 (Ωm)	VES 5 (Ωm)
1.0	533	402	128	315	118
1.5	502	391	133	281	175
2.0	411	387	142	294	216
3.0	272	144	74	383	590
5.0	229	185	74	483	563
7.0	255	286	79	447	605
7.0	211	317	85	468	648
10.0	138	485	116	545	690
15.0	268	839	199	741	627
20.0	304	1397	271	895	701
25.0	372	2067	390	1166	787
30.0	460	2826	516	1468	929
30.0	429	2987	420	1503	912
40.0	596	3032	625	1881	1283
50.0	790	3276	588	2017	1718
60.0	1075	3351	619	2311	2185
70.0	1320	3573	685	2737	2582
80.0	1626	3614	720	2815	2848
100.0	2331	3906	812	3107	3892
120.0	3011	4122	906	3305	4322
140.0	3828	4605	1073	3559	4870
160.0	4022	4831	1155	3990	5116
200.0	5106	5119	1318	4212	6463

Table 3: Lithological Log for VES Station 01

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology
1	538	1.3	1.3	Topsoil
2	153	7.5	8.8	Weathered Basement (Sand/Clay/Mica)
3	915	5.6	14.4	Fresh Basement
4	23580			Resistive Basement/Possible Fractures

Table 4: Lithological Log for VES Station 02

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology
1	530	0.8	0.8	Topsoil
2	89	1.3	2.1	Weathered Basement
3	40460.6	34.8	36.9	Fresh Basement
4	5833.4			Resistive Basement

Table 5: Lithological Log for VES Station 03

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology
1	150	1.2	1.2	Topsoil
2	35	2.2	3.4	Saturated Weathered Basement
3	3436	26.0	29.4	Fresh Basement
4	1009			Fractured/Resistive Basement

Table 6: Lithological Log for VES Station 04

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Interpreted Lithology
1	291	1.1	1.1	Topsoil
2	446	6.2	7.3	Weathered Basement
3	5357	18.3	25.6	Fresh Basement
4	7666			Resistive Basement

Table 7: Lithological Log for VES Station 05

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology
1	75	0.4	0.4	Topsoil
2	785	9.7	10.1	Sandy/Weathered Basement
3	795	8.2	18.3	Fresh Basement/Fractured Basement
4	28016			Fresh Basement

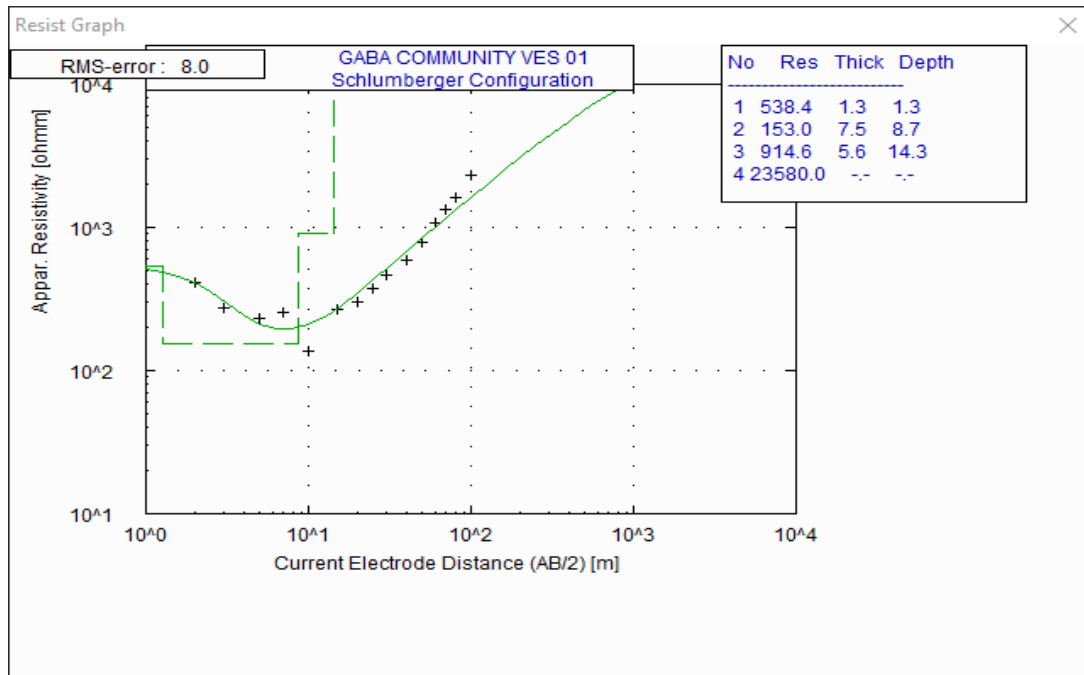


Figure 3: Sounding Curve for VES Station 01

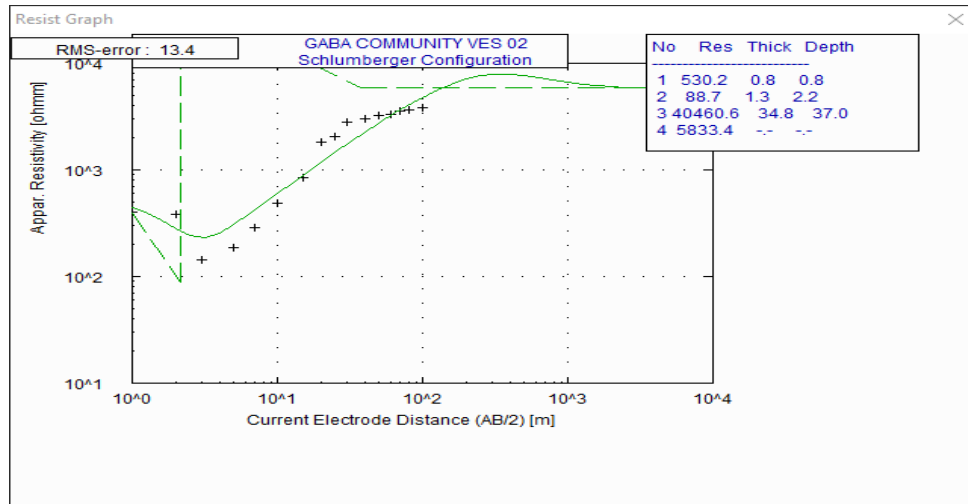


Figure 4: Sounding Curve for VES Station 02

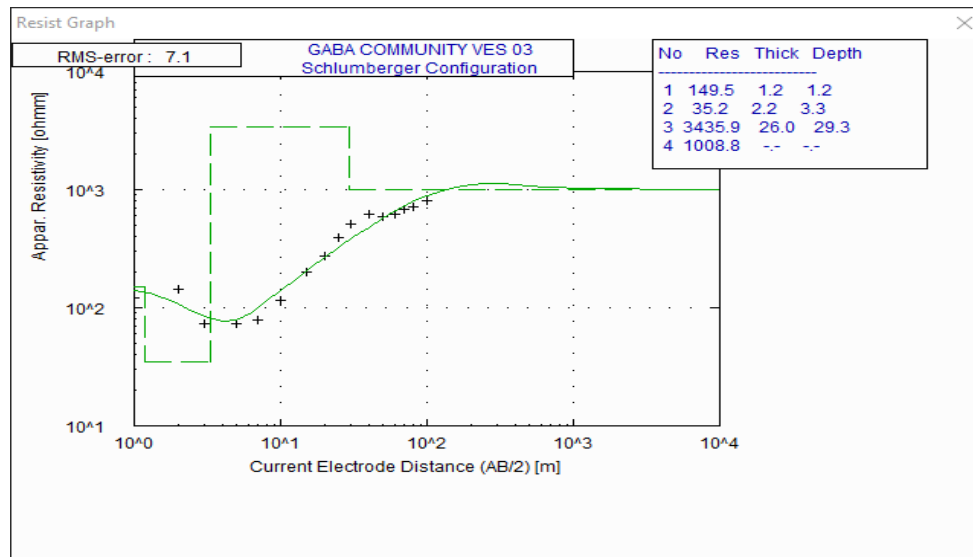


Figure 5: Sounding Curve for VES Station 03

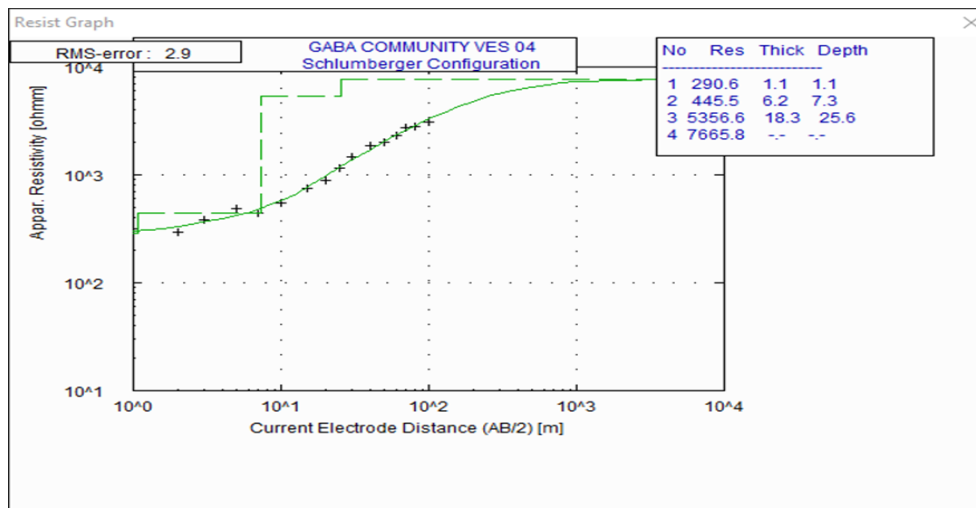


Figure 6: Sounding Curve for VES Station 04

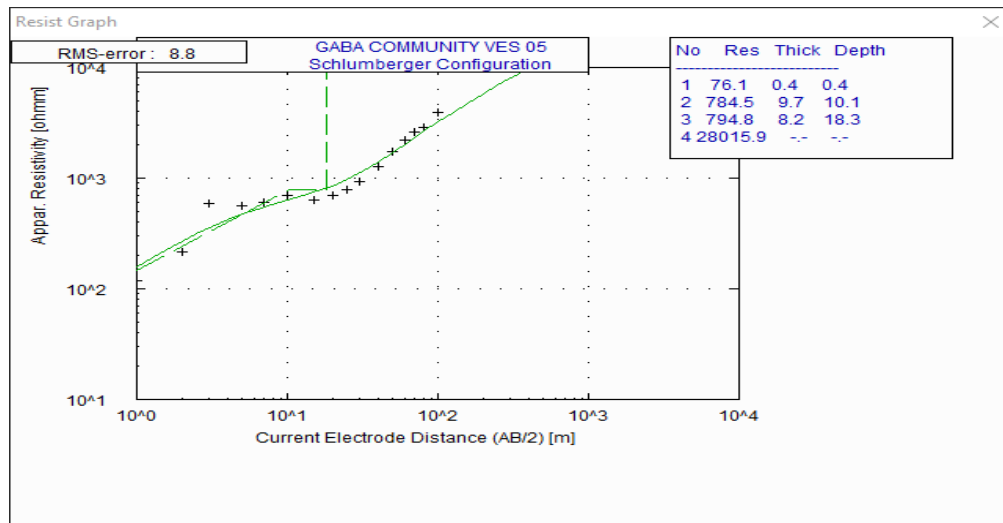


Figure 7: Sounding Curve for VES Station 05

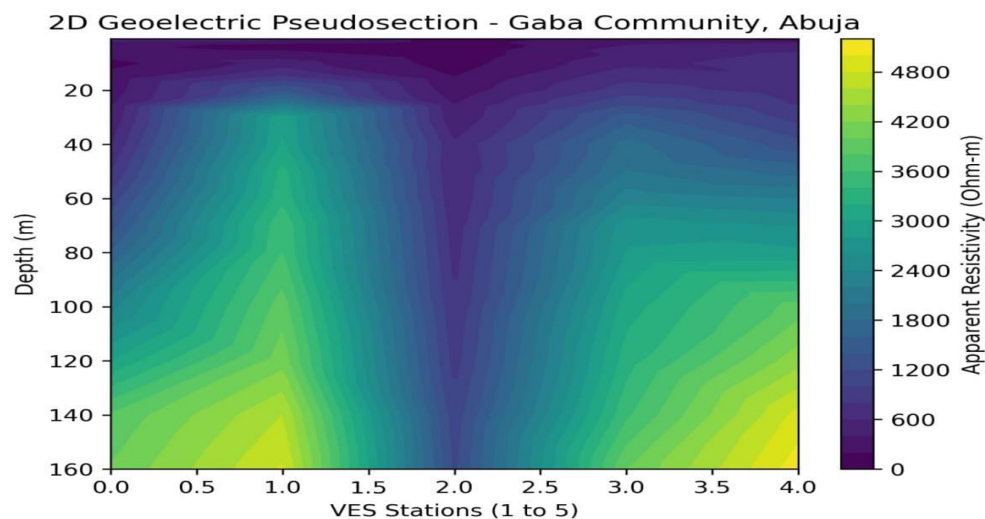


Figure 8: 2D Geo-electric Pseudo-section of the Study Area

Table 8: Comparative Assessment of Geo-electric Parameters and Result Summary

VES	AB/2 (m)	CT	OT (m)	AR (Ωm)	AT (m)	DB (m)	S (mhos)	PC	T (Ωm ²)	RMSE (%)	GP
1	200	H	14.4	153	7.5	14.4	0.049	Poor	1147.5	8.0	Moderate-High
2	200	HK	2.1	89	1.3	36.9	0.015	Poor	115.7	13.4	Low
3	200	H	3.4	35	2.2	29.4	0.063	Poor	77	7.1	High
4	200	A	7.3	446	6.2	25.6	0.014	Poor	2765	2.9	Moderate
5	200	KH	10.1	785	9.7	18.3	0.012	Poor	7614.5	8.8	Moderate

Here CT is the Curve Type, OT- Overburden Thickness (m), AR Aquifer Resistivity (Ωm), AT - Aquifer Thickness (m), DB - Depth to Basement (m), S - Longitudinal Conductance (S) (mhos), PC-

Protective Capacity, T- Transverse Resistance (T) (Ωm²), RMSE - Root Mean Square Error (%) and GP is the Groundwater Potential.

Table 9: Computed Groundwater Potential Index (GPI)

VES	h (m)	$\rho(\Omega m)$	$T(\Omega m^2)$	S (mhos)	OB (m)	GPI	Class
1	7.5	153	1147.5	0.049	14.4	0.558	Moderate-High
2	1.3	89	115.7	0.015	2.1	0.223	Low
3	2.2	35	77	0.063	3.4	0.609	High
4	6.2	446	2765	0.014	7.3	0.336	Moderate
5	9.7	785	7614.5	0.012	10.1	0.500	Moderate

Table 10: Hydrogeophysical Interpretation and Groundwater Potential Assessment Gaba Community, Bwari Area

VES No	CT	WLT (m)	DB (m)	FZP	RDD (m)	TAZ	EYP
1	H	7.5	14.4	Possible	28-35	Weathered layer + upper fractured basement	Moderate-High
2	HK	1.3	36.9	Poorly Developed	40-45	Thin weathered deep fractured zone	Low
3	H	2.2	29.4	Likely Fractured	32-38	Saturated weathered + fractured basement	High
4	A	6.2	25.6	Limited	28-32	Weathered basement	Moderate
5	KH	9.7	18.3	Minor Fracture	22-28	Thick weathered zone	

Where CT – Curve Type, WLT - Weathered Layer Thickness, DB- Depth to Basement (m), FZP- Fractured Zone Presence, RDD- Recommended Drilling Depth (m), TAZ- Target Aquifer Zone, and EYP- Expected Yield Potential.

Discussion

The geo-electric characterization of the subsurface layers (Tables 3–7; Figures 3–7) reveals a heterogeneous, multi-layered structure typical of crystalline basement terrains. Four principal geoelectric units were delineated: topsoil, weathered basement, fractured basement, and fresh basement. This stratification conforms to established hydrogeological models of the Nigerian Basement Complex, where groundwater occurrence is largely restricted to weathered and fractured zones due to negligible primary porosity (Olorunfemi & Fasuyi, 1993; Wright, 1992).

The topsoil layer exhibits resistivity values ranging from 75 to 538 Ωm and is generally thin. These values are characteristic of unconsolidated materials such as lateritic soils and sandy clay, whose electrical properties are controlled by moisture content and clay fraction (Telford et al., 1990). The underlying weathered basement layer shows resistivity values between 35 and 785 Ωm (Table 8), reflecting variations in lithology, degree of weathering, and saturation. The low resistivity value observed at VES 3 (35 Ωm) indicates a clay-rich and water-saturated medium, suggesting favourable aquifer conditions. This is consistent with previous findings that associate low resistivity zones with enhanced groundwater potential in basement terrains (Ezeamaka et al., 2022).

The fractured basement layer, identified in selected VES locations (Tables 5 and 7), exhibits moderate to relatively high resistivity values. Despite this, such zones may constitute productive aquifers where fractures are interconnected and water-filled, thereby enhancing

secondary porosity and permeability (Olorunfemi et al., 1999). In contrast, the fresh basement is characterized by high resistivity values (Tables 3–7), indicating compact and impermeable crystalline rocks that act as hydraulic barriers and define the lower boundary of groundwater occurrence (Keller & Frischknecht, 1966).

The VES curve types identified (Table 8; Figures 3–7)—H, HK, A, and KH—reflect distinct subsurface resistivity distributions and corresponding hydrogeological conditions. H-type curves observed at VES 1 and VES 3 indicate a conductive intermediate layer bounded by more resistive layers, a configuration typical of saturated weathered zones and favourable for groundwater accumulation (Zohdy et al., 1974; Ariyo, 2005). The HK-type curve at VES 2 suggests alternating resistive and conductive layers associated with a thin weathered layer overlying resistive basement, indicating poor groundwater potential. The A-type curve at VES 4 reflects a progressive increase in resistivity with depth, implying limited weathering and reduced aquifer development, consistent with similar basement studies (Adeniji et al., 2013). The KH-type curve at VES 5 indicates a relatively thick weathered layer underlain by resistive basement, suggesting moderate groundwater potential depending on fracture connectivity.

The anomalously high resistivity value of 40,460 Ωm recorded at VES 2 (Table 4) is interpreted as an inversion artefact arising from equivalence and suppression effects in resistivity sounding (Olayinka & Yaramanci, 2000). Such effects occur when thin conductive layers overlie highly resistive formations, resulting in non-unique inversion solutions. The value is therefore considered

representative of fresh basement conditions rather than a true resistivity magnitude, in agreement with similar observations in basement terrain studies (Adamu et al., 2021). The RMS errors, ranging from 2.9% to 13.4%, indicate acceptable model reliability.

The Dar-Zarrouk parameters (Table 8) provide further insight into aquifer characteristics. Longitudinal conductance (S) values range from 0.012 to 0.063 mhos, indicating generally weak aquifer protective capacity. According to established classifications, such values imply limited attenuation of surface contaminants and high vulnerability to pollution (Henriet, 1976; Oladapo & Akintorinwa, 2007). Transverse resistance (T) values vary considerably, reflecting differences in aquifer thickness and resistivity. Higher T values observed at VES 4 and VES 5 suggest relatively greater transmissivity and storage potential; however, this does not necessarily correspond to higher groundwater yield due to variations in saturation and lithology. This underscores the limitation of relying on a single parameter for groundwater evaluation in complex basement terrains (Ekanem & Akpan, 2016).

The integrated Groundwater Potential Index (GPI) model (Table 9) provides a comprehensive evaluation by combining multiple hydrogeophysical parameters. GPI values range from 0.223 to 0.609, indicating significant spatial variability across the study area. VES 3 exhibits the highest groundwater potential (0.609), followed by VES 1 (0.558), due to favourable combinations of moderate aquifer thickness, low resistivity, and relatively higher longitudinal conductance, indicative of saturated weathered zones. In contrast, VES 2 shows the lowest potential due to its thin overburden and poor aquifer development, while VES 4 and VES 5 exhibit moderate potential.

Overall, groundwater occurrence in the study area is controlled by the thickness and saturation of the weathered layer, as well as the presence and connectivity of fractures within the basement. The integration of multiple geophysical parameters through the GPI approach enhances the reliability of groundwater assessment and borehole siting, consistent with recent studies in similar geological settings (Ebele et al., 2024; Osumaje et al., 2024)

CONCLUSION

This study has demonstrated the effectiveness of vertical electrical sounding (VES) in delineating subsurface geoelectric layers and evaluating groundwater potential within a crystalline basement terrain. Four layers: topsoil, weathered basement, fractured basement, and fresh basement were identified, with groundwater occurrence largely confined to the weathered and fractured zones. The results show that aquifer development is primarily controlled by the thickness and saturation of the weathered layer, as well as fracture connectivity within

the basement. Low resistivity values and moderate overburden thickness, particularly at VES 3 and VES 1, indicate favourable groundwater conditions, whereas thin overburden and resistive formations correspond to poor potential zones, as observed at VES 2.

The Dar-Zarrouk parameters reveal generally weak aquifer protective capacity, suggesting high vulnerability to surface contamination. However, variations in transverse resistance highlight differences in transmissivity across the study area. The integrated Groundwater Potential Index (GPI) model further enhances interpretation by combining multiple parameters, providing a more reliable assessment of groundwater potential.

Overall, the study establishes that the integration of geophysical parameters through the GPI approach offers a robust framework for groundwater evaluation and borehole siting in basement complex terrains. The findings provide valuable guidance for sustainable groundwater development in the study area and similar geological settings.

RECOMMENDATIONS

It is recommended that borehole drilling be preferentially located around VES 3 and VES 1, targeting depths between 28 m and 35 m to ensure penetration into the fractured basement zone. Future investigations should integrate geophysical methods with hydrogeological and pumping test data to further validate aquifer productivity and sustainable yield.

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