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Deployment of Electrical Resistivity Method for Evaluation of Sustainable Groundwater Resources in Lapai, Niger State, Nigeria

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ABSTRACT
Groundwater accessibility in basement complex terrains is governed by the hydraulic properties of weathered and fractured aquifer systems. Despite growing demand driven by rapid urbanisation, systematic hydrogeophysical characterisation of such aquifers remains limited across central Nigeria. This study deployed the Schlumberger vertical electrical sounding (VES) technique using the SYSCAL Pro resistivity meter (IRIS Instruments, France) at twelve stations to evaluate the groundwater potential of Lapai, Niger State, underlain by the migmatite-gneiss basement complex. Acquired data were processed through partial curve-matching and computer-assisted iterative inversion to determine subsurface resistivity distribution, aquifer depth, and groundwater prospectivity. All interpreted VES curves exhibit the H-type configuration ($\rho_1 > \rho_2 < \rho_3$), confirming a three-layer subsurface model. The uppermost lateritic layer ranges in thickness from 2 to 6 metres. The second layer, with resistivity values of 60–140 Ωm occurring at depths of 2–23 metres, is interpreted as a saturated weathered basement aquifer. The third layer represents fresh, locally fractured basement encountered at depths of 30–60 metres, constituting a secondary aquifer target. The study concludes that sustainable groundwater development is technically feasible through boreholes drilled to approximately 70 metres, targeting both the weathered and fractured basement aquifer units.

INTRODUCTION

The provision of safe and reliable potable water remains one of the most consequential developmental challenges confronting rural and peri-urban communities in sub-Saharan Africa. Nigeria continues to record an unacceptably high incidence of waterborne morbidity attributable to dependence on shallow, unprotected water sources across its central basement complex zone. Lapai, the administrative headquarters of Lapai Local Government Area in Niger State, exemplifies this predicament: a rapidly expanding population in excess of infrastructure capacity has rendered systematic geophysical aquifer delineation both an urgent scientific priority and a practical prerequisite for any viable water supply programme.

The basement complex of central Nigeria is underlain by Precambrian crystalline rocks — principally migmatitic gneisses, granites, schists, and quartzites — that are inherently devoid of primary porosity and permeability (Rahaman, 1976). Groundwater occurrence in such geological settings is exclusively governed by secondary porosity features: the weathered residual overburden (regolith) and the networks of tectonic fractures and joints penetrating the competent rock below (Dada, 2006; Jones & Hockey, 1964). The hydraulic productivity of any borehole drilled into this environment is a function of the thickness, lateral continuity, and degree of saturation of these secondary structures — characteristics that cannot be established from surface geology alone and that necessitate prior geophysical investigation (Olayinka, 1996).

The Schlumberger vertical electrical sounding (VES) technique has been established over several decades as the most cost-effective method for hydrogeophysical characterisation of basement complex terrains in Nigeria (Olayinka & Yaramanci, 2000; Olorunfemi & Fasuyi, 1993; Oyedele et al., 2009). By measuring the variation of apparent resistivity with progressively increasing electrode separation, VES surveys provide quantitative estimates of true layer resistivities, thicknesses, and depths (Telford et al., 1990). Previous investigations in comparable Niger State settings include studies at Minna (Obiora & Ibuot, 2018) and Bida (Batagarawa & Onoduku, 2014), yet comparable data for the Lapai area have not previously been reported, constituting a significant gap in the regional hydrogeophysical database.

This investigation was undertaken to address that gap. The specific objectives were: (i) to establish the geoelectric stratigraphy at twelve VES stations distributed across the Lapai area; (ii) to derive three-layer resistivity models for each station through partial curve-matching and iterative forward-model inversion; (iii) to classify each VES response by curve type and characterise the subsurface hydrogeological regime; (iv) to construct an apparent resistivity pseudo-section illustrating the lateral continuity and depth variation of aquifer horizons; and (v) to assess groundwater prospectivity and derive evidence-based borehole siting recommendations.

Geology and Study Area

Lapai is situated in the southern sector of Niger State, central Nigeria, within the coordinate range of latitudes 8°52′N to 9°05′N and longitudes 6°28′E to 6°42′E. The area falls within the North Central Basement Complex Province of Nigeria, which constitutes part of the Pan-African mobile belt and is characterised by Precambrian crystalline rocks of the migmatite-gneiss suite (Kearey et al., 2002). The suite was subjected to multiple phases of metamorphism and tectonic deformation during the Pan-African orogeny at approximately 600 Ma, generating the networks of fractures and shear zones that represent the principal secondary porosity conduits for groundwater storage and transmission.

The dominant lithologies at outcrop are migmatitic gneisses, granitic gneisses, pelitic schists, and quartzites, intruded by younger granite and pegmatite. The basement is mantled by a variably developed lateritic and sandy residual overburden produced by prolonged tropical chemical weathering. The climate is characterised by a wet season from May to October and a dry season from November to April, with mean annual rainfall of approximately 1,100 mm. Drainage is directed broadly eastward through minor tributaries of the Gbako River, a sub-catchment of the River Niger.

MATERIALS AND METHODS

Field Acquisition

Twelve VES stations were established at strategic locations across the study area to ensure representative coverage of the principal geomorphological and geological units. The Schlumberger electrode configuration was adopted for all soundings, with current electrodes (C_1C_2) expanded symmetrically about a fixed centre point and potential electrodes (P_1P_2) repositioned at prescribed intervals to maintain an adequate signal-to-noise ratio. Current electrode half-spacing (AB/2) was extended progressively from 1 m to 100 m, providing a theoretical depth of investigation of approximately 70–90 m below ground surface (Barker, 1989), sufficient to intersect the weathered and fractured basement aquifer horizons.

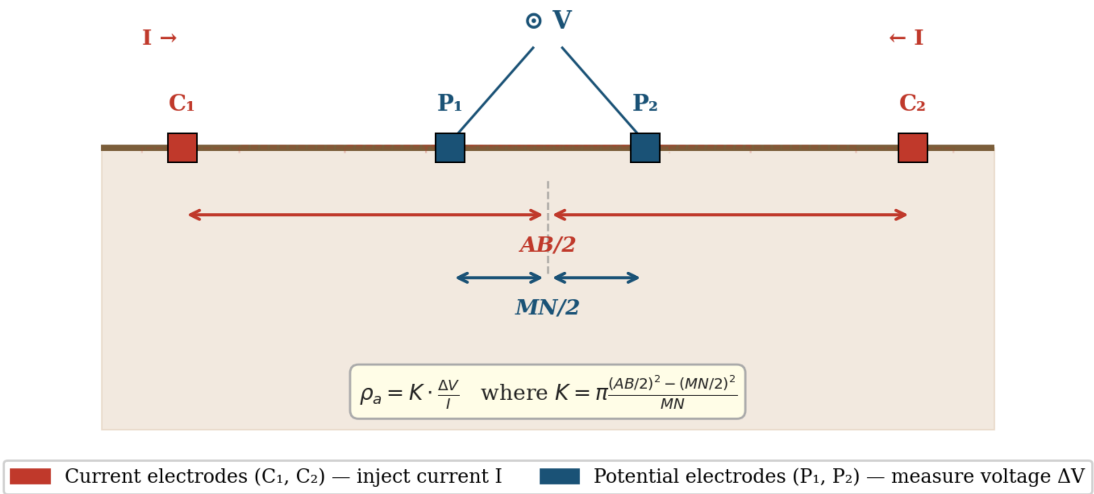


Figure 1: Schematic representation of the Schlumberger electrode array showing current electrodes (C_1, C_2) and potential electrodes (P_1, P_2), the half-spacings AB/2 and MN/2, and the geometric factor K used to compute apparent resistivity. Modified after Telford et al. (1990)

Apparent resistivity was computed at each measurement step from the standard Schlumberger relationship (Telford et al., 1990):

$$\rho_a = K \cdot (\Delta V / I) \qquad (1)$$

where $K = \pi[(AB/2)^2 - (MN/2)^2] / MN$ is the Schlumberger geometric factor, ΔV is the measured potential difference between the potential electrodes, and I is the injected current. (Telford et al., 1990). The SYSCAL Pro resistivity meter (IRIS Instruments, France) was employed throughout, providing high-precision digital data recording. GPS coordinates were acquired at each station for spatial referencing.

Data Processing and Inversion

Field apparent resistivity data were plotted as bilogarithmic curves of ρ_a against AB/2 and subjected to preliminary qualitative interpretation by partial curve-matching, using standard two-layer master curves and auxiliary charts following the procedure of Orellana and Mooney (1966). The resulting initial estimates served as starting models for computer-assisted iterative least-squares inversion using IPI2Win (Bobachev et al., 2003), which minimises the root-mean-square misfit between observed and theoretically computed apparent resistivity curves.

Theoretical forward-model curves were computed from the interpreted three-layer parameters using the recursive Koefoed kernel (Koefoed, 1979):

$$\rho_a(L) = L^2 \int[T(k) - \rho_1]\, J_1(kL)\, k\, dk + \rho_1 \qquad (2)$$

where T(k) is the upward-propagating impedance kernel, J_1 is the Bessel function of the first kind of order one, and L denotes AB/2 (Koefoed, 1979). These theoretical curves are presented alongside the field data in Figures 2 and 3, affording a direct visual assessment of inversion quality.

Curve Type Classification and Groundwater Prospectivity

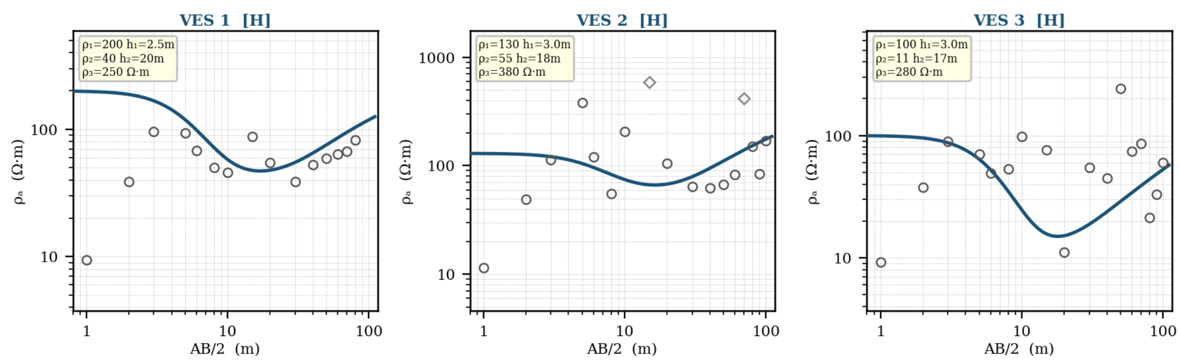
Each accepted three-layer inversion model was classified according to the relative magnitudes of the interpreted true layer resistivities: H-type ($\rho_1 > \rho_2 < \rho_3$), A-type ($\rho_1 < \rho_2 < \rho_3$), K-type ($\rho_1 < \rho_2 > \rho_3$), and Q-type ($\rho_1 > \rho_2 > \rho_3$) (Koefoed, 1979; Telford et al., 1990). Groundwater prospectivity (GWP) was assessed from the resistivity and thickness of Layer 2 for H/HA-type stations, and from the depth and resistivity of Layer 3 for K-type stations, following Olorunfemi and Fasuyi (1993).

RESULTS AND DISCUSSION

Apparent Resistivity Data and Field Curve Quality

Tables 1(a) and 1(b) present the measured apparent resistivity values for VES 1–6 and VES 7–12, respectively, at the full range of electrode spacings employed. One definitive data outlier was identified: VES 9 recorded ρ_a = 7,130 Ωm at AB/2 = 5 m, a value two full orders of magnitude above both the preceding measurement (282 Ωm at AB/2 = 3 m) and the succeeding measurement (99 Ωm at AB/2 = 6 m). This anomalous reading is attributed to a localised near-surface electrical heterogeneity and was excluded from inversion; it is denoted by an asterisk in Table 1(b). Additional suspicious readings at VES 2, VES 8, and VES 11 are retained but flagged † and were assigned reduced inversion weight.

The individual VES sounding curves for all twelve stations are presented as bilogarithmic panels in Figures 2 and 3, with observed field data shown as open circles and the theoretical forward-model curves as coloured lines. Figure 5 presents all twelve theoretical curves together, grouped by curve type.



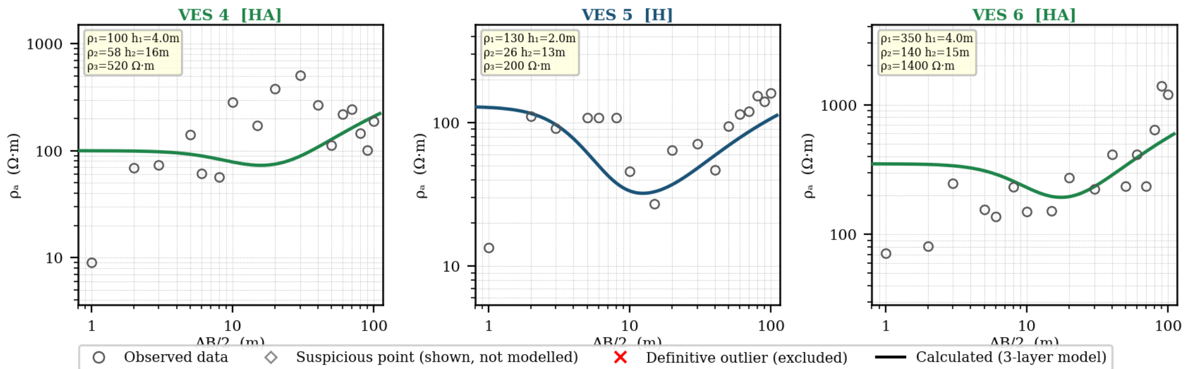


Figure 2: Schlumberger VES sounding curves for stations 1–6. Open circles = observed apparent resistivity; coloured lines = theoretical three-layer forward-model curves. Grey diamonds denote measurements assigned reduced inversion weight. The H-type conductive trough is resolved in the model curves for all six stations

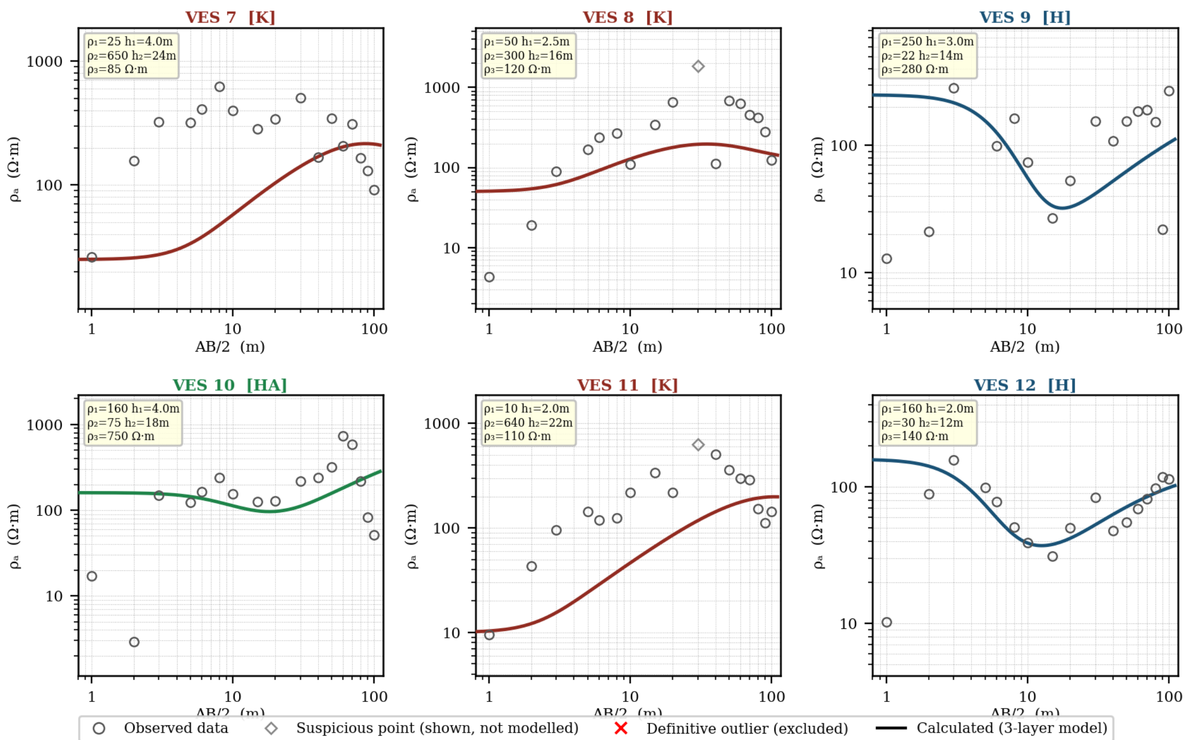


Figure 3: Schlumberger VES sounding curves for stations 7–12. Red dotted lines (VES 7, 8, 11) represent K-type models. The definitive outlier at VES 9 (AB/2 = 5 m; ρ_a = 7,130 Ωm) is marked × and excluded from display

Table 1(a): Measured apparent resistivity (Ωm) for VES stations 1–6

AB/2 (m)	VES 1	VES 2	VES 3	VES 4	VES 5	VES 6
1	9.4	11.5	9.2	9.0	13.4	71.1
2	38.7	49.2	37.5	68.9	110.3	81.0
3	96.2	112.9	89.5	73.1	91.7	247.0
5	93.3	379.8	70.4	140.6	107.8	155.5
6	67.8	121.3	49.0	61.4	108.6	137.2
8	50.1	55.3	53.6	57.2	108.6	232.0
10	46.0	207.0	98.8	284.8	46.0	149.0
15	87.6	588†	76.7	173.0	27.1	151.0
20	55.0	106.0	11.1	380.8	64.0	275.0
30	38.6	64.0	54.4	507.0	71.0	224.7

40	53.0	62.0	45.0	267.4	47.0	412.0
50	59.0	67.0	241.3	113.0	94.7	235.8
70	67.0	418.9†	86.0	244.7	119.9	234.4
80	82.4	150.0	21.2	145.0	154.3	642.4
100	—	170.6	60.0	190.0	161.4	1196.1

† Suspicious measurement retained; assigned reduced inversion weight. "—" denotes measurement not taken

Table 1(b): Measured apparent resistivity (Ωm) for VES stations 7–12

AB/2 (m)	VES 7	VES 8	VES 9	VES 10	VES 11	VES 12
1	26.1	4.3	13.0	17.2	9.6	10.3
2	157.3	18.9	21.0	2.9	43.5	88.6
3	322.3	88.9	282.0	149.1	96.3	158.4
5	320.7	169.2	(7130)*	123.0	144.3	99.8
6	407.7	238.8	99.0	163.1	118.3	77.8
8	622.9	270.0	164.0	237.6	125.0	51.0
10	400.1	110.0	74.0	155.5	217.9	39.0
15	282.5	342.2	27.0	126.5	337.5	31.0
20	343.3	654.4	53.0	127.0	219.8	50.0
30	503.8	1870.7†	155.0	219.0	627.2†	84.0
40	167.0	112.0	108.0	241.0	505.0	48.0
50	345.0	688.0	155.0	316.0	362.1	55.0
70	311.0	460.0	190.0	584.0	288.0	82.0
80	166.0	417.8	153.3	219.0	151.7	98.0
100	91.4	123.8	269.6	51.0	143.7	114.0

* Definitive outlier excluded from inversion. † Suspicious measurement: retained, reduced inversion weight

Geoelectric Layer Models and Curve Classification

Of the twelve stations interpreted, nine yield three-layer H or HA-type models and three yield K-type models, consistent with the basement complex hydrogeological framework documented by Olorunfemi and Fasuyi (1993) and Olayinka and Yaramanci (2000). For the nine H and HA-type stations, the theoretical model curves unambiguously display the diagnostic conductive trough — a reduction in ρ_a at intermediate electrode spacings reflecting the transition from the resistive lateritic Layer 1 into the conductive saturated weathered Layer 2, followed by a recovery as the current volume expands to encompass the more resistive basement Layer 3. This trough is most strongly expressed at VES 3 and VES 5, where Layer 2 resistivity values of 11 and 26 Ωm, respectively, produce a marked minimum in the apparent resistivity curve.

The K-type classification of VES 7, 8, and 11 is directly demonstrated by the raw apparent resistivity measurements. At VES 7, the apparent resistivity increases monotonically from 26.1 Ωm at AB/2 = 1 m to a peak of 622.9 Ωm at AB/2 = 8 m, thereafter declining consistently to 91.4 Ωm at AB/2 = 100 m — the K-type signature of a resistive intermediate Layer 2 (ρ_2 = 650 Ωm) overlying a more conductive Layer 3 (ρ_3 = 85 Ωm). Analogous behaviour is confirmed at VES 8 and VES 11. In all three K-type stations, Layer 2 is interpreted as a dry, compacted laterite horizon (duricrust) that has impeded downward percolation of meteoric water and precluded development of a productive saturated weathered zone.

Pseudo-Section Analysis

The apparent resistivity pseudo-section (Figure 4) provides a spatially integrated representation of the subsurface resistivity structure across the twelve-station transect. A laterally persistent low-resistivity zone (blue–green tones) is evident at pseudo-depths corresponding to AB/2 values of approximately 8–30 m beneath the H and HA-type stations. The white dashed line at mean $D_2 \approx 19$ m demarcates the mean depth to the base of the weathered zone — the minimum recommended borehole penetration depth for the H/HA-type station group. The broad lateral continuity of the low-resistivity band beneath the H/HA-type stations suggests that the saturated weathered basement constitutes a regionally connected aquifer system of significance for community-scale water supply planning.

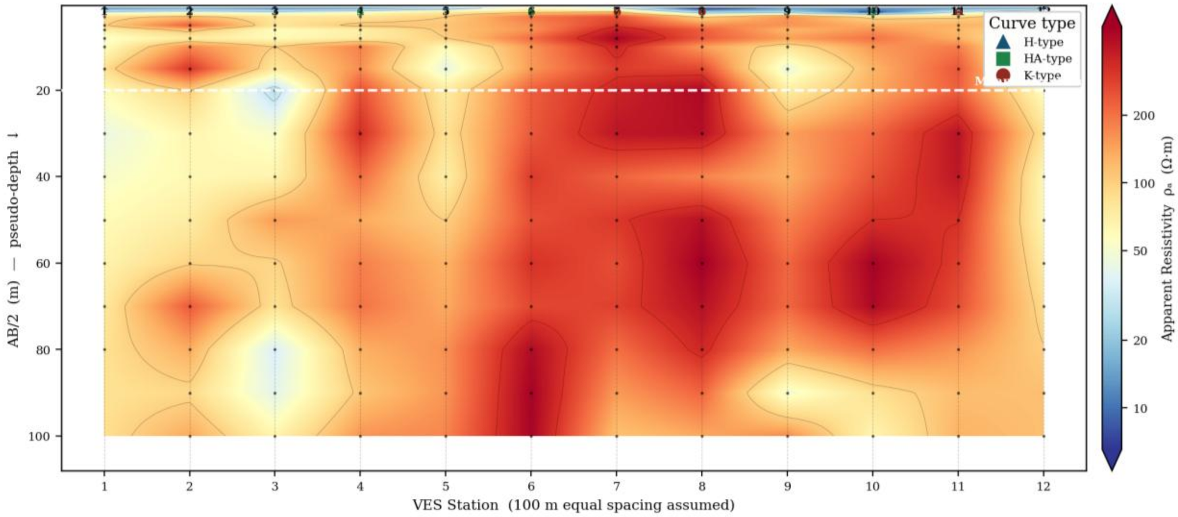


Figure 4: Apparent resistivity pseudo-section for all twelve VES stations. Colour scale: blue–green = conductive (saturated weathered aquifer); yellow–red = resistive (overburden or dry intermediate layer). White dashed line: mean $D_2 \approx 19$ m

Groundwater Prospectivity Assessment

Table 2 presents the full suite of interpreted geoelectric parameters and GWP ratings for all twelve stations. VES 6 is classified as very good: Layer 2 resistivity of 140 Ωm (low clay, high hydraulic conductivity), 15 m saturated thickness, and exceptionally resistive fresh basement (ρ_3 = 1,400 Ωm). VES 4 and VES 10 are classified as good (Layer 2 thicknesses of 16–18 m; ρ_2 = 58–75 Ωm). The three K-type stations (VES 7, 8, 11) require boreholes penetrating at least 10 m into Layer 3, implying target depths of 30–40 m.

Table 2: Interpreted three-layer geoelectric parameters and groundwater prospectivity (GWP) for all twelve VES stations

VES	h_1 (m)	ρ_1 (Ωm)	h_2 (m)	ρ_2 (Ωm)	D_2 (m)	ρ_3 (Ωm)	Curve	GWP
1	2.5	200	20	40	22.5	250	H	Good
2	3.0	130	18	55	21.0	380	H	Good
3	3.0	100	17	11	20.0	280	H	Moderate
4	4.0	100	16	58	20.0	520	HA	Good
5	2.0	130	13	26	15.0	200	H	Moderate
6	4.0	350	15	140	19.0	1400	HA	Very Good
7	4.0	25	24	650	28.0	85	K	Moderate
8	2.5	50	16	300	18.5	120	K	Moderate
9	3.0	250	14	22	17.0	280	H	Good
10	4.0	160	18	75	22.0	750	HA	Good
11	2.0	10	22	640	24.0	110	K	Moderate
12	2.0	160	12	30	14.0	140	H	Moderate

h_1, ρ_1 = Layer 1 thickness (m) and resistivity (Ωm); h_2, ρ_2 = Layer 2 thickness and resistivity; $D_2 = h_1+h_2$ = depth to base of weathered zone (m); ρ_3 = Layer 3 resistivity; H: $\rho_1>\rho_2<\rho_3$; HA: H-type with $\rho_3>4\rho_1$; K: $\rho_1<\rho_2>\rho_3$; GWP: Very Good = HA, ρ_2>100 Ωm; Good = H/HA, ρ_2=40–100 Ωm; Moderate otherwise

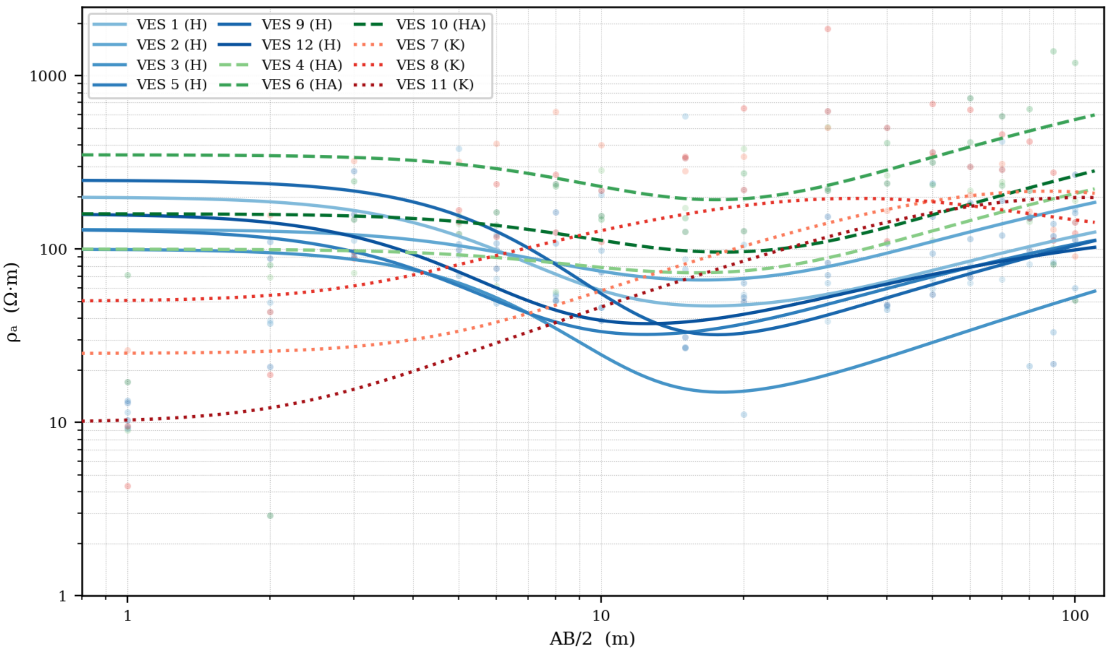


Figure 5: Composite VES curves for all twelve stations. Faded dots = observed field data; bold lines = theoretical model curves. Solid blue = H-type; dashed green = HA-type; dotted red = K-type.

Discussion

The hydrogeological framework delineated in this study is broadly consistent with that reported for comparable basement complex settings elsewhere in Niger State (Batagarawa & Onoduku, 2014; Obiora & Ibuot, 2018) and across the broader West African Precambrian basement province (Olayinka & Yaramanci, 2000; Olorunfemi & Fasuyi, 1993). The dominant occurrence of H and HA-type curve responses — nine of twelve stations — confirms the prevalence of a conductive saturated weathered basement as the principal aquifer type, consistent with the geological history of tropical chemical weathering in the Pan-African basement complex (Dada, 2006; Rahaman, 1976). The range of Layer 2 resistivity values (11–140 Ωm) reflects the spatial heterogeneity of the weathering profile typical of Nigerian basement complex terrains subjected to differential lateritisation.

The identification of three K-type stations constitutes a hydrogeologically significant finding: any borehole drilled at VES 7, 8, or 11 that targets Layer 2 would encounter the high-resistivity dry duricrust and return a non-productive hole. This risk is entirely avoidable through prior VES investigation (Olayinka, 1996). The lateral continuity of the weathered aquifer established by the pseudo-section supports a multi-borehole abstraction strategy for the H/HA-type zones, provided pumping rates are managed to avoid interborehole hydraulic interference. Hydrochemical sampling will be necessary to characterise water quality before commissioning for potable water supply.

CONCLUSION

This investigation has demonstrated the scientific efficacy of the Schlumberger vertical electrical sounding technique as a hydrogeophysical characterisation tool in the basement complex terrain of Lapai, Niger State. Twelve VES stations were deployed, and three-layer resistivity models derived through partial curve-matching and IPI2Win inversion were verified by independently computed theoretical forward-model curves.

(i) In direct fulfilment of Objectives i and ii, nine of twelve stations yield H or HA-type models confirming a conductive saturated weathered basement (Layer 2) as the primary groundwater target, with Layer 2 resistivity values of 11–140 Ωm, thicknesses of 12–22 m, and depths to the base of the weathered zone (D_2) of 14–22.5 m. Three stations (VES 7, 8, 11) yield K-type models in which the productive aquifer is restricted to the fractured basement Layer 3, at D_2 depths of 18.5–28 m. (ii) Addressing Objective iv, the apparent resistivity pseudo-section confirms the lateral continuity of the weathered aquifer beneath the H/HA-type stations and clearly delineates the K-type zones. (iii) Pursuant to Objective v, VES 6 constitutes the highest-priority borehole siting target, with very good groundwater prospectivity. Boreholes to approximately 70 m are recommended at H/HA-type stations; boreholes of 30–40 m depth are prescribed at K-type stations to penetrate the productive fractured basement.

This study makes an original contribution to the knowledge base by providing the first systematic geoelectric characterisation of the subsurface hydrogeological framework of Lapai, Niger State — a scientifically significant gap that has previously impeded evidence-based borehole siting decisions. The identification of K-type geoelectric responses at three stations, and the demonstration that these stations carry high borehole failure risk, constitutes actionable intelligence of direct relevance to Niger State water resources planning authorities and community water supply programmes. The geoelectric dataset generated provides a reusable baseline for integrated hydrogeophysical investigations in the region.

The authors acknowledge limitations inherent to a VES-based investigation conducted without complementary geophysical methods. The one-dimensional nature of the Schlumberger VES technique assumes horizontal layering and cannot resolve lateral geological discontinuities within the inter-station spacing. The interpreted layer models have not been ground-truthed against borehole lithological logs or pumping test data, and the absence of hydrochemical analysis means that groundwater quality remains uncharacterised. Future investigations should integrate the present VES dataset with two-dimensional electrical resistivity tomography (ERT), induced polarisation (IP) surveys, electromagnetic (EM) methods, hydrochemical profiling, and borehole geophysical logging, to provide a comprehensive, validated characterisation of the Lapai aquifer system adequate for sustainable water resource management.

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