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Integrated Geophysical Appraisal of Groundwater Potential in a Crystalline Basement Terrain Using Vertical Electrical Sounding: A Case Study from Chikun and Environs, North-Central Nigeria

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Abstract

This study conducts a detailed geophysical assessment of groundwater potential in the crystalline basement terrain of Chikun and its environs in North-Central Nigeria, employing the Vertical Electrical Sounding (VES) technique. The region is geologically characterized by porphyritic granite, granitic gneiss, and mica schist, which exhibit varying degrees of weathering and fracturing—key factors influencing groundwater accumulation and movement. A total of fifteen VES stations were surveyed within the Kakuri Sheet 144 NW, revealing four to six distinct geo-electric layers. These layers include topsoil, sandy clay, consolidated sand, highly weathered basement, slightly weathered basement, and fresh basement rock. Resistivity values recorded across the area ranged from 195.3 to 604.4 Ωm. Zones with lower resistivity were interpreted as water-saturated layers, indicative of potential aquifer units. Notably, VES points 1, 2, 5, 8, 9, 13, and 15 displayed favorable geoelectrical characteristics for groundwater development, making them suitable candidates for borehole drilling. The fractured and weathered basement units constitute the primary aquifer zones, providing a dependable source of groundwater within this otherwise low-permeability hard rock environment. The findings affirm the effectiveness of VES as a non-invasive, cost-efficient method for delineating subsurface hydrogeological structures and identifying viable groundwater zones. This integrated geophysical approach not only enhances groundwater exploration and development in the study area but also offers a practical and replicable model for similar crystalline basement terrains across sub-Saharan Africa—especially in regions facing seasonal water scarcity and increasing demand for sustainable water supply.

Keywords
Groundwater potential,
Vertical electrical sounding,
Crystalline basement,
Geo-electric layers,
Chikun, Nigeria

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INTRODUCTION

In many developing regions, particularly those underlain by crystalline basement rocks, the quest for reliable and sustainable sources of potable water has become an increasingly urgent challenge due to population growth, climatic variability, and uneven surface water distribution. Groundwater, which resides in the pore spaces and fractures of geologic formations, represents a vital source of freshwater globally. Its strategic importance is even more pronounced in semi-arid and hard rock terrains where surface water bodies are either seasonal or completely absent (Muchingami et al., 2021; Gaikwad et al., 2021).

In such settings, the accurate delineation of aquifer zones becomes paramount for efficient water resource development. Basement complex terrains, characterised by low porosity and permeability in their fresh state, typically depend on secondary porosity induced through weathering and fracturing to host economically viable aquifers (Olatinsu & Salawudeen, 2021; Adabanija et al., 2021). However, aquifer development in such environments is not uniform and relies heavily on the degree of weathering, structural deformation, and lithological variation within the subsurface. Consequently, a detailed understanding of these subsurface characteristics is essential to avoid failed boreholes and optimise groundwater development strategies.

In North-Central Nigeria, specifically in Chikun and its environs within the Kakuri Sheet 144 NW, these challenges are compounded by inconsistent and poorly documented hydrogeological investigations. The region is predominantly underlain by Precambrian crystalline rocks such as mica schist, porphyritic granite, and granitic gneiss (Aboh, 2009; Jatau & Ajodo, 2005). Due to recurring dry seasons, increasing anthropogenic activities, and inadequate surface water retention, the dependence on groundwater resources has escalated dramatically over the past decades. However, existing borehole failure rates and shallow wells that dry up seasonally highlight the pressing need for systematic geophysical appraisal of the subsurface.

To address these concerns, this study applies Vertical Electrical Sounding (VES), a non-invasive, cost-effective, and reliable method within the electrical resistivity framework, to characterise the groundwater potential of the Chikun crystalline basement terrain. The Schlumberger electrode configuration, noted for its superior depth of penetration and reduced lateral sensitivity, was employed to provide a high-resolution image of the subsurface layering, resistivity contrasts, and aquifer-bearing horizons.

The integration of geological mapping with VES interpretations aims to not only delineate geoelectric layers but also to evaluate their water-bearing capacities based on resistivity signatures and depth distributions. This multidisciplinary approach has proven successful in similar basement terrains across Africa and Asia (Ifeanyichukwu et al., 2021; Gobashy et al., 2021; Shang et al., 2021), offering insights into aquifer geometry, hydrostratigraphy, and fracture connectivity.

The anticipated outcomes will be instrumental in siting productive boreholes, reducing exploration risks, and supporting sustainable water supply systems in the study area. Thus, this study not only contributes to the geophysical and hydrogeological understanding of the Chikun area but also provides a reproducible methodological framework for groundwater exploration in analogous basement settings within sub-Saharan Africa and beyond.

Local Geology and Structures of the Study Area

The study area lies within the Precambrian Basement Complex of North-Central Nigeria (Ijaleye et al. 2020; Ayuba et al. 2024; Adamu et al. 2024a, 2024b, 2021; Odey et al. 2024a, 2024b) and is underlain by three principal lithologies: mica schist, porphyritic granite, and granitic gneiss. These rocks are typical constituents of the Nigerian schist belt (Rahaman, 1988; Adoze et al. 2024; Adamu et al. 2024a; Umar et al. 2022; Umaru et al. 2020). Field mapping reveals that mica schist dominates the central and western zones, granitic gneiss appears in the southeast, while porphyritic granite prevails in the northwestern sector. The granitic gneiss is well foliated and coarse-grained, trending north-south, while the porphyritic granite exhibits leucocratic texture, pronounced jointing, and an NW structural orientation (Fig. 1 and 2).

Mica schist exposures exhibit quartz veins and pegmatite intrusions, with observable foliation, folding, and fractures—structural features vital to groundwater accumulation. The regional structural trend follows a NE–SW alignment, confirmed by joint patterns and mapped lineaments such as faults and valleys (Mabee et al., 1994; Goki et al., 2011). These structures control fluid movement and the anisotropic flow of groundwater. High intersection density enhances aquifer connectivity and recharge potential, especially within weathered and fractured bedrock zones (Odey et al., 2024a and 2024b).

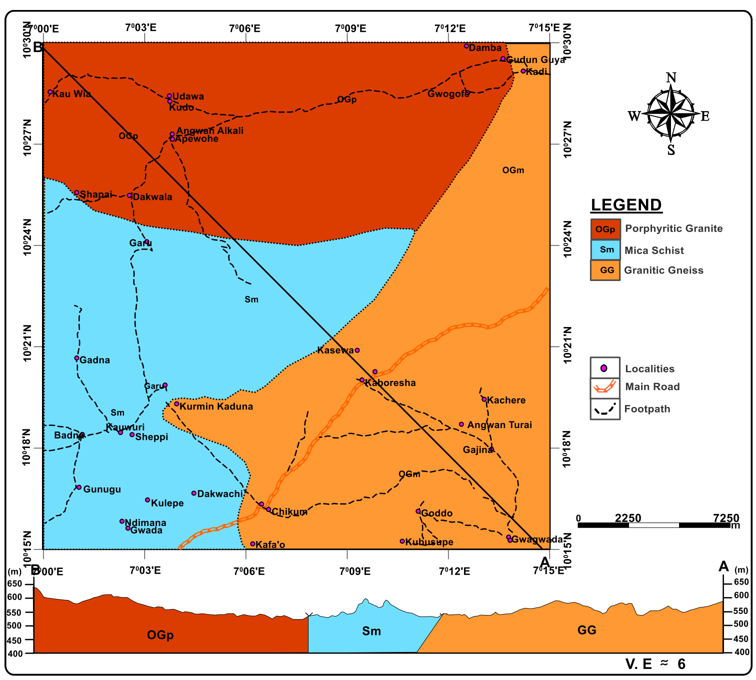

Figure 1: Geologic map of the study area

Figure 2. (a) Outcrop exposure and photomicrograph **in XPL** of granitic gneiss east of Gudun Guya (N10° 29' 18.5" and E007° 12' 42.3"), (b) Outcrop exposure and photomicrograph **in XPL** of Porphyritic granite outcrop in Damba 2(N10° 29' 26.1" and E007° 12' 43.0"), (c) Outcrop exposure and photomicrograph **in XPL** of mica schist at Kulepe northeast of Ndimana (N10° 16' 39.3" and E007° 3' 00.5")

2. MATERIALS AND METHODS

2.1 Location and Accessibility

The study area lies within latitudes 10°15′–10°30′N and longitudes 7°00′–7°15′E, covering approximately 733.86 km² in Chikun Local Government Area of Kaduna State, North-Central Nigeria (Fig. 3). It falls within the Kakuri Topographic Sheet 144 NW and is accessible via the Kaduna–Abuja highway and the Buruku–Birnin Gwari–Lagos road. A network of footpaths and livestock tracks further enhances ground access to the site (Muchingami et al., 2021; Ifeanyichukwu et al., 2021; Odey et al. 2024a, 2024b).

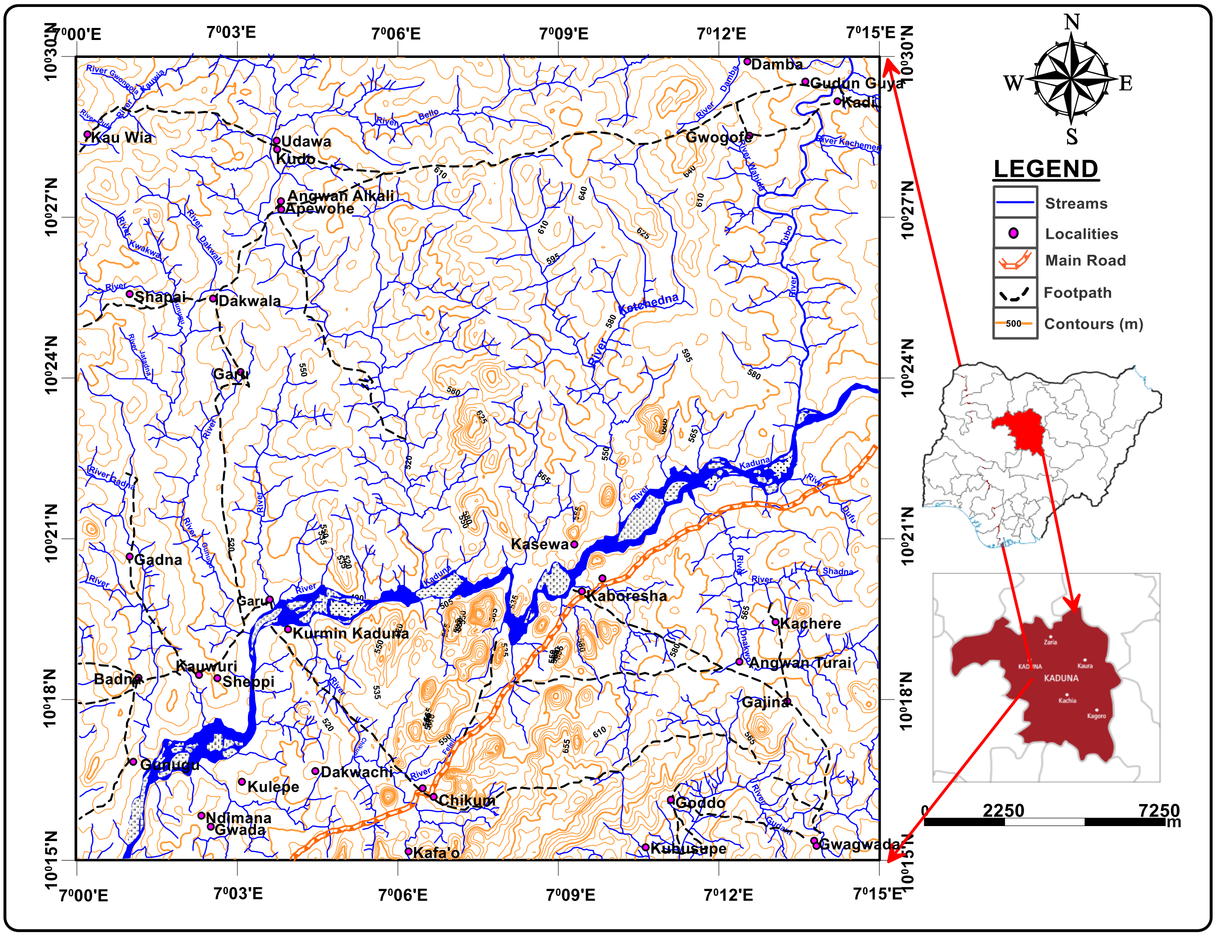

Figure 3. Location and accessibility map of the study area

2.2 Geophysical Survey Design

The Schlumberger electrode configuration was adopted for vertical electrical sounding (VES) due to its superior depth penetration and reduced sensitivity to lateral inhomogeneities (Gaikwad et al., 2021). A total of fifteen VES stations were established, spaced approximately 200 m apart. For each VES, the current electrode spacing (AB/2) ranged from 1.5 m to a maximum of 70 m, while the potential electrode spacing (MN/2) was varied at 0.5 m, 1.5 m, and 7.5 m. Electrical current was introduced through two outer electrodes, while the resulting voltage differences were recorded between the inner pair. Data acquisition involved repeated measurements and periodic calibration every 20–30 minutes to minimise the influence of subsurface inhomogeneities. This ensured higher resolution and data reliability for accurate geo-electric layer delineation and hydrogeological interpretation (Adabanija et al., 2021; Olatinsu & Salawudeen, 2021). The processed data were interpreted using standard curve-matching techniques, supplemented with computer-aided inversion models, allowing precise estimation of layer resistivity and thickness. The survey methodology successfully enabled identification of water-bearing horizons and structural features associated with groundwater accumulation within the crystalline basement terrain.

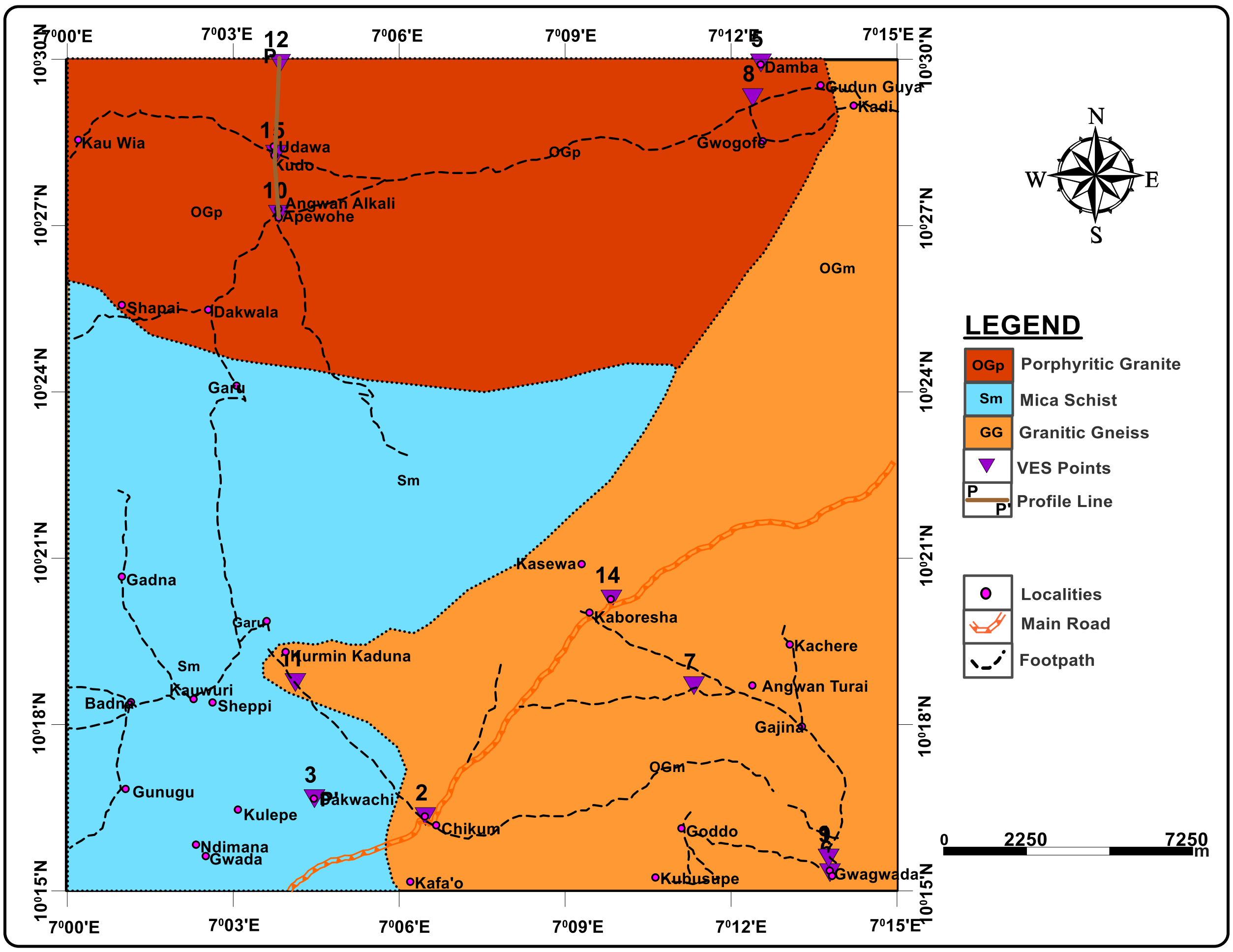

Figure 4. Geologic map with VES points in the study area

3. RESULTS AND DISCUSSION

The vertical electrical sounding (VES) investigation conducted across Chikun and its environs within the Kakuri Sheet 144 NW revealed a complex subsurface characterised by a sequence of four to six distinct geoelectric layers. These include the topsoil, sandy clay, consolidated sand, highly weathered basement, partially weathered/fractured basement, and fresh basement (Table 1). This geoelectric configuration reflects the heterogeneous lithological setting and structural disposition typical of crystalline basement terrains (Muchingami et al., 2021; Adabanija et al., 2021).

The topmost layer—comprising loose lateritic soils—exhibited relatively high resistivity values averaging 391.0 Ωm. This layer, generally unsaturated, represents the vadose zone and varies in thickness from approximately 0.5 m to 2.3 m. Beneath it lies the regolith (sandy clay) layer, with resistivity values around 291.0 Ωm and an average thickness of 7.51 m. This unit is of particular hydrological importance, as it forms part of the weathered zone known for its water retention capabilities (Gaikwad et al., 2021; Olatinsu & Salawudeen, 2021).

The third layer, identified as consolidated sand, is moderately resistive (204.1 Ωm) and saturated, signifying its aquiferous nature. It serves as the principal groundwater-bearing formation, particularly where overlain by the regolith and underlain by weathered or fractured basement.

In several VES locations (e.g., VES 1, 2, 5, 9, and 13), this layer extends to depths of 22.12 m and reflects favourable aquifer conditions (Adabanija et al., 2021). The fourth and fifth layers—highly weathered and partially weathered/fractured basement—exhibit resistivity ranges from 200 Ωm to 427 Ωm. Their hydrological potential is strongly influenced by the degree of fracturing and the presence of clay materials. The highly weathered zone (average 262.6 Ωm) contributes significantly to groundwater yield, especially in VES 8 and VES 15, where its thickness exceeds 10 m. In contrast, the slightly weathered/fractured basement layer, while less porous, still facilitates groundwater transmission when well-jointed (Ifeanyichukwu et al., 2021).

At the base, the fresh basement manifests as a resistive horizon (>604.4 Ωm) with minimal to no groundwater potential due to its crystalline, impermeable nature. It represents the limiting boundary for vertical groundwater migration. This lithological boundary typically occurs at depths ranging from 30.85 m to 87.50 m, depending on the VES location. A synthesis of the resistivity data from all fifteen VES points (Table 2; Fig. 7 and 8) indicates a clear spatial variation in subsurface layering. Three of the sites revealed four layers, seven sites showed five layers, four exhibited six, and one site presented seven distinguishable layers. These variations reflect localised geological influences and the degree of weathering and fracturing—a critical factor in groundwater potential (Gobashy et al., 2021).

The geophysical interpretation revealed that borehole siting is most viable in locations such as VES 1, 2, 5, 8, 9, 13, and 15, where resistivity values fall between 195.3 and 215.1 Ωm—indicative of saturated weathered or fractured zones. Similarly, moderate groundwater prospects exist in VES 3, 4, 6, 7, 10, 11, 12, and 14, with resistivity values between 213.3 and 259.0 Ωm. These are attributed to semi-confined aquifers that may respond well to borehole development, albeit with seasonal yield fluctuations (Shang et al., 2021). Pumping test observations further corroborate the VES interpretations. Water levels declined during the pumping phase but exhibited partial recovery during rest periods, indicating recharge through infiltration (Aboh, 2009). This recharge mechanism is highly seasonal, with higher yields recorded during the rainy season due to increased infiltration and lower yields in the dry season due to sustained abstraction. A geoelectric cross-section constructed from a linear connection of VES points (P' to P) delineates the structural and stratigraphic framework of the subsurface. It vividly illustrates the vertical and lateral continuity of the aquiferous units and their truncation by fresh basement at depth. The primary aquifer in this region lies within the highly weathered and fractured basement, echoing earlier findings by Jatau and Ajodo (2005) and Offodile (1992). The distribution of the porphyritic granite, granitic gneiss, and mica schist within the study area (Fig. 1) influences the geoelectric response and aquifer geometry. These rocks exhibit varied degrees of weathering and fracturing, which in turn modulate groundwater storage and flow dynamics. According to Clark (1985), groundwater occurrence in crystalline basements is primarily fracture-controlled. The presence and interconnectivity of fractures enhance permeability and storage potential. However, fracture density and aperture typically diminish with depth, as observed by Du-Preez and Barber (1965), hence limiting deeper aquifer productivity. Overall, the integration of geological mapping with Schlumberger-array VES data provided robust insight into the aquifer systems in Chikun and its environs. The results affirm that sustainable groundwater exploitation is feasible when boreholes are strategically located within zones characterised by thick weathered profiles and interconnected fracture systems.

Table 1. VES Location, Layer resistivity, Layer thickness, total depth to basement, Geoelectric Layers and Coordinates

S/No	VES LOCATION	Layer Average Resistivity (Ohm-m)							Layer Thickness (m)						Total Depth to Basement	No of Geoelectric Layers	Coordinates
		1	2	3	4	5	6	7	1	2	3	4	5	6			
1	Gwagwada	391.0	291.0	204.1	262.6	402.2	-	-	0	7.51	22.12	27.57	87.50	-	30	5	N10^{0} 15’ 35.6” E7^{0} 13' 45.8''
2	Chikun	384.9	196.3	274.8	355.5	524.5	-	-	0	5.68	18.51	26.12	87.50	-	30	5	N10^{0} 16’ 20.4” E7^{0} 6’ 28.6”
3	Dakwachi	296.3	238.6	287.0	300.0	479.5	-	-	0	6.68	18.51	26.12	30.57	87.50	40	5	N10^{0} 16’ 39.8” E7^{0} 4’ 28.1”
4	Kulepe	333.1	230.9	276.6	321.9	437.0	604.4	-	0	7.24	21.37	30.85	87.50	-	40	6	N10^{0} 16’ 40.3” E7^{0} 2’ 58.4”
5	Damba	310.4	306.5	203.0	278.8	331.2	481.6	-	0	5.42	21.39	30.85	38.40	87.50	40	6	N10^{0} 29’ 56” E7^{0} 12’ 32.4”
6	Gajina	322.0	259.0	274.3	310.4	480.6	-	-	0	6.68	20.51	28.12	33.57	87.50	40	5	N10^{0} 15’ 19.7” E7^{0} 13' 47.3''
7	AngwaTurai	329.8	306.2	283.2	232.2	240.3	679.8	-	0	3.42	9.24	23.39	32.85	87.50	45	6	N10^{0} 18’ 42.1” E7^{0} 11’ 19.7”
8	Gwogofe	309.7	211.5	302.9	514.7	-	-	-	0	5.31	16.10	19.47	87.50	-	30	4	N10^{0} 29’ 18.5” E7^{0} 12’ 23.5”
9	GudunGuya	330.0	317.7	258.3	215.1	352.1	378.8	577.1	0	6.46	20.04	30.62	87.50	-	35	6	N10^{0} 15’ 35.6” E7^{0} 13’ 45.8”
10	Angwa Alkali	406.3	261.1	249.1	328.7	541.5	-	-	0	6.64	21.87	32.14	44.31	-	50	5	N10^{0} 27’ 12.2” E7^{0} 03’ 49.5”
11	Kurmin Kaduna	353.6	298.7	277.8	227.8	600.3	-	-	0	6.68	19.51	27.12	47.57	87.50	50	5	N10^{0} 18’ 45.5” E7^{0} 04' 7.4''
12	Udawa	366.3	246.6	309.5	787.0	-	-	-	0	5.82	26.92	87.50	-	-	58	4	N10^{0} 29’ 55.6” E7^{0} 03' 50.8''
13	SabonKauwia	396.8	305.2	315.7	210.9	265.9	314.9	511.6	0	6.07	16.87	22.59	32.92	87.50	40	5	N10^{0} 30' 6.9'' E7^{0} 1’ 50.9”
14	Kaburesha	318.7	213.3	279.4	328.3	490.2	-	-	0	7.68	20.51	28.12	48.57	87.50	50	5	N10^{0} 20’ 15.8” E7^{0} 09’ 50.2”
15	Kudo	373.8	195.3	238.0	571.1	-	-	-	0	7.15	22.40	40.44	87.50	-	45	4	N10^{0} 28’ 17.2” E7^{0} 03’ 46.4”

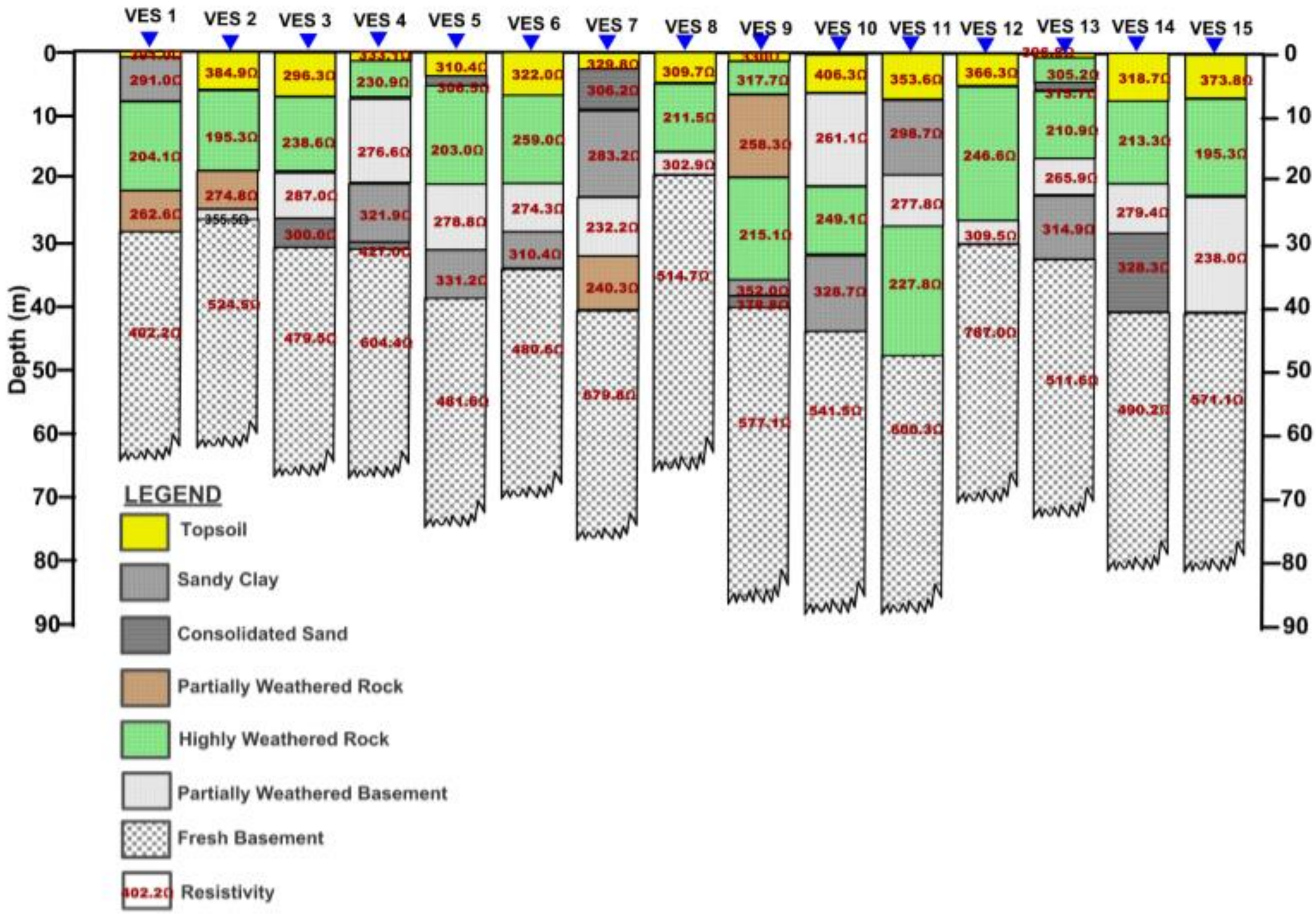

Figure 5. Generalized Geo-electric section across the three lithologic units of the study area showing the probable aquiferous zones

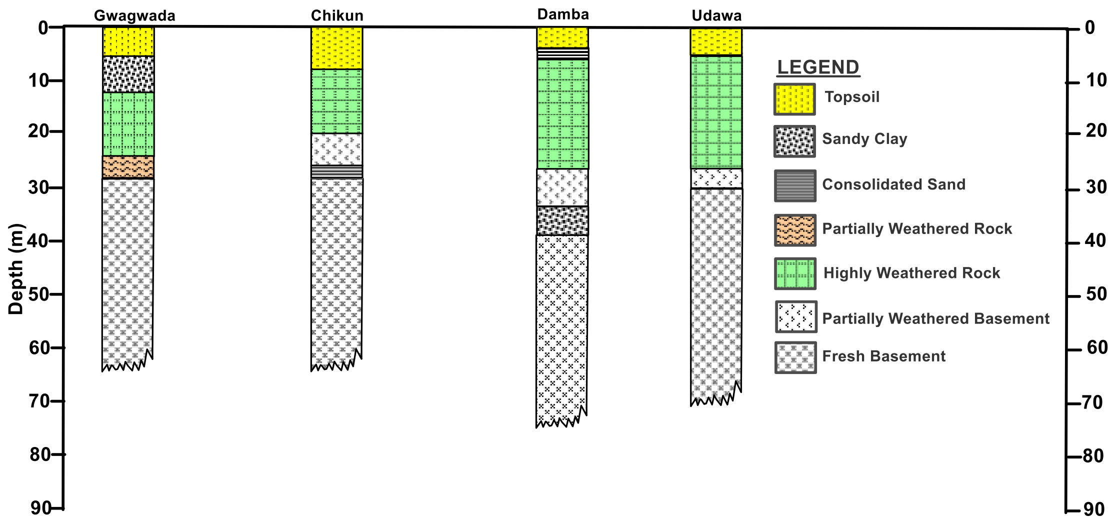

Figure 6. Lithologic logs of boreholes in the study area

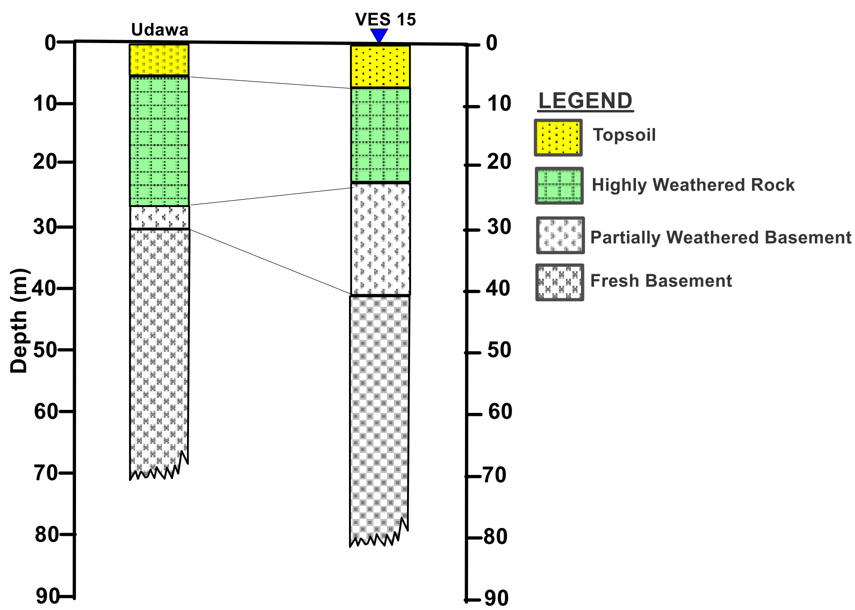

Figure 7. Correlation of VES with lithology in the study area

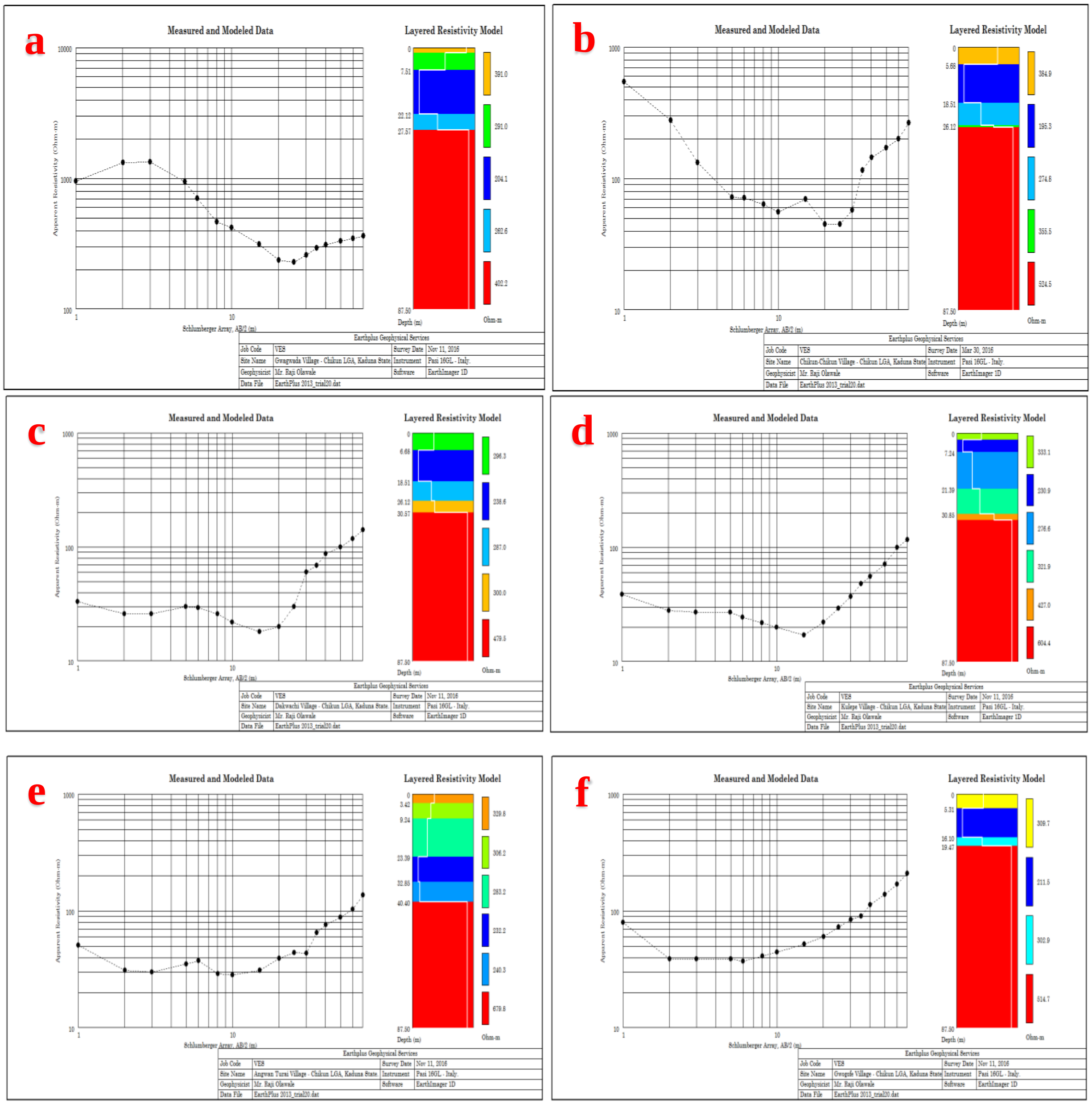

Figure 8. Selected Vertical Electrical Sounding for six (6) locations in the study area (a) Electrical resistivity curve of VES1. (b) Electrical resistivity curve of VES2. (c) Electrical resistivity curve of VES3. (d) Electrical resistivity curve of VES4. (e) Electrical resistivity curve of VES7. (f) Electrical resistivity curve of VES8.

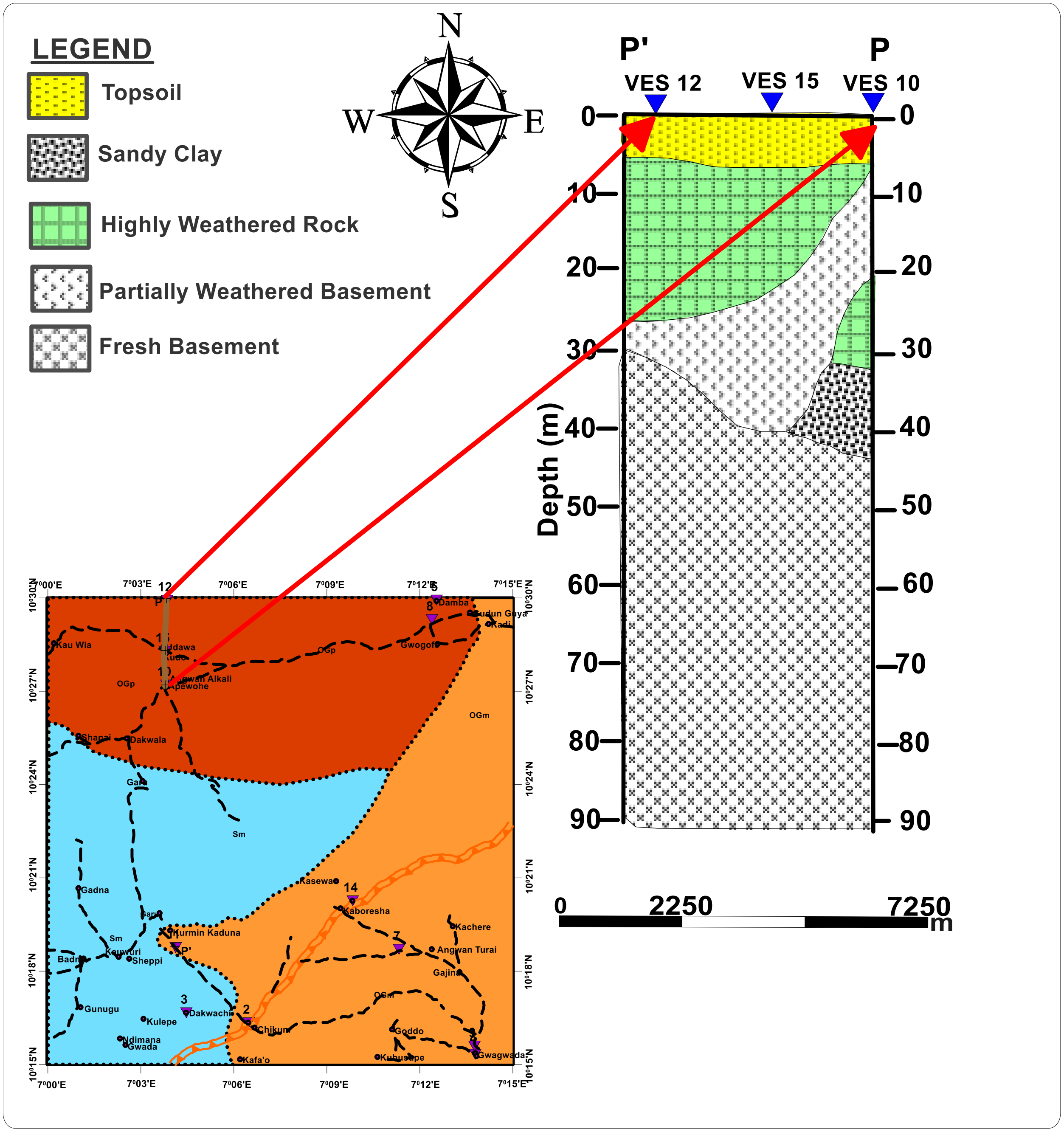

Figure 9. Geo-electric cross section across P' to P

4. CONCLUSION

This integrated geophysical investigation has significantly contributed to a deeper understanding of the groundwater potential within the Chikun crystalline basement terrain of North-Central Nigeria. Through the deployment of Vertical Electrical Sounding (VES) using the Schlumberger array, the study successfully delineated the subsurface into four to six geo-electric layers—ranging from topsoil, sandy clay, consolidated sand, highly weathered basement, partially weathered basement, to fresh basement rock. These layers exhibit varying thicknesses and resistivity values, thereby revealing zones of differing groundwater storage capacities. The most promising aquiferous units were identified within the highly weathered and partially fractured basement horizons, which serve as the principal repositories for groundwater in the area. Specifically, locations such as VES 1, 2, 5, 8, 9, 13, and 15 were characterised by relatively low resistivity values (195.3–215.1 Ωm), indicating higher groundwater saturation and hence favourable for borehole siting. In contrast, areas with higher resistivity values, particularly those associated with fresh basement, are less prospective for groundwater development due to their minimal porosity and permeability. The research affirms that groundwater occurrence in crystalline basement terrains is largely controlled by secondary porosity induced through weathering and fracturing—a conclusion consistent with findings by Clark (1985), Du-Preez and Barber (1965), and Offodile (1992).

The effectiveness of VES in delineating such features highlights its importance as a non-invasive tool in hydrogeological investigations. Moreover, the correlation between lithologic logs and resistivity curves substantiates the reliability of geophysical interpretation in groundwater exploration, offering a practical and cost-effective approach for water resource planning in similar geological settings. The spatial variation in aquifer thickness and resistivity also provides vital insights for sustainable groundwater abstraction, ensuring that boreholes are optimally located to reduce failure rates and improve water yield efficiency. In conclusion, this study not only provides a scientific basis for informed groundwater development in Chikun and its environs but also offers a replicable framework for other regions underlain by crystalline basement rocks. It is therefore recommended that future groundwater exploration efforts in the region and beyond adopt an integrated geophysical approach, incorporating VES and geological mapping, for enhanced aquifer targeting and sustainable water resource management.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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