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# Hydrogeological Evaluation of Abuja Municipal Area Council (AMAC) Using Vertical Electrical Sounding (VES)

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**Abstract: This study presents an integrated hydrogeological assessment of the Abuja Municipal Area Council (AMAC), Nigeria, using Vertical Electrical Sounding (VES) in conjunction with borehole lithological data to delineate subsurface stratigraphy and evaluate groundwater potential within the basement complex terrain. Twenty VES surveys conducted across key locations revealed a consistent geoelectric sequence comprising topsoil, lateritic or clayey overburden, a saprolitic weathered basement, a partially weathered gneissic horizon, and an underlying fractured crystalline basement. The principal curve types identified (KQ, HQ, QH, KA, KAQ, and KHA) indicate diverse hydrostratigraphic conditions and structural controls on groundwater occurrence. Correlation of VES interpretations with borehole logs demonstrated strong spatial agreement, confirming the reliability of the integrated geophysical–geological approach. Results show that the principal aquifer horizon occurs within the fractured basement at depths of approximately 38–70 m, where fracture zones and weathering intensity significantly enhance groundwater storage and yield. Thick saprolitic and partially weathered units serve as important recharge pathways and secondary storage zones, particularly at sites such as AMAC03, AMAC09, AMAC17, and AMAC20. Lower deep resistivity values at sites including AMAC18 and AMAC19 suggest zones of pronounced fracturing with higher yield potential, whereas shallow, highly resistive basement signatures indicate limited groundwater prospects dependent on discrete fracture systems. The study underscores the hydrogeological significance of overburden structure, secondary porosity, and fracture connectivity in controlling groundwater availability across AMAC. The integrated methodology enhances the accuracy of aquifer delineation and provides a robust framework for sustainable groundwater exploration and resource management in crystalline basement terrains. Future work should include expanded geophysical survey coverage, advanced 2D/3D imaging, and integration of hydrogeological models with regional water demand projections to support long-term groundwater security.**

***Keywords:*** *Vertical Electrical Sounding (VES); Groundwater Potential; Borehole lithology; Fractured Aquifer; Hydrogeological Assessment.*

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## I. INTRODUCTION

The Abuja Municipal Area Council (AMAC), located within the Federal Capital Territory of Nigeria, has experienced a rapid increase in population and urbanization, resulting in heightened demand for groundwater resources. Hydrogeological evaluations are critical to assess the potential and quality of these resources, particularly in regions where surface water is insufficient or unreliable [1]. Groundwater is a vital resources, serving as the largest global reservoir of freshwater for domestic, agricultural, and industrial consumption [2]; [3]. It accounts for approximately 99% of the Earth's total liquid freshwater, with roughly 50% of the global population relying on it for domestic supply and nearly 25% of agricultural irrigation depending on this hidden resource [4]. Despite its abundance, only 0.7% of the total global water is deemed usable, with aquifers, Earth's natural underground reservoirs, holding 97% of this fresh liquid water [5]. However, despite being the most substantial freshwater stock, groundwater remains significantly underutilized, contributing to less than 27% of the total water used globally [6].

Groundwater resources in fractured basement terrains have become increasingly critical for water supply in many

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parts of the world, particularly in Sub-Saharan Africa, where surface water is often unreliable or seasonal [7]; [8]. The evaluation and management of these resources require robust methods for characterizing subsurface geology and aquifer potential. Among the various investigative techniques, geophysical methods, especially the Vertical Electrical Sounding (VES) technique—have gained prominence due to their cost-effectiveness, non-invasiveness, and ability to provide valuable information about subsurface layers [9]; [10].

➢ *Hydrogeological Setting of Basement Complexes*

Basement complex terrains are predominantly composed of crystalline rocks, which are inherently impermeable. Groundwater occurrence in such regions is largely controlled by the degree of weathering and fracturing of the bedrock [11]. The weathered layer, often referred to as the regolith, acts as an important aquifer where it is sufficiently thick and saturated [12]. Fractures and joints within the bedrock further enhance groundwater storage and movement, making their identification and characterization crucial for effective groundwater exploration [13]. The VES method, a form of electrical resistivity surveying, is widely used for groundwater exploration in basement complex areas. This method involves injecting electrical current into the ground and measuring the resulting potential differences to infer the resistivity structure of the subsurface [10]. Recent studies have demonstrated that integrating VES with other geophysical techniques, such as electromagnetic and seismic methods, can improve the resolution and reliability of subsurface characterization. For example, [14] combined VES with ground magnetic and electromagnetic methods to enhance the identification of fracture zones, thereby improving groundwater targeting in basement terrains.

While geoelectrical methods provide indirect evidence of subsurface properties, borehole data offer direct lithological and hydrogeological information. The correlation of VES-derived geoelectric layers with borehole logs enhances the accuracy of subsurface models and facilitates the prediction of aquifer properties such as thickness, transmissivity, and yield [13]; [12]. According to [8], integrating VES and borehole data can significantly reduce uncertainties in groundwater exploration, especially in structurally complex terrains. The employment of Geographic Information Systems (GIS) for data integration and visualization has also gained traction, providing a platform for spatial analysis and groundwater potential mapping [14].

As water demand continues to rise in urban and peri-urban areas like the Abuja Municipal Area Council (AMAC), the need for sustainable groundwater management underscores the importance of reliable hydrogeological evaluation techniques. This study evaluates the hydrogeological characteristics and groundwater potential of the Abuja Municipal Area Council (AMAC) through an integrated interpretation of Vertical Electrical Sounding (VES) data and borehole lithologic parameters. The objectives of this study are to delineate the subsurface geoelectric layers across the Abuja Municipal Area Council (AMAC) using Vertical Electrical Sounding (VES) measurements and to characterize the aquifer units based on resistivity values, layer thicknesses, and depth to basement. Additionally, it seeks to correlate VES-derived geoelectric sections with available lithological and hydrogeological information to enhance subsurface interpretation.

## II. METHODOLOGY

Twenty (20) VES were conducted in AMAC (At University of Abuja Permanent Site, Kado-Galadima Road, Zhiga Kuchi, Shagari, Ijoyapi, Katampe) using the conventional Schlumberger array.

Table1 Locations of VES

| Sn | Locations | Longitude | Latitude | Sn | Locations | Longitude | Latitude | Sn | Locations | Longitude | Latitude |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | AMAC01 | 7.2509 | 9.1128 | 8 | AMAC08 | 7.555 | 9.1092 | 15 | AMAC15 | 7.4112 | 9.0473 |
| 2 | AMAC02 | 7.2512 | 9.1123 | 9 | AMAC09 | 7.5551 | 9.1093 | 16 | AMAC16 | 7.4112 | 9.0479 |
| 3 | AMAC03 | 7.3305 | 9.1175 | 10 | AMAC10 | 7.1859 | 8.9886 | 17 | AMAC17 | 7.411 | 9.0506 |
| 4 | AMAC04 | 7.3874 | 9.1256 | 11 | AMAC11 | 7.1818 | 8.988 | 18 | AMAC18 | 7.411 | 9.0513 |
| 5 | AMAC05 | 7.3875 | 9.1251 | 12 | AMAC12 | 7.1721 | 8.9911 | 19 | AMAC19 | 7.4108 | 9.0521 |
| 6 | AMAC06 | 7.5106 | 9.1267 | 13 | AMAC13 | 7.1751 | 8.9731 | 20 | AMAC20 | 7.4108 | 9.0526 |
| 7 | AMAC07 | 7.5109 | 9.1268 | 14 | AMAC14 | 7.4113 | 9.0467 | 21 | AMAC21 | 7.237 | 8.9645 |

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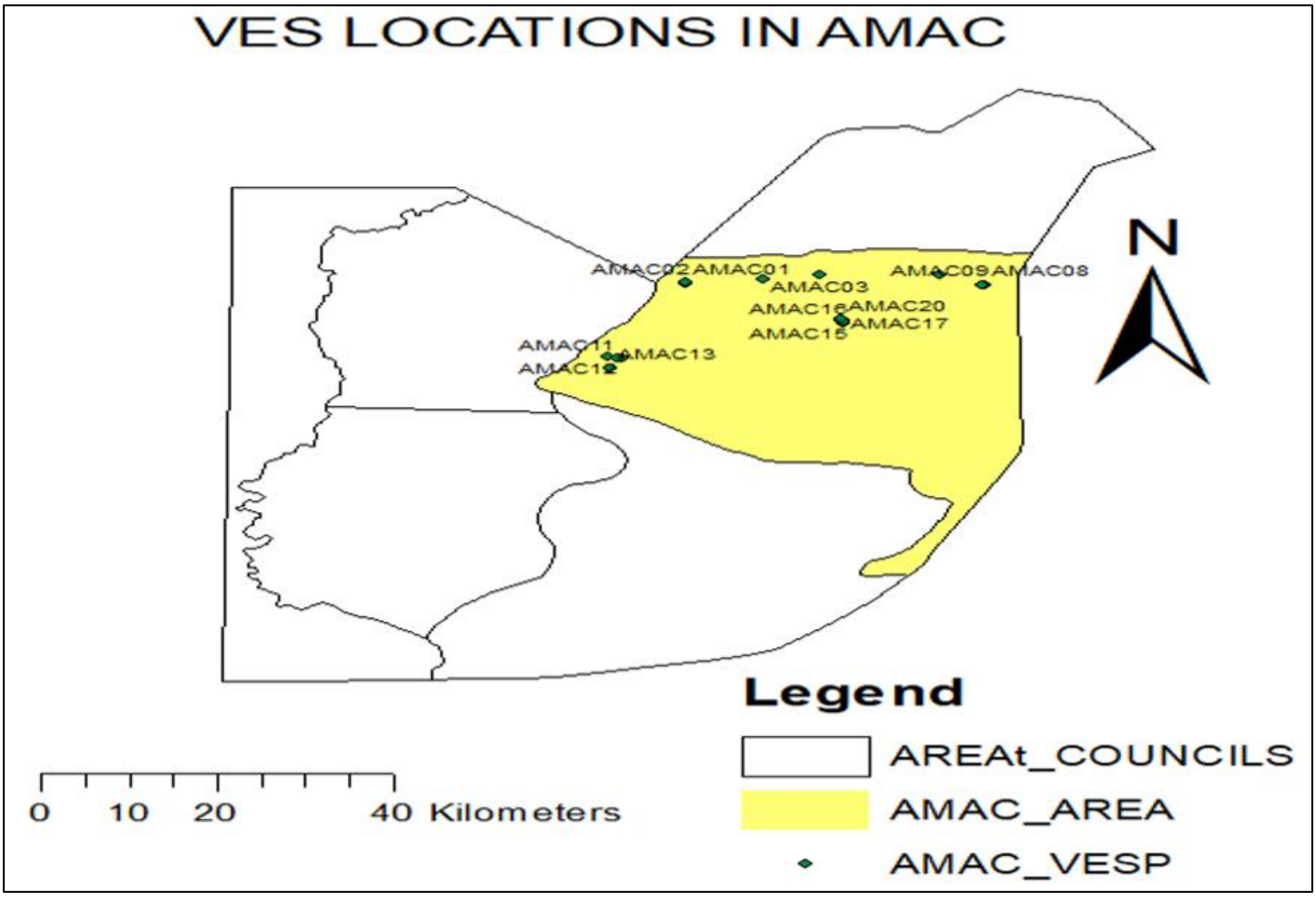


Fig 1 The Study Area Showing VES Locations

The AMAC Vertical Electrical Soundings (VES) (Fig.1) identified predominantly four or five subsurface layers: topsoil, weathered or clay-rich soil, water-bearing zones, and basement rock. The principal curve types observed are KQ, HQ, QH, KA, KAQ, and KHA which correspond to distinct subsurface configurations, reflecting variations in material thickness, stratification, and hydrogeological conditions. These curve types indicate differences in lithology, moisture content, and groundwater potential (see typical plots in Fig 2 and Fig 3).

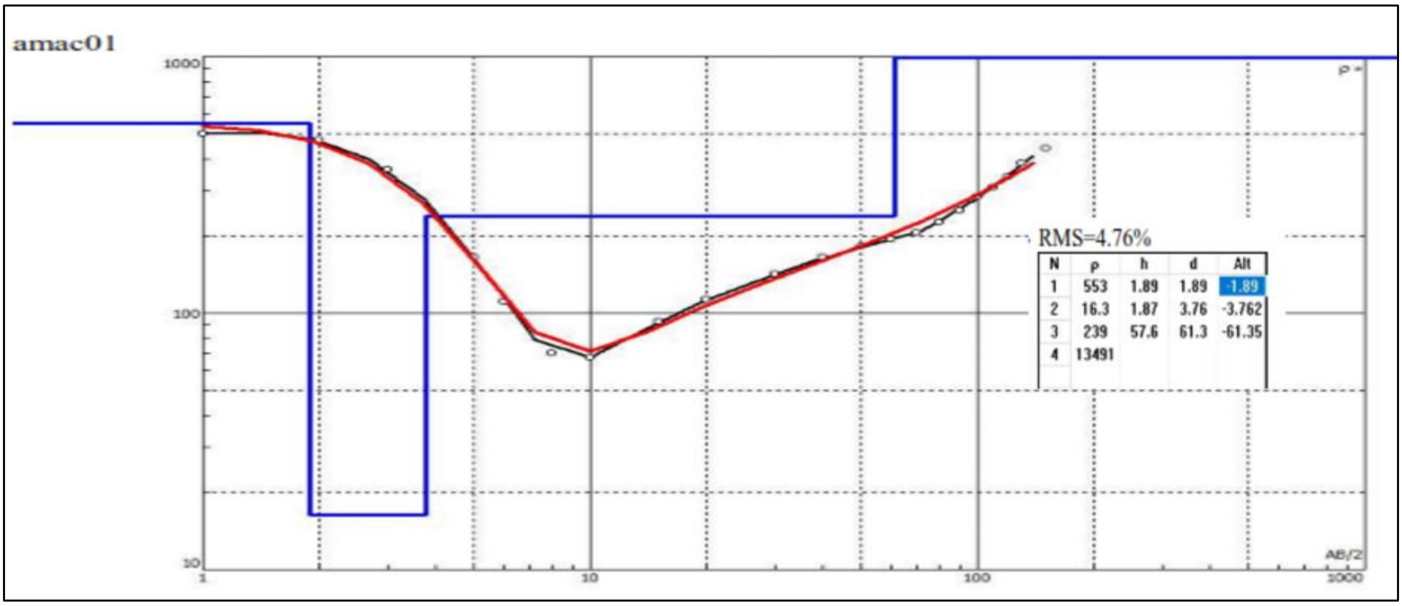


Fig 2 Typical Plot of VES AMAC01

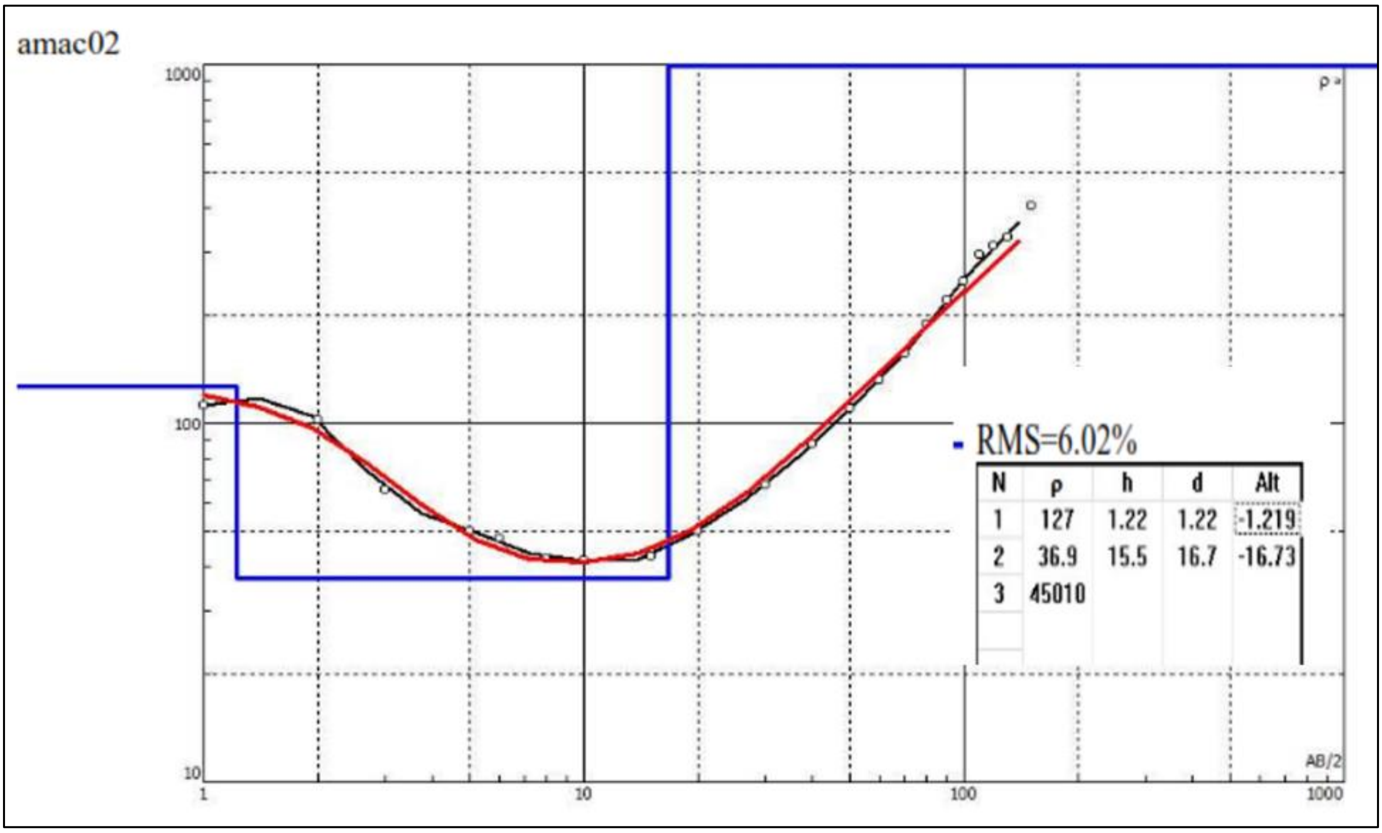

Fig 3 Typical Plot of VES AMAC02

## III. RESULTS

*a) The Interpretation of AMAC VES*

➢ *AMAC01*

Layer 1: ρ = 647 Ω·m, thickness = 1.81 m, depth = 1.81 m. This is interpreted as topsoil or loose sand; it is moderately resistive and shallow. Layer 2: ρ = 37 Ω·m, thickness = 3.11 m, depth = 4.92 m. This layer is interpreted as clay or weathered laterite; it has low resistivity and may retain water if porous. Layer 3: ρ = 217 Ω·m, thickness = 72.70 m, depth = 77.62 m. This is interpreted as a weathered or fractured basement or sandy aquifer; it has moderate resistivity and good aquifer potential. Layer 4: ρ = 14173 Ω·m. This is interpreted as fresh basement rock; it is highly resistive and impermeable.

This site exhibits a QH curve type, characterized by a decrease in resistivity followed by a sharp increase. This pattern is typical of a sequence comprising topsoil, an aquifer, and basement rock, and is consistent with the pattern observed at the previous site: a shallow resistive topsoil overlying aquifer-bearing materials and underlain by impermeable basement.

➢ *AMAC02*

Layer 1: ρ = 99 Ω·m, thickness = 1.57 m, depth = 1.57 m; interpreted as shallow sandy or loamy topsoil. Layer 2: ρ = 29 Ω·m, thickness = 13 m, depth = 14.6 m; interpreted as low-resistivity clay or fine-grained material, possibly confining. Layer 3: ρ = 39201 Ω·m; interpreted as fresh, impermeable basement. Curve type here is Q which indicates a shallow conductive layer over the basement, suggesting limited aquifer potential.

➢ *AMAC03*

Layer 1: ρ = 44 Ω·m, thickness = 3.33 m. This layer is interpreted as shallow clay or loose material. Layer 2: ρ = 1637 Ω·m, thickness = 4.21 m, depth = 7.54 m. This layer is interpreted as coarse sand or weathered rock, suggesting potential aquifer development. Layer 3: ρ = 71 Ω·m, thickness = 8.4 m, depth = 15.94 m. This layer is interpreted as slightly conductive, possibly due to the presence of clayey sand. Layer 4: ρ = 816 Ω·m. This is interpreted as fractured basement or weathered rock; a secondary aquifer may be present. Curve type is KQ, this curve type indicates alternating resistive and conductive layers, suggesting complex water-bearing zones.

➢ *AMAC04*

Layer 1: ρ = 179 Ω·m, thickness = 0.73 m; interpreted as shallow, moderately resistive topsoil. Layer 2: ρ = 34.1 Ω·m, thickness = 1.49 m, depth = 2.21 m; interpreted as clayey or weathered, likely water retentive. Layer 3: ρ = 254952 Ω·m; interpreted as solid, impermeable basement. Curve type here is Q, which indicates a simple decrease, then sharp basement interface; shallow aquifer potential is limited.

➢ *AMAC05*

Layer 1: ρ = 588 Ω·m, thickness = 0.64 m. This is interpreted as sandy topsoil. Layer 2: ρ = 245 Ω·m, thickness = 2.54 m, depth = 3.18 m. This is interpreted as coarse sand or weathered rock; this layer may have potential for a shallow aquifer. Layer 3: ρ = 26.5 Ω·m, thickness = 3.04 m, depth =

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6.22 m. This is interpreted as a clayey or silt layer that may restrict flow. Layer 4: ρ = 174335 Ω·m. This is interpreted as a basement and considered impermeable. As observed elsewhere, curve type is QH, which confirms the presence of a shallow aquifer above the basement, supporting the previous site interpretations.

➢ *AMAC06*

Layer 1: ρ = 228 Ω·m, thickness = 1.39 m. This is interpreted as topsoil or sand. Layer 2: ρ = 564 Ω·m, thickness = 1.11 m, depth = 2.50 m. This layer is interpreted as weathered rock, indicated by its resistivity, and has moderate aquifer potential. Layer 3: ρ = 37.6 Ω·m, thickness = 3.9 m, depth = 6.40 m. This layer is interpreted as clay and may confine an underlying aquifer. Layer 4: ρ = 85532 Ω·m. This is interpreted as a basement. Curve type is KQ which consists of alternating layers; aquifer potential is interpreted to exist in the resistive weathered layer.

➢ *AMAC07*

Layer 1: ρ = 172 Ω·m, thickness = 0.50 m. This is interpreted as sandy topsoil; it is shallow with moderate resistivity. Layer 2: ρ = 334 Ω·m, thickness = 1.76 m, depth = 2.26 m. This is interpreted as weathered or fractured sand or gravel, indicating a good shallow aquifer. Layer 3: ρ = 29 Ω·m, thickness = 3.02 m, depth = 5.22 m. This is interpreted as a clayey layer; it may act as a semi-confining layer. Layer 4: ρ = 89034 Ω·m. This is interpreted as a basement and considered impermeable. Curve type is KQ indicating an alternating resistive and conductive layers; a resistive aquifer is interpreted to exist above clay over basement.

➢ *AMAC08*

Layer 1: ρ = 225 Ω·m, thickness = 0.50 m this is interpreted as sandy topsoil; Layer 2: ρ = 54.1 Ω·m, thickness = 1.78 m, depth = 2.28 m interpreted as clay/weathered silt; likely confining; Layer 3: ρ = 604 Ω·m, thickness = 49.3 m, depth = 51.6 m interpreted as weathered/fractured basement or coarse sand; major aquifer potential; Layer 4: ρ = 31887 Ω·m interpreted as fresh

Basement which is impermeable. Curve type is HQ, indicating a conductive layer over a resistive aquifer above the basement.

➢ *AMAC09*

Layer 1: ρ = 123 Ω·m, thickness = 0.50 m interpreted as topsoil; Layer 2: ρ = 90.7 Ω·m, thickness = 2.01 m, depth = 2.51 m interpreted as clay/weathered silt that is semi-confining; Layer 3: ρ = 278 Ω·m, thickness = 16.2 m, depth = 18.7 m interpreted as sandy or weathered rock which has a moderate aquifer potential; Layer 4: ρ = 1670 Ω·m interpreted as fractured basement with limited permeability. Curve type is HQ, indicating a conductive layer above a resistive aquifer and basement.

➢ *AMAC10*

Layer 1: ρ = 115 Ω·m, thickness = 1.91 m interpreted as topsoil; Layer 2: ρ = 440 Ω·m, thickness = 2.34 m, depth = 4.25 m interpreted as weathered rock having a shallow aquifer potential; Layer 3: ρ = 51.5 Ω·m, thickness = 0.37 m, depth = 4.62 m interpreted as clay/silty layer that has a minor confining effect; Layer 4: ρ = 1281 Ω·m interpreted as fractured basement or secondary aquifer. The curve type here is KQ, indicating alternating layers indicate aquifers over basement.

➢ *AMAC11*

Layer 1: ρ = 66 Ω·m, thickness = 0.50 m. This is interpreted as topsoil; it is slightly conductive. Layer 2: ρ = 1264 Ω·m, thickness = 0.34 m, depth = 0.84 m. This is interpreted as weathered sand or gravel, representing a shallow aquifer. Layer 3: ρ = 152 Ω·m, thickness = 7.86 m, depth = 8.70 m. This layer is interpreted as clay or silty sand; it may confine water. Layer 4: ρ = 1348 Ω·m. This is interpreted as a fractured basement; a secondary aquifer may be possible. Here the curve type is KA. This curve type shows an increase followed by a decrease, ending in a resistive basement.

➢ *AMAC12*

Layer 1: ρ = 87 Ω·m, thickness = 0.5 m. This is interpreted as topsoil. Layer 2: ρ = 1644 Ω·m, thickness = 0.5 m, depth = 1 m. This is interpreted as weathered sand or gravel, suggesting shallow aquifer potential. Layer 3: ρ = 126 Ω·m, thickness = 17.6 m, depth = 18.6 m. This is interpreted as a clayey layer that may confine water. Layer 4: ρ = 47835 Ω·m. This is interpreted as a basement; it is considered impermeable. Curve type is KQ indicating a resistive shallow layer over a conductive confining unit.

➢ *AMAC13*

Layer 1: ρ = 474 Ω·m, thickness = 1.37 m. This is interpreted as sandy topsoil and is moderately resistive. Layer 2: ρ = 77 Ω·m, thickness = 0.3 m, depth = 1.67 m. This layer is interpreted as clay and is semi-confining. Layer 3: ρ = 214 Ω·m, thickness = 11.4 m, depth = 13.07 m. This is interpreted as weathered sand or gravel, identified as the main aquifer. Layer 4: ρ = 1750 Ω·m. This is interpreted as a fractured basement and has secondary aquifer potential. Curve type here is HQ, which shows a conductive clay layer over a resistive aquifer above the basement.

➢ *AMAC14*

Layer 1: ρ = 36 Ω·m, thickness = 0.56 m. This is interpreted as topsoil and is very conductive. Layer 2: ρ = 786 Ω·m, thickness = 1.85 m, depth = 2.42 m. This layer is interpreted as weathered sand, indicating potential aquifer conditions. Layer 3: ρ = 199 Ω·m, thickness = 16.1 m, depth = 18.5 m. This is interpreted as clayey sand; it serves as a secondary aquifer. Layer 4: ρ = 58881 Ω·m. This is interpreted as a basement; it is considered impermeable. Curve type is KQ that identifies a resistive weathered layer within clay above the basement.

➢ *AMAC15*

Layer 1: ρ = 428 Ω·m, thickness = 0.6 m interpreted as topsoil; Layer 2: ρ = 1043 Ω·m, thickness = 0.62 m, depth = 1.22 m interpreted as weathered sand indicating a shallow

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aquifer; Layer 3: ρ = 33 Ω·m, thickness = 0.76 m, depth = 1.98 m interpreted as clay which is semi-confining; Layer 4: ρ = 281 Ω·m, thickness = 39.4 m, depth = 41.38 m interpreted as the main aquifer in weathered/fractured rock; Layer5: ρ = 52103 Ω·m interpreted as basement; impermeable. Curve type is KAQ, indicating a complex, alternating aquifer and confining layers over the basement.

- *AMAC16*

Layer 1: ρ = 204 Ω·m, thickness = 0.5 m. This is interpreted as topsoil. Layer 2: ρ = 17800 Ω·m, thickness = 0.75 m, depth = 1.25 m. This is interpreted as a resistive weathered layer and represents a minor aquifer. Layer 3: ρ = 430 Ω·m, thickness = 2.16 m, depth = 3.41 m. This layer is interpreted as sandy or weathered rock; it is the main aquifer. Layer 4: ρ = 9506 Ω·m. This is interpreted as a basement; a secondary aquifer may exist in fractures. Curve type is KQ, which highlights a resistive aquifer over fractured basement.

- *AMAC17*

Layer 1: ρ = 249 Ω·m, thickness = 0.5 m interpreted as topsoil; Layer 2: ρ = 8225 Ω·m, thickness = 0.43 m, depth = 0.93 m interpreted as weathered sand that is a minor aquifer; Layer 3: ρ = 650 Ω·m, thickness = 18.5 m, depth = 19.43 m interpreted as the main aquifer that is of weathered rock; Layer4: ρ = 315 Ω·m, thickness = 62.6 m, depth = 82.03 m interpreted as clay because of its low-resistivity layer and confining; Layer5: ρ = 25327 Ω·m interpreted as fractured basement secondary aquifer. Curve type is KHA, which is a complex; aquifer zones are separated by semi-confining layers.

- *AMAC18*

Layer 1: ρ = 67 Ω·m, thickness = 0.5 m. This is interpreted as conductive topsoil. Layer 2: ρ = 6715 Ω·m, thickness = 0.57 m, depth = 1.07 m. This is interpreted as weathered sand, with minor aquifer potential. Layer 3: ρ = 156 Ω·m, thickness = 2.11 m, depth = 3.18 m. This is interpreted as clay; it is semi-confining. Layer 4: ρ = 14844 Ω·m. This is interpreted as a basement; it is fractured and may hold a secondary aquifer. Curve type is KQ, which shows alternating resistive and conductive layers, indicating shallow and secondary aquifer potential.

- *AMAC19*

Layer 1: ρ = 84 Ω·m, thickness = 0.5 m. This is interpreted as topsoil. Layer 2: ρ = 8519 Ω·m, thickness = 0.99 m, depth = 1.49 m. This is interpreted as weathered sand; an aquifer is present and shallow. Layer 3: ρ = 243 Ω·m, thickness = 8.07 m, depth = 9.56 m. This is interpreted as a sandy weathered layer; it is the main aquifer. Layer 4: ρ = 1146 Ω·m. This is interpreted as a basement; a secondary aquifer may be present. Curve type is KQ, this curve type identifies a resistive aquifer above fractured basement.

- *AMAC20*

Layer 1: ρ = 76 Ω·m, thickness = 0.5 m indicating topsoil; Layer 2: ρ = 10357 Ω·m, thickness = 0.78 m, depth = 1.28 m indicating a weathered sand; minor aquifer; Layer 3: ρ = 456 Ω·m, thickness = 30.1 m, depth = 31.38 m (Main aquifer; weathered/fractured rock); Layer 4: ρ = 2047 Ω·m (Basement; secondary aquifer). Curve type is KQ, indicating a strong aquifer over the basement.

*b) Summary of all the Vertical Electrical Soundings (VES) Interpretations AMAC01–AMAC20*

Across all sites, VES data reveal a consistent sequence: a shallow, often moderately resistive topsoil; one or more underlying conductive or resistive layers (signalling clay, weathered rock, sand, or gravel); and a final, highly resistive basement interpreted as fresh, impermeable bedrock. The number of recognized layers per VES ranges from three to five, with variations in thickness and resistivity reflecting local geological changes.

- *Hydrogeological Implications*

- *Aquifer Potential:*

Most VES profiles indicate the presence of at least one aquifer, typically located within weathered/fractured basement or coarse sand layers beneath the topsoil. These aquifers are often semi-confined or confined by overlying clay or silt layers with low resistivity.

- *Basement*:

All sites terminate with a highly resistive basement, interpreted as fresh bedrock and considered impermeable. In some cases, a secondary aquifer is interpreted within fractured basement zones.

- *Confining Units:*

Clay and silt layers, identified by low resistivity, frequently act as confining or semi-confining units, either above or between aquifer zones.

- *Thickness and Depth:*

Aquifer-bearing layers vary widely in thickness and depth, from shallow (less than 5 m) to deeper reservoirs (over 70 m thick in some VES, e.g., AMAC01 and AMAC15).

*c) Curve Types and Interpretation*

The primary curve types identified in this geoelectrical vertical electrical sounding (VES) study are as follows:

- *KQ Curve Type:*

This is the most prevalent curve type, observed at multiple sites (e.g., AMAC03, AMAC06, AMAC07, AMAC10, AMAC12, AMAC14, AMAC16, AMAC18, AMAC19, AMAC20). The KQ type is characterized by alternating resistive and conductive layers, which typically represent a resistive weathered or fractured aquifer situated above a conductive clay or weathered zone, with basement rock beneath.

- *QH Curve Type:*

Identified at sites such as AMAC01 and AMAC05, this curve type is characterized by a decrease in resistivity followed by a sharp increase. This pattern typically represents a sequence consisting of topsoil, aquifer-bearing materials, and an underlying impermeable basement.

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- *Q Curve Type:*

Observed at AMAC02 and AMAC04, the Q type exhibits a monotonic decrease in resistivity. This pattern generally indicates the presence of a shallow conductive layer, such as clay or weathered material, overlying the basement, and suggests limited aquifer potential.

- *HQ Curve Type:*

Detected at AMAC08, AMAC09, and AMAC13, this type is characterized by a conductive surface layer overlying a resistive aquifer layer, followed by the basement.

- *KA and KAQ Curve Types:*

These more complex curve types, observed at AMAC11 and AMAC15, indicate subsurface sequences with multiple alternating aquifer and confining layers.

- *KHA Curve Type:*

Identified at AMAC17, this curve type represents complex stratigraphy comprising semi-confining and aquifer layers.

In summary, the most prevalent curve types in the study area are KQ, QH, Q, and HQ, with KQ being the most frequently observed. These curve types reflect the complex stratification of aquifer and non-aquifer materials that is characteristic of basement complex terrains.

- *Site-Specific Highlights*

✓ Major aquifer sites, including AMAC01, AMAC03, AMAC08, AMAC13, AMAC15, AMAC17, and AMAC20, exhibit thick aquifer zones that are commonly located within weathered or fractured basement rocks.
✓ Limited aquifer potentials are AMAC02 and AMAC04, which are dominated by thick, conductive clay zones with only shallow, minor aquifer potential.
✓ Sites with complex aquifer structures, such as AMAC10, AMAC14, AMAC16, AMAC17, and AMAC19, display multiple aquifer horizons that are frequently separated by semi-confining layers.

The VES results collectively demonstrate that the area is characterised by a layered subsurface, with variable but generally favourable hydrogeological conditions. Aquifer potential is generally highest within weathered or fractured basement zones and coarse sands, particularly where these are overlain by semi-confining clay layers. Basement rock universally marks the lower limit of groundwater potential. The diversity of curve types reflects a range of aquifer geometries, from simple to highly complex, with the most productive sites associated with thick, resistive, weathered layers and fractured basement rocks.

*d) VES To Borehole Correlated Interpretation (AMAC01–AMAC20)*

The following section presents a correlation between geoelectric profiles (VES - Vertical Electrical Sounding, a resistivity-based subsurface mapping technique) and lithological layers for AMAC01 to AMAC20, interpreted using borehole logs (Fig. 4). The identified subsurface sequence includes: 0–2 m of topsoil, 2–7 m of lateritic clay or gravel (iron-rich and clayey), 7–20 m of weathered basement or saprolite (decomposed rock), 20–38 m of partially weathered gneiss (metamorphic rock), and 38–70 m of fractured basement aquifer (cracked bedrock, often water-bearing). Each summary aligns the VES resistivity and thickness data with the most probable subsurface units as depicted in fig 5.

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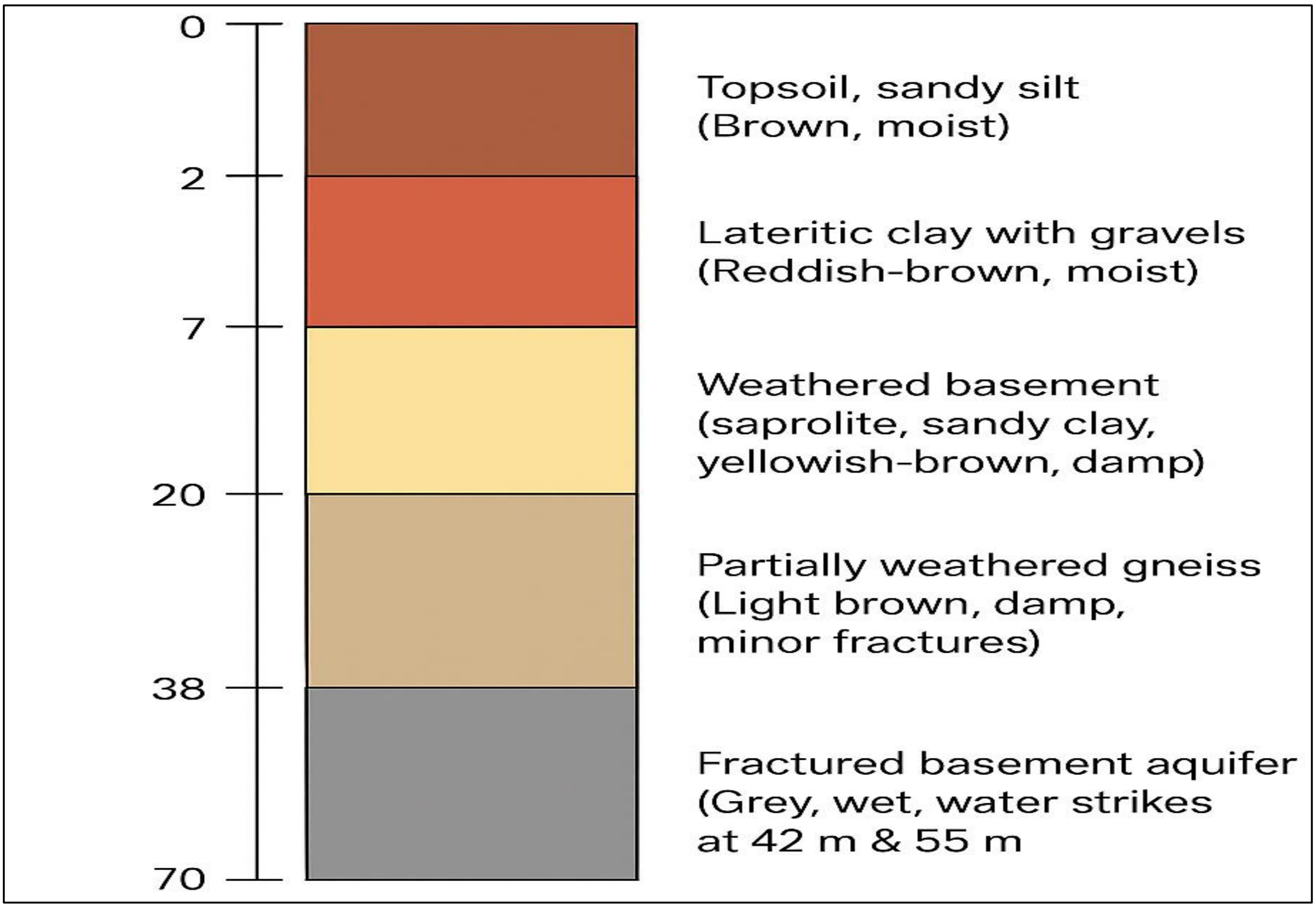


Fig 4 Borehole Lithology (Drilled 1000 Meters from VES AMAC-14)

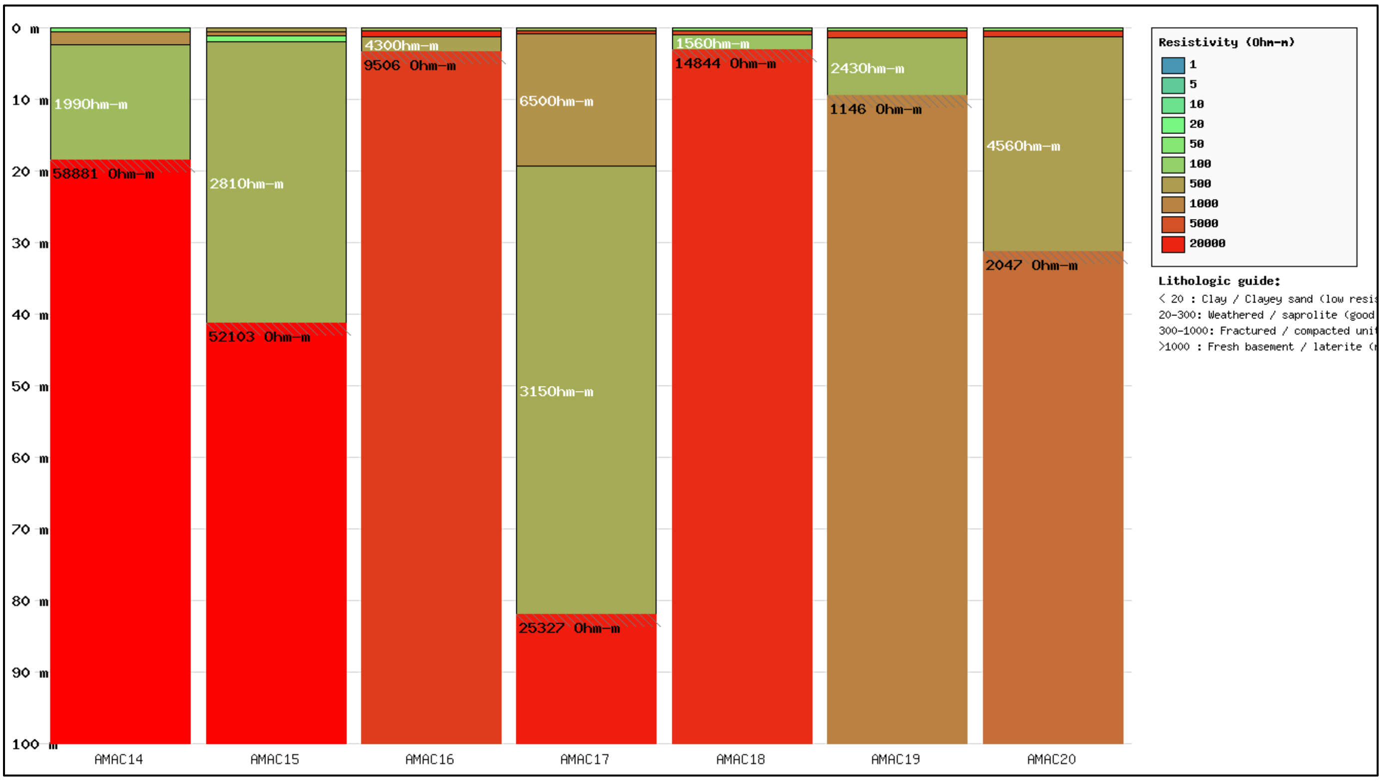


Fig 5 Geoelectric Section of AMAC Profile (VES AMAC14 to AMAC20)

➢ *AMAC01*

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The VES at AMAC01 delineates a thin, resistive surficial unit (Layer 1: 647 Ωm, 1.81 m) that correlates with the 0–2 m sandy silt topsoil, followed by a very conductive intermediate layer (Layer 2: 37 Ωm, 3.11 m) matching the lateritic clay with gravels (2–7 m). A thick, moderately conductive unit (Layer 3: 217 Ωm, thickness 72.70 m to about 77.6 m depth) corresponds to the weathered basement/saprolite and extends downward through the partially weathered gneiss. Its lateral extent and bulk resistivity indicate pervasive weathering and moisture retention across the upper basement. The deep, very high resistivity response (Layer 4: 14,173 Ωm) marks the transition to fresh, competent basement at depth. Taken together, the data suggest that the principal groundwater occurrence is controlled by fractures within the deeper basement beneath the resistive block; the thick saprolite/transition zone (Layer 3) provides secondary storage and a buffer for recharge, while productive zones are likely localised in discrete fracture networks in the underlying fresh basement. The VES–borehole correspondence for AMAC01 therefore supports a structurally controlled fractured aquifer regime with moderate to good prospectivity where fractures are present (See Fig. 4).

➢ *AMAC02*

The AMAC02 sounding begins with a shallow, moderately conductive topsoil signature (Layer 1: 99 Ωm, 1.57 m) that ties to the 0–2 m sandy silt, underlain by a thicker conductive layer (Layer 2: 29 Ωm, 13.00 m) consistent with an expanded interval of lateritic/clayey weathered material and shallow saprolite (2–20 m equivalent). The very high resistivity basin (Layer 3: 39,201 Ωm) at depth indicates a dominant fresh basement signature for the bulk volume sampled. Although the VES returns a resistive deep layer, the shared AMAC lithology and regional borehole evidence indicate a fractured basement aquifer below ~38 m; thus, groundwater is likely hosted in low-porosity fracture networks within an otherwise resistive bedrock. The VES at AMAC02 highlights a thick conductive overburden and a resistive bedrock, a configuration that implies groundwater yields depend on fracture intensity rather than thick, porous media. Therefore, targeted drilling and hydraulic testing are recommended to confirm the presence of productive fracture zones.

➢ *AMAC03*

The AMAC03 soundings show a near-surface conductive topsoil/saprolitic package (Layer 1: 44 Ωm, 3.33 m), followed by a relatively resistive shallow unit (Layer 2: 1,637 Ωm, 4.21 m) that can be attributed to lateritic clay with gravel lenses, and a moderately low resistivity mid-zone (Layer 3: 71 Ωm, 8.40 m to ~15.9 m) matching the saprolite/weathered basement interval. A deep, high-resistivity layer (Layer 4: 816 Ωm) marks the transition toward more competent bedrock. Correlating these signatures with the AMAC lithology indicates that weathering is pronounced in the upper 15–20 m, producing conductive horizons, while the basement becomes more resistive below. Groundwater potential is therefore expected in the fractured basement below the resistive transition, with possible supplementary storage in the thicker saprolitic interval. However, the relatively moderate resistivity of the deep layer suggests some fracturing/alteration, which is favourable for groundwater occurrence where connectivity exists.

➢ *AMAC04*

At AMAC04, the sounding records a thin resistive surface unit (Layer 1: 179 Ωm, 0.73 m) over a conductive near-surface layer (Layer 2: 34.1 Ωm, 1.49 m) consistent with topsoil and lateritic/clayey materials. A pronounced, very high resistivity response (Layer 3: 254,952 Ωm) dominates the deeper part of the sounding and corresponds to a largely competent, fresh basement with minimal bulk porosity. When correlated with the AMAC lithology, the VES suggests a shallow weathered overburden underlain quickly by highly resistive bedrock; consequently, any groundwater is likely confined to narrow fractures in the basement rather than open, porous saprolite. A borehole is required to verify fracture frequency, but the VES implies limited distributed groundwater storage and dependence on structurally controlled fracture conduits.

➢ *AMAC05*

The AMAC05 profile begins with a shallow resistive topsoil (Layer 1: 588 Ωm, 0.64 m) over a moderately resistive lateritic unit (Layer 2: 245 Ωm, 2.54 m), followed by a conductive shallow interval (Layer 3: 26.5 Ωm, 3.04 m to approximately 6.22 m) that maps to the weathered saprolite. Beneath these units, a very high-resistivity deep layer (Layer 4: 174,335 Ωm) marks a fresh, competent basement. Correlating to the AMAC lithology indicates a classic sequence of surficial soils and weathered basement overlaying resistive bedrock; groundwater occurrence is therefore controlled by discrete fractures in the basement with some secondary storage in the weathered saprolite where it is sufficiently developed. The VES signature at AMAC05 suggests moderate recharge to the saprolite, but that productive yields will depend on the presence and connectivity of basement fractures encountered during drilling.

➢ *AMAC06*

The AMAC06 sounding begins with a thin surficial unit (Layer 1: 228 Ωm, 1.39 m) that correlates with the sandy-silt topsoil (0–2 m). A more resistive second layer (Layer 2: 564 Ωm, 1.11 m) maps to the lateritic clay with gravels (2–7 m), while the third, low-resistivity horizon (Layer 3: 37.6 Ωm, 3.90 m to ~6.40 m) corresponds to the weathered basement/saprolite interval (7–20 m). The very high resistivity deep response (Layer 4: 85,532 Ωm) marks the transition to competent basement. Correlating these signatures with the AMAC lithology indicates that the main groundwater potential resides in the fractured basement at depth (the regional fractured aquifer typically occurs at depths of 38–70 m), with secondary storage possible within the shallow saprolite where it is developed. The strong contrast between conductive saprolite and a resistive basement suggests that productive yields will be fracture-controlled and that drilling should target known fracture zones or structural lineaments.

➢ *AMAC07*

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At AMAC07 the VES records a very shallow topsoil signature (Layer 1: 172 Ωm, 0.50 m) over a resistive lateritic layer (Layer 2: 334 Ωm, 1.76 m), followed by a conductive weathered interval (Layer 3: 29 Ωm, 3.02 m to ~5.22 m) and a high resistivity basement signature (Layer 4: 89,034 Ωm). These responses correlate to the shared lithologic sequence, thin topsoil, lateritic cap, saprolitic weathering, and then fresh gneiss. The conductive saprolite indicates appreciable weathering and potential for limited pore storage; however, the dominant groundwater prospect remains the deeper, fractured basement beneath the resistive signature. Given the pronounced resistive basement, aquifer productivity will depend on fracture density and connectivity; therefore, siting drillholes on mapped fractures or inferred structural zones is recommended.

- *AMAC08*

The AMAC08 sounding shows a thin surficial layer (Layer 1: 225 Ωm, 0.50 m), a moderately conductive near-surface unit (Layer 2: 54.1 Ωm, 1.78 m) likely representing lateritic/clayey materials, and a thick, relatively resistive mid-to-deep interval (Layer 3: 604 Ωm, 49.30 m to approximately 51.6 m) that can be correlated with an extensive partially weathered gneiss and upper basement transition. A deeper resistive signature (Layer 4: 31,887 Ωm) indicates more competent bedrock. Correlation with the AMAC lithology suggests a substantial depth to the fractured aquifer, with the thick transition zone providing secondary storage and a gradual change from weathered to fresh rock. The moderate resistivity of the thick intermediate layer implies pervasive alteration and fracture development, which are favourable for groundwater occurrence in open fractures, making AMAC08 a promising target for deeper drilling focused on fracture intercepts.

- *AMAC09*

AMAC09 presents a thin topsoil (Layer 1: 123 Ωm, 0.50 m), a shallow lateritic interval (Layer 2: 90.7 Ωm, 2.01 m), and a moderately thick, resistive mid-unit (Layer 3: 278 Ωm, 16.20 m to approximately 18.7 m) above a lower resistivity deep unit (Layer 4: 1,670 Ωm). When correlated with the AMAC stratigraphy, these signatures indicate a developed weathering profile through the saprolite into a partially weathered gneiss, with the deepest sounding layer representing the approach to fresher basement. Groundwater is expected to be concentrated in fractures within the basement (38–70 m), with the saprolitic and partially weathered zones providing limited storage and recharge pathways. The relatively moderate resistivity at depth suggests some alteration/fracturing that may improve local aquifer yields.

- *AMAC10*

The AMAC10 VES shows a shallow, slightly conductive topsoil (Layer 1: 115 Ωm, 1.91 m), an underlying resistive lateritic/gravel unit (Layer 2: 440 Ωm, 2.34 m), a thin low-resistivity interval (Layer 3: 51.5 Ωm, 0.37 m to about 4.62 m) consistent with localized saprolite or moisture accumulation, and a deeper resistive horizon (Layer 4: 1,281 Ωm). Correlation to the AMAC lithology indicates the usual sequence of topsoil, lateritic cap, weathered basement, transition to fresh gneiss; the thin conductive zone suggests limited saprolite development here. Consequently, the fractured basement remains the principal aquifer target, and although shallow storage appears limited, the moderate resistivity of the deep layer suggests that fracture permeability may be favourable for groundwater where structural conduits are intersected during drilling.

- *AMAC11*

The VES curve at AMAC11 reveals a very thin topsoil layer (Layer 1: 66 Ωm, 0.50 m) corresponding to the sandy silt surface material (0–2 m). This is followed by a resistive layer (Layer 2: 1,264 Ωm, 0.34 m), which likely represents the lateritic clay and gravelly zone (2–7 m). Beneath this lies a moderately resistive layer (Layer 3: 152 Ωm, 7.86 m to approximately 8.70 m) that correlates well with the weathered basement (saprolitic sandy clay) occurring between 7 and 20 m. The deepest layer (Layer 4: 1,348 Ωm) indicates a transition to the partially weathered or fresh basement gneiss. The progressive increase in resistivity with depth signifies the transition from conductive overburden to competent bedrock. The main groundwater-bearing zone is expected to lie within the fractured basement below 38 m, while the weathered zone provides only minor storage. Thus, AMAC11 exhibits moderate groundwater potential controlled primarily by basement fracturing.

- *AMAC12*

The AMAC12 sounding displays a shallow conductive topsoil (Layer 1: 87 Ωm, 0.5 m) corresponding to the sandy silt topsoil (0–2 m), underlain by a highly resistive layer (Layer 2: 1,644 Ωm, 0.5 m) representing the lateritic horizon (2–7 m). The third layer (Layer 3: 126 Ωm, 17.6 m to approximately 18.6 m) corresponds to the weathered basement or saprolite zone (7–20 m), which is moderately conductive and can retain limited groundwater. The deepest layer (Layer 4: 47,835 Ωm) marks the transition to a fresh, resistive gneissic basement. Despite the high resistivity signature at depth, borehole evidence across the AMAC area indicates the presence of productive fractures between 38 m and 70 m, confirming that groundwater occurrence is structurally controlled. The correlation suggests that the saprolitic horizon serves as a recharge pathway, while the fractured basement hosts the main aquifer.

- *AMAC13*

The AMAC13 VES delineates a shallow, resistive topsoil (Layer 1: 474 Ωm, 1.37 m) matching the 0–2 m sandy silt, followed by a thin, conductive layer (Layer 2: 77 Ωm, 0.3 m) corresponding to the lateritic clay horizon (2–7 m). A thicker, moderately resistive layer (Layer 3: 214 Ωm, 11.4 m to ~13.07 m) reflects the weathered basement (saprolite) extending down to about 20 m. The deep, highly resistive unit (Layer 4: 1,750 Ωm) marks the transition to partially weathered gneiss and fresh basement. The resistivity trend indicates moderate weathering in the middle horizon, suggesting potential for minor groundwater storage, while the main aquifer is located in the deeper, fractured basement, expected to be at depths of 38–70 m. AMAC13, therefore, demonstrates good structural control over groundwater

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potential, with recharge likely occurring through the overlying weathered zones.

➢ *AMAC14*

The correlation between VES AMAC14 and the borehole lithological log reveals a close agreement between the geoelectric layers and the subsurface geology. The first layer has a resistivity of 36 Ωm and a thickness of 0.56 m. It corresponds to the topsoil of sandy silt (0–2 m), which is moist and unconsolidated. The second layer exhibits a much higher resistivity of 786 Ωm and a thickness of 1.85 m. This layer aligns with lateritic clay and gravels (2–7 m) and reflects the compact, relatively resistive nature of lateritic materials. The third layer, with a moderate resistivity of 199 Ωm, extends to a depth of 18.5 m. It represents the weathered basement (saprolite zone) and consists of sandy clay. This indicates moderate permeability due to partial decomposition of the parent rock.

The fourth layer is characterised by a very high resistivity value of 58,881 Ωm. It corresponds to the partially weathered to fresh gneiss encountered between 20 m and 38 m. This layer marks the transition to the competent basement, with limited fractures that restrict water movement. At greater depths (38–70 m), the fractured basement aquifer is encountered. Borehole water strikes at 42 m and 55 m confirm this. Although this zone was not fully captured as a distinct low-resistivity layer in the VES curve which is possibly due to the dominance of resistive gneiss as the borehole data confirm that these fractures host groundwater.

Consequently, the correlation indicates that the primary groundwater-bearing horizon is located within the fractured basement beneath the partially weathered gneiss. This indicates that the AMAC14 site has a productive aquifer system controlled by structural discontinuities. The good alignment between geoelectric and lithological data enhances confidence in the VES interpretation for groundwater prospect evaluation in the AMAC area (see Fig.5).

➢ *AMAC15*

The VES–borehole correlation for AMAC15 shows overall agreement but also a few important mismatches worth noting:

The very shallow VES layers (Layer 1: 428 Ωm to 0.6 m; Layer 2: 1,043 Ωm to 1.22 m; Layer 3: 33 Ωm to 1.98 m) map to the surficial sequence in the lithological log (0–2 m topsoil; 2–7 m lateritic clay/gravel; 7–20 m weathered basement). However, the VES places most of this contrast in the upper 2 m. In particular, the low resistivity Layer 3 (33 Ωm) at about 1.0–2.0 m depth likely reflects a near-surface conductive zone. This may be a clayey or saturated pocket, or damp saprolite, rather than the full 7–20 m saprolitic column recorded in the borehole. This suggests a thin, conductive near-surface horizon that dominates the VES response at small electrode spacings. This is characteristic of thin-layer or equivalence effects.

The thick, moderately resistive VES Layer 4 (281 Ωm, thickness 39.4 m, reaching about 41.4 m depth) broadly corresponds to the partially weathered gneiss interval (20–38 m) and the top of the fractured basement. Its moderate resistivity is consistent with partially weathered or fractured rock that contains moisture and weathering products. This represents a transition zone between overburden and fresh bedrock. Because Layer 4 extends to about 41 m in the VES, it partially overlaps the beginning of the fractured aquifer indicated in the borehole.

VES Layer 5 shows very high resistivity (52,103 Ωm) below approximately 41.4 m. According to a simple resistivity interpretation, this would indicate a fresh, competent basement. However, this appears to conflict with the lithological log, which records a fractured basement aquifer between 38 and 70 m. Water strikes occur at 42 m and 55 m. The most likely explanation is that the groundwater in AMAC15 is hosted in narrow fractures and fracture networks within an otherwise highly resistive gneissic matrix. Such fractures often do not lower the bulk resistivity enough to produce a distinct low-resistivity layer on a 1-D VES sounding. This is especially true if fracture porosity is small compared to the matrix volume and the current spacing is large. The borehole proves there is a productive fractured aquifer at about 42–55 m, even though the VES bulk resistivity remains high.

The main groundwater-bearing horizon for AMAC15 is the fractured basement, encountered between 38–70 m (water strikes at 42 m and 55 m), as confirmed by the borehole, despite VES indicating a largely resistive block below approximately 41 m.

The moderate-resistivity thick Layer 4 (to approximately 41 m) likely represents the partially weathered/fractured gneiss transition zone and may contain some storage/permeability.

Near-surface thicknesses from VES appear to be compressed compared with those from the borehole. The VES shows conductive material concentrated in the upper 2 m.

- *To Reduce Ambiguity, The Followings Need To Be Done:*

✓ Run a 2-D ERT profile or time-domain EM / TEM over the site to better image fracture zones and lateral variation (these methods resolve narrow conductive features better than 1-D VES).
✓ Increase VES current spacing and include longer spreads to improve depth resolution and perform reciprocal soundings to check consistency.

Moderate Lithology and water strikes give high confidence that a fractured aquifer exists at 38–70 m. The VES resistivity contrasts are influenced by thin-layer or equivalence effects and low volumetric fracture porosity. This causes the apparent resistive signature at depth.

➢ *AMAC16*

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The AMAC16 sounding shows a thin surficial unit (Layer 1: 204 Ωm, 0.5 m) that correlates with the sandy-silt topsoil (0–2 m) and a very high resistivity cap (Layer 2: 17,800 Ωm, 0.75 m to about 1.25 m) that matches the lateritic clay/gravel horizon (2–7 m). A shallow-to-mid resistivity zone (Layer 3: 430 Ωm, 2.16 m to about 3.4 m) corresponds to the upper weathered basement/saprolite and indicates some moisture retention and moderate secondary porosity. The deeper high-to-moderate resistivity response (Layer 4: 9,506 Ωm) marks the transition toward competent gneissic basement. Correlating these signatures with the shared AMAC sequence suggests that the primary groundwater resource is the deeper fractured basement (expected to be between 38–70 m), with limited secondary storage in the thin saprolitic interval. Productive yields will therefore be fracture-controlled and best targeted where structural lineaments or known fracture zones occur.

- *AMAC17*

The correlation between the lithological log and the VES AMAC17 interpretation reveals a strong agreement between the geoelectric layers and the subsurface geological sequence.

The first layer has a resistivity value of 249 Ωm and a thickness of 0.5 m. It corresponds to the topsoil of sandy silt (0–2 m), which is brown and moist. This reflects a thin, conductive surface layer.

The second layer shows a much higher resistivity of 8,225 Ωm and a thickness of 0.43 m. It represents the lateritic clay with gravels (2–7 m). The high resistivity reflects the presence of iron oxide and gravelly materials, which compact the layer, reducing its conductivity.

The third layer has a moderate resistivity of 650 Ωm and extends to a depth of approximately 19.4 m. It aligns with the weathered basement or saprolitic zone (7–20 m). This layer consists of sandy clay materials that are slightly conductive and can hold limited groundwater due to their weathered nature.

The fourth layer has a resistivity of 315 Ωm and a substantial thickness of 62.6 m. It correlates with the partially weathered gneiss (20–38 m) and extends into the upper part of the fractured basement. The moderate resistivity suggests the rock is partly decomposed and fractured. It retains some moisture and offers moderate groundwater potential.

The fifth layer shows a very high resistivity of 25,327 Ωm. This represents the fractured basement aquifer found between 38 and 70 m. Borehole measurements recorded water strikes at 42 m and 55 m. Despite the high resistivity, borehole evidence confirms that the fractures within this basement host significant groundwater. This accumulation likely occurs in localised zones that are not fully resolved by 1-D VES interpretation.

Conclusively, the correlation between the borehole lithology and VES AMAC17 indicates that the main groundwater-bearing horizon is located within the fractured basement beneath the partially weathered gneiss. The overlying saprolitic and lateritic layers comprise the unsaturated, weathered overburden. This integration validates the reliability of the geoelectric interpretation. It also highlights the structural control of groundwater occurrence in the AMAC area. Productive aquifers are primarily associated with deep fractures in the basement complex.

- *AMAC18*

AMAC18 begins with a very thin topsoil (Layer 1: 67 Ωm, 0.5 m) over a highly resistive lateritic cap (Layer 2: 6,715 Ωm, 0.57 m to about 1.07 m). The third layer (156 Ωm, 2.11 m to about 3.18 m) correlates with the weathered basement/saprolite and indicates moderate conductivity associated with residual clays and moisture. A deeper resistive signature (Layer 4: 14,844 Ωm) indicates fresh to partially weathered gneiss. Correlating these geoelectric responses with the AMAC stratigraphy suggests limited near-surface storage in a modest saprolitic zone and a primary, fracture-hosted aquifer in the deeper basement; groundwater prospectivity therefore depends on the presence and connectivity of fractures in the resistive bedrock.

- *AMAC19*

The AMAC19 VES shows a thin topsoil (Layer 1: 84 Ωm, 0.5 m), an extremely resistive lateritic layer (Layer 2: 8,519 Ωm, 0.99 m to about 1.49 m), and a thicker, moderately conductive saprolitic interval (Layer 3: 243 Ωm, 8.07 m to approximately 9.56 m) consistent with weathered basement. The deepest moderate resistivity response (Layer 4: 1,146 Ωm) marks the partially weathered to fresh gneiss. In the context of the AMAC lithology, these signatures point to a meaningful weathered zone that can provide limited storage and recharge pathways while the principal aquifer remains the fractured basement at depth; the relatively lower deep resistivity compared with other sites may indicate more pervasive fracturing or alteration, which is favourable for groundwater yields where fractures are well connected.

- *AMAC20*

AMAC20 records a thin topsoil (Layer 1: 76 Ωm, 0.5 m), a highly resistive lateritic cap (Layer 2: 10,357 Ωm, 0.78 m to about 1.28 m), and a substantial mid-depth moderately resistive unit (Layer 3: 456 Ωm, 30.1 m to approximately 31.4 m) that correlates with an extensive weathered/partially weathered gneiss. The deeper signature (Layer 4: 2,047 Ωm) indicates a transition toward a fresher basement. Correlation with the standard AMAC sequence suggests an unusually thick transition/weathered interval here, which may provide appreciable secondary storage. The main productive horizon remains the deeper fractured basement; therefore, AMAC20 offers promising recharge and intermediate storage potential, but final yields will depend on fracture density within the underlying bedrock.

*e) Resistivity Ranges Across All VES Stations (AMAC01–AMAC20)*

- *Topsoil Layer (Layer 1) Resistivity Range: 36–647 Ωm*

General Characteristics

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- Typically sandy, silty, or clayey topsoil.
- This layer represents the non-saturated overburden, which generally holds little groundwater and therefore has limited hydrogeological importance.
- Low resistivity values (36–100 Ωm) are indicative of clayey, moist soils such as those identified at AMAC14 and AMAC18.
- High resistivity values (>300 Ωm) are associated with dry sandy or lateritic soils, for instance, at AMAC01, AMAC05, and AMAC13.

➢ *Hydrogeological Significance*

This layer provides minimal storage for groundwater, further emphasizing its limited role and mainly functions as a recharge pathway for deeper aquifers.

- *Lateritic / Clayey Weathered Layer (Layer 2) Resistivity Range: 29–17,800 Ωm*

This layer shows the greatest variability, reflecting transitions from:

✓ Low resistivity (29–100 Ωm) is characteristic of clayey materials and confining units, such as AMAC01 and AMAC02.
✓ Moderate resistivity (200–1500 Ωm) generally corresponds to weathered rock or sandy laterite and may indicate a shallow aquifer, as observed at AMAC07, AMAC10, and AMAC11.
✓ Very high resistivity (8,000–17,800 Ωm) is typical of strongly indurated or partially weathered basement, such as those at AMAC16, AMAC17, and AMAC20.

➢ *Hydrogeological Significance:*

- Portions of the layer that are rich in clay and display low resistivity act as confining or semi-confining hydrogeological units.
- Intervals with moderate resistivity may contain shallow perched aquifers, contributing to groundwater potential.
- Zones with very high resistivity indicate proximity to the unweathered, fresh basement layer.

*f) Weathered/Saprolitic Basement (Layer 3) Resistivity Range: 26–650 Ωm*

This is the main groundwater-bearing horizon in many VES locations.

- Across AMAC, most sites have values between 50 and 300 Ωm, including AMAC01, AMAC09, AMAC13, AMAC17, and AMAC19.
- Exceptionally low value (26 Ωm, AMAC05) indicates a clay-rich weathered zone.
- Moderately high values (400–650 Ωm) correspond to coarse saprolite or weathered gneiss, for example, at AMAC16 and AMAC17.

➢ *Hydrogeological Significance*

- Represents the primary aquifer zone across the study area.
- Good secondary porosity from granular decomposition or early-stage fracturing.
- Thickness varies widely (2–72 m), controlling recharge and storage.

*g) Fractured/Fresh Basement (Final Layer) Resistivity Range: 1,146–254,952 Ωm*

- Most locations have extremely high resistivity values (20,000–250,000 Ωm), indicating a fresh basement.
- At some stations, only moderately high values (1,000–3,000 Ωm) are observed, reflecting fractured basement rather than fully fresh rock. Examples include AMAC09, AMAC10, AMAC13, AMAC17, and AMAC20.

➢ *Hydrogeological Significance*

- A fresh basement is impermeable and therefore lacks aquifer potential.
- Basement layers with moderate resistivity may host aquifers controlled by fractures.
- Serves as the hydraulic base of the local groundwater system.

Table 2 Generalized Resistivity Trends Across AMAC (AMAC01–20)

| | | |
|---|---|---|
| **Topsoil** | 36–647 Ωm | Unsaturated overburden; limited aquifer significance |
| **Clay/Laterite (Layer 2)** | 29–17,800 Ωm | Confining layer to shallow aquifers or weathered transition zone |
| **Weathered/Saprolitic Basement (Main Aquifer)** | 26–650 Ωm | Primary aquifer zone; thickness controls yield |
| **Fractured Basement** | 1,000–20,000 Ωm | Secondary aquifer (fracture-controlled) |
| **Fresh Basement** | >20,000 up to 254,952 Ωm | Impermeable; aquifer base |

➢ *Hydrogeological Interpretation*

- Aquifer systems in AMAC are predominantly weathered–fractured basement aquifers, with resistivity between 50 and 300 Ωm.
- Clayey layers (<100 Ωm) often overlie the aquifer, acting as semi-confining units that locally enhance artesian conditions.

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- Very high resistivity (>20,000 Ωm) consistently marks the fresh basement, indicating the termination of groundwater potential.
- Stations with thick weathered horizons (AMAC03, AMAC08, AMAC17, AMAC20) exhibit higher storage and yields.
- Stations with thin saprolite and shallow basement (AMAC02, AMAC04) show poor aquifer potential.

*h) Summary of The Correlation in AMAC*

This study analyzes the basement aquifer systems in the AMAC area using geoelectrical and lithological methods. It combines Vertical Electrical Sounding (VES) data from twenty locations (AMAC01–AMAC20) with matching borehole logs. Five main geoelectric layers are identified:

- Thin topsoil of sandy silt with low to moderate resistivity,
- A lateritic or clayey layer with higher resistivity,
- A moderately conductive saprolitic weathered basement,
- A partially weathered gneissic transition zone, and
- A fractured crystalline basement at depth.

The uppermost topsoil and laterite layers form an unsaturated overburden with limited groundwater significance. Below these, the saprolite and partially weathered basement indicate progressive rock decomposition. These horizons are more porous and act as primary recharge pathways. Resistivity in these layers is influenced by clay content, weathering, and moisture. Subsurface layer thickness varies significantly across the area, ranging from approximately 3 m to over 80 m.

Correlation of VES data with borehole lithology confirms that the main groundwater-bearing horizons are found within the fractured basement zone, typically between 38 and 70 m. This pattern is consistent at sites such as AMAC03, AMAC09, AMAC17, and AMAC20, where thicker weathered profiles improve recharge and storage capacity. In contrast, areas with low deep resistivity, such as AMAC18 and AMAC19, indicate increased basement fracturing, which supports higher-yielding aquifers. Secondary groundwater storage is present in the saprolite and weathered transition zones, but productive yields depend primarily on the density and connectivity of deep basement fractures.

Integrating VES and lithologic data shows strong spatial consistency and confirms resistivity sounding as a reliable method for mapping aquifer layers. However, challenges remain, including thin surface layers and difficulty detecting small or short fracture zones with 1-D resistivity data. Using 2-D or 3-D surveys and targeted drilling is recommended to improve aquifer mapping and reduce uncertainty.

This study demonstrates that groundwater potential in the AMAC area is mainly determined by basement fracturing, rock weathering, and lithological variations. Combining geoelectrical and geological data offers a robust approach for assessing aquifer potential and provides clear guidance for sustainable groundwater management in complex crystalline rocks.

**Table 3: Aquifer Characteristics of All the VES locations (AMAC01 - AMAC20)**

| Location | Longitude | Lattitude | Aquifer Layer | Aquifer Resistivity (Ωm) | Aquifer Thickness (m) | Depth to Aquifer (m) | Overburden Thickness (m) |
|---|---|---|---|---|---|---|---|
| AMAC01 | 7.2509 | 9.1128 | 3 | 217.00 | 72.70 | 4.92 | 77.62 |
| AMAC02 | 7.2512 | 9.1123 | 2 | 29.00 | 13.00 | 1.57 | 14.60 |
| AMAC03 | 7.3305 | 9.1175 | 3 | 71.00 | 8.40 | 7.54 | 15.94 |
| AMAC04 | 7.3874 | 9.1256 | 2 | 34.10 | 1.49 | 0.73 | 2.21 |
| AMAC05 | 7.3875 | 9.1251 | 3 | 26.50 | 3.04 | 3.14 | 6.22 |
| AMAC06 | 7.5106 | 9.1267 | 3 | 37.60 | 3.90 | 2.50 | 6.40 |
| AMAC07 | 7.5109 | 9.1268 | 3 | 29.00 | 3.02 | 2.26 | 5.22 |
| AMAC08 | 7.5550 | 9.1092 | 3 | 604.00 | 49.30 | 2.28 | 51.60 |
| AMAC09 | 7.5551 | 9.1093 | 3 | 278.00 | 16.20 | 2.51 | 18.70 |
| AMAC10 | 7.1859 | 8.9886 | 3 | 51.50 | 0.37 | 4.25 | 4.62 |
| AMAC11 | 7.1818 | 8.9880 | 3 | 152.00 | 7.86 | 0.84 | 8.70 |
| AMAC12 | 7.1721 | 8.9911 | 3 | 126.00 | 17.60 | 1.00 | 18.60 |
| AMAC13 | 7.1751 | 8.9731 | 3 | 214.00 | 11.40 | 1.67 | 13.07 |
| AMAC14 | 7.4113 | 9.0467 | 3 | 199.00 | 16.10 | 2.42 | 18.50 |
| AMAC15 | 7.4112 | 9.0473 | 4 | 281.00 | 39.40 | 1.98 | 41.38 |
| AMAC16 | 7.4112 | 9.0479 | 3 | 430.00 | 2.16 | 1.25 | 3.41 |
| AMAC17 | 7.4110 | 9.0506 | 3 | 315.00 | 62.60 | 19.43 | 82.03 |
| AMAC18 | 7.4110 | 9.0513 | 3 | 156.00 | 2.11 | 1.07 | 3.18 |
| AMAC19 | 7.4108 | 9.0521 | 3 | 243.00 | 8.07 | 1.49 | 9.56 |
| AMAC20 | 7.4108 | 9.0526 | 3 | 456.00 | 30.10 | 1.28 | 31.38 |

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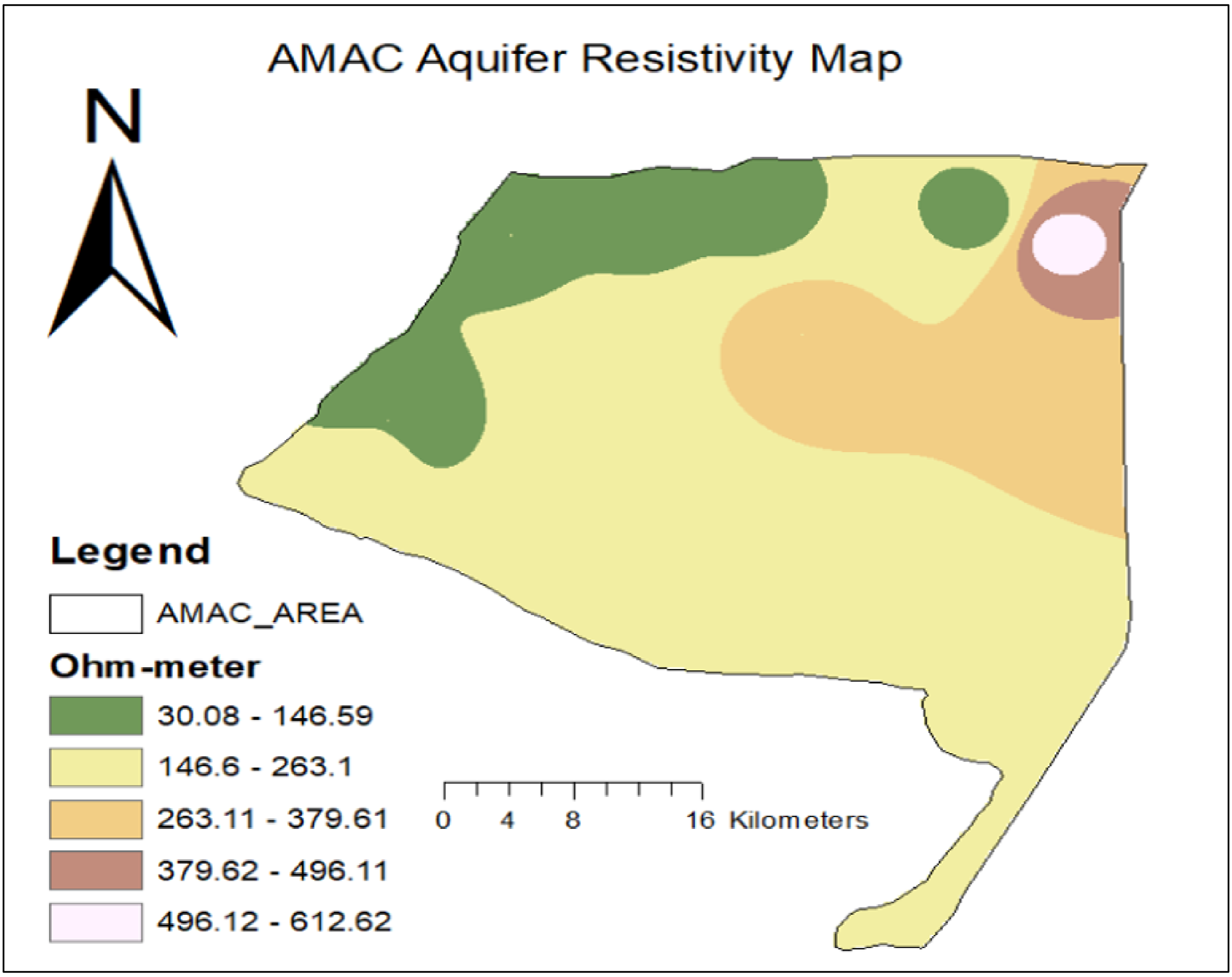


Fig 6 Aquifer Resistivity Map of AMAC

Table 4 Aquifer Resistivity Analysis

| Sn | Aquifer Resistivity (Ωm) | Area (km$^2$) | Coverage (%) |
|---|---|---|---|
| 1 | 30.08 - 146.59 | 501.229 | 28.357 |
| 2 | 146.6 - 263.1 | 452.973 | 25.627 |
| 3 | 263.11 - 379.61 | 712.063 | 40.285 |
| 4 | 379.62 - 496.11 | 63.460 | 3.590 |
| 5 | 496.12 - 612.62 | 37.841 | 2.141 |

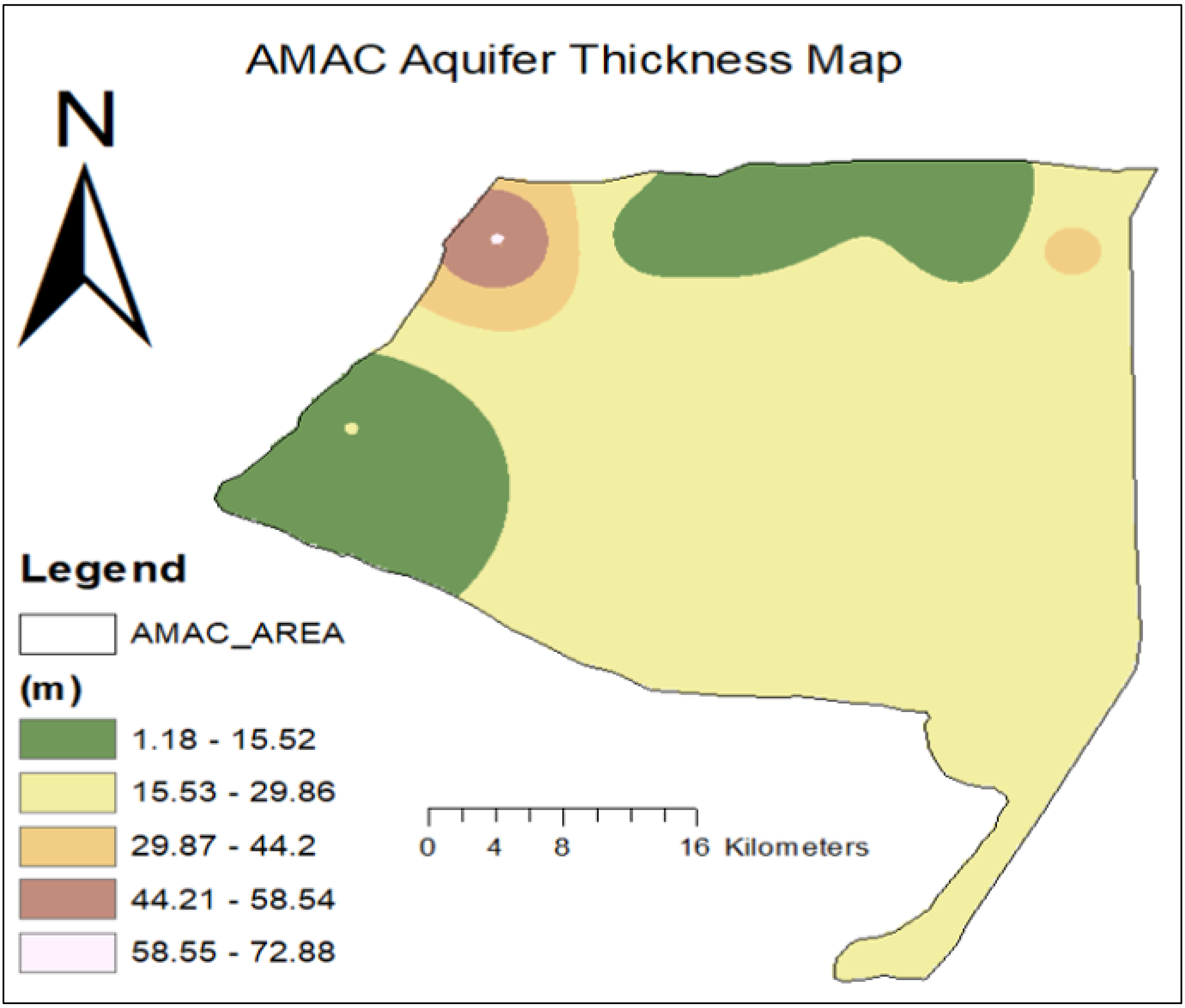


Fig 7 Aquifer Thickness Map of AMAC

Table 5 Aquifer Thickness Analysis

| Sn | Aquifer Thickness (m) | Area (km$^2$) | Coverage (%) |
|---|---|---|---|
| 1 | 1.18 - 15.52 | 367.706 | 20.808 |
| 2 | 15.53 - 29.86 | 1235.235 | 69.901 |
| 3 | 29.87 - 44.2 | 97.011 | 5.490 |
| 4 | 44.21 - 58.54 | 33.535 | 1.898 |
| 5 | 58.55 - 72.88 | 33.636 | 1.903 |

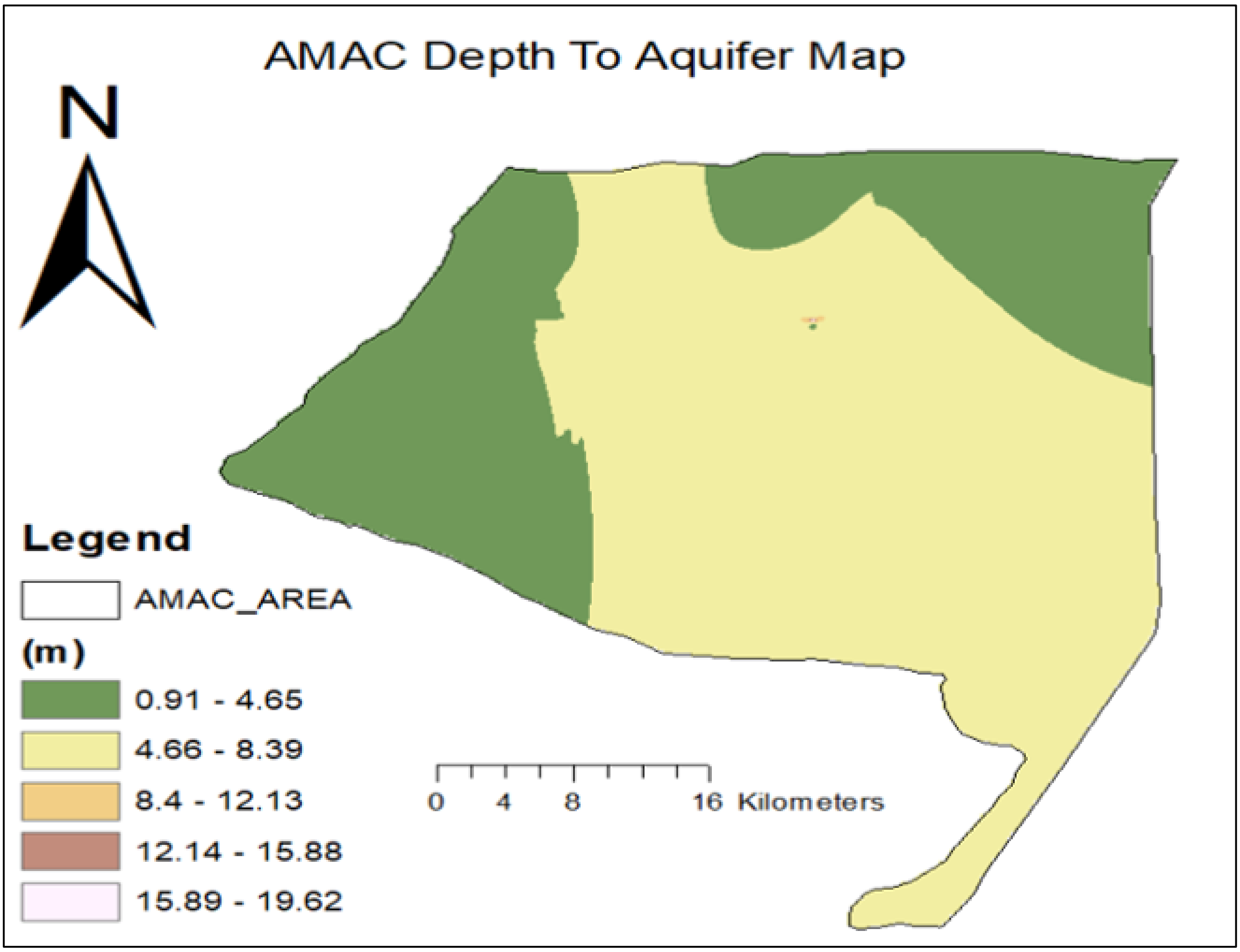


Fig 8 Depth to Aquifer Map of AMAC

Table 6 Depth to Aquifer Analysis

| Sn | Depth To Aquifer (m) | Area (km2) | Coverage (%) |
|---|---|---|---|
| 1 | 0.91 - 4.65 | 243.478 | 13.778 |
| 2 | 4.66 - 8.39 | 250.620 | 14.182 |
| 3 | 8.4 - 12.13 | 233.861 | 13.234 |
| 4 | 12.14 - 15.88 | 646.781 | 36.601 |
| 5 | 15.89 - 19.62 | 392.389 | 22.205 |

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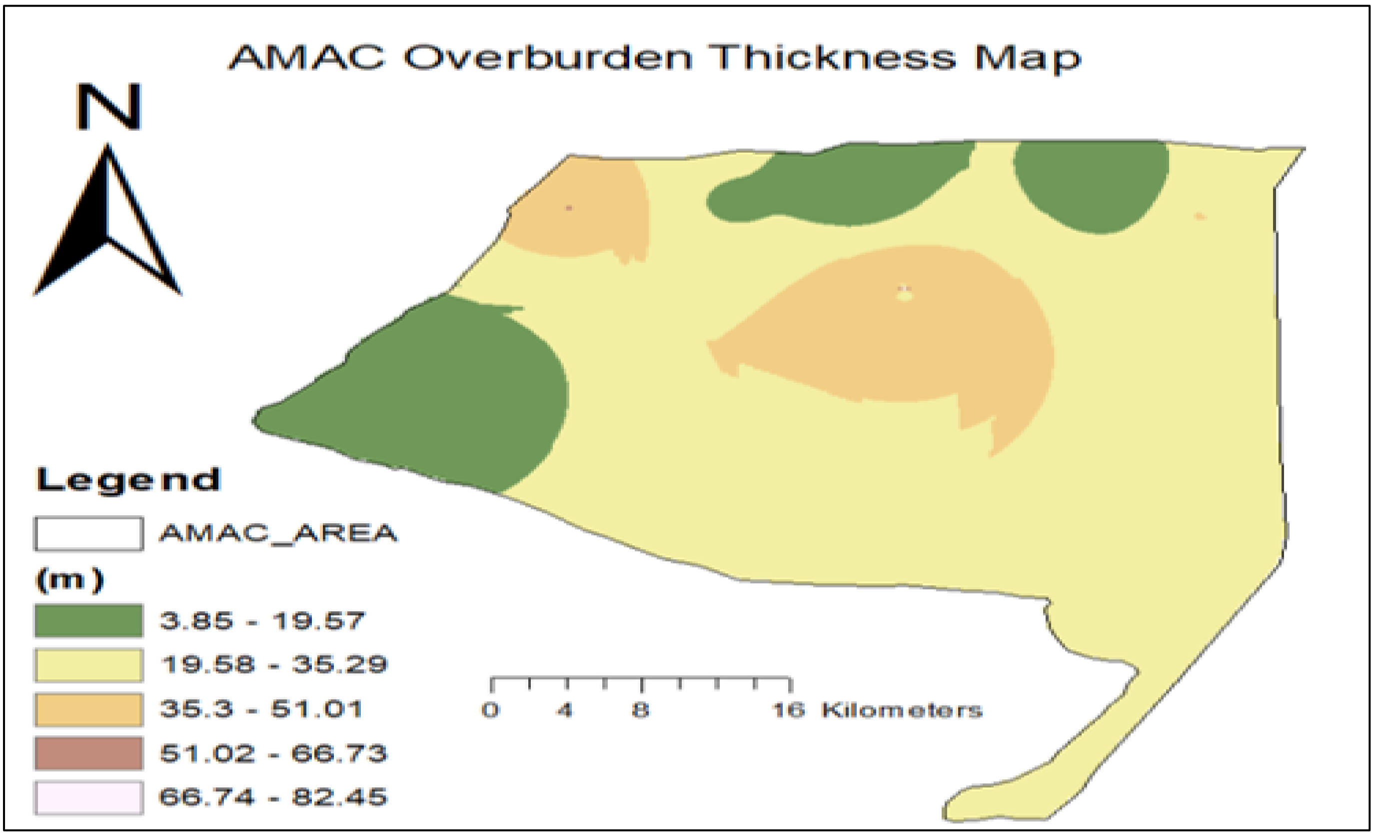


Fig 9 Overburden Thickness Map of AMAC

Table 7 Overburden Thickness Analysis

| Sn | Thickness (m) | Area (km2) | Coverage (%) |
|---|---|---|---|
| 1 | 3.85 - 19.57 | 304.281 | 17.217 |
| 2 | 19.58 - 35.29 | 1211.131 | 68.528 |
| 3 | 35.3 - 51.01 | 251.764 | 14.245 |
| 4 | 51.02 - 66.73 | 0.068 | 0.004 |
| 5 | 66.74 - 82.45 | 0.100 | 0.006 |

Table 8: Borehole Lithological Log AMAC

| Depth (m) | Lithologies |
|---|---|
| 0–2 | Topsoil, sandy silt (Brown, moist) |
| 2–7 | Lateritic clay with gravels (Reddish-brown, moist) |
| 7–20 | Weathered basement (saprolite, sandy clay, yellowish-brown, damp) |
| 20–38 | Partially weathered gneiss (Light brown, damp, minor fractures) |

*i) Comprehensive Analysis and Correlation of Tables 4–7 with Table 8*

A comparative interpretation of aquifer resistivity, aquifer thickness, depth to aquifer, and overburden thickness (Tables 4–7) with the borehole lithological log (Table 8) provides a clear understanding of the hydrogeological framework of the Abuja Municipal Area Council (AMAC). The correlations strongly validate the VES-derived parameters and show remarkable consistency with actual subsurface geology.

➢ *Aquifer Resistivity (Table 4) in Relation to Lithology (Table 8)*

The resistivity distribution across AMAC closely aligns with the lithological units encountered in borehole logs.

Low to Moderate Resistivity (30–263 Ωm) in Table 4, corresponds strongly to the weathered basement (7–20 m) and partially weathered gneiss (20–38 m) described in Table 8.

- *These formations typically consist of:*

✓ Conductive saprolite (sandy clay)
✓ Moderately resistive, partially weathered gneiss
✓ Fractured, moisture-bearing units

Approximately 54% of AMAC (Sn1 + Sn2) in Table 4 falls within this category, confirming that the dominant aquifer material is a weathered/fractured basement system, which aligns with the lithologic profile (Table 8).

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- *High Resistivity Values (263–612 Ωm) in Table 4 Correlate with:*

- ✓ Fresher crystalline basement
- ✓ Lateritic horizons (2–7 m)
- ✓ Unsaturated or poorly saturated rock units

These comprise about 46% of the area, indicating wide spatial coverage of non-aquifer or weak-aquifer units, especially where the basement is shallow or unweathered.

- *Aquifer Thickness (Table 5) Versus Lithology (Table 8)*

The dominant aquifer thickness of 15–30 m, representing 69.9% (Table 5) of the total area, aligns precisely with the combined thickness of (Table 8):

- ✓ Weathered basement (7–20 m)
- ✓ Partially weathered gneiss (20–38 m)

These intervals yield a combined saturated zone of 13–31 m, matching the VES-derived aquifer thickness range in Table 5.

- *Interpretation*

The lithological evidence confirms that AMAC's aquifers are predominantly hosted within deeply weathered and partially weathered basement units, which provide adequate groundwater storage through secondary porosity.

- *Depth to Aquifer (Table 6) Versus Lithological Evidence (Table 8)*

Table 8 shows the onset of aquifer saturation from approximately 7 m, marking the transition from overburden to water-bearing saprolite.

Table 6 indicates that more than 58.8% of AMAC have an aquifer depth of 12-20 m. This matches the lithological succession in Table 8:

- ✓ 0–7 m: Overburden (topsoil and laterite)
- ✓ ≥7 m: Start of saturated weathered basement

Thus, the VES-derived depth-to-aquifer values correspond accurately to the borehole-established aquifer depth, confirming model reliability.

- *Overburden Thickness (Table 7) Versus Lithology (Table 8)*

The overburden from Table 8 consists of:

- ✓ Topsoil and lateritic clay: 0–7 m
- ✓ Transitional/weathered unit (saprolite): 7–20 m

The VES-derived overburden thickness (Table 7) shows that 68.5% of the area has an overburden thickness of 19.6–35.3 m, effectively representing the entire unsaturated and weakly saturated weathered zone.

- *Interpretation*

This demonstrates that VES effectively captures the full extent of loose to moderately compacted overburden materials overlying the basement aquifer system.

> *Integrated Hydrogeological Interpretation*

- *Dominant Aquifer System*

All tables consistently indicate that AMAC is underlain by a basement complex aquifer, comprising:

- ✓ Weathered saprolite
- ✓ Partially weathered gneiss
- ✓ Deep fractured crystalline basement (38–70 m)

This combination produces secondary porosity and permeability, the key controls on groundwater occurrence in basement terrains.

- *Recharge and Storage Characteristics*

Zones characterized by Low resistivity (30–146 Ωm), Thick aquifer units (15–30 m) and High overburden thickness (>20 m) represent the most promising groundwater zones, indicating:

- ✓ Highly weathered, permeable materials
- ✓ Good storage capacity
- ✓ Strong recharge potential

- *Structural Controls on Groundwater*

Moderate resistivity (263–379 Ωm), which dominates the area (40%), reflects fracturing within the basement, which enhances secondary porosity, transmissivity and groundwater movement.

- *Aquifer Depth and Drilling Implications*

With aquifers occurring at depths between 12 and 20 m, drilling should target depths of 40–70 m to intersect deep fractured basement and high-yield zones (evident in water strikes at 42 m and 55 m in Table 8).

- *Validation of VES with Lithological Log*

Strong correlations across all parameters confirm that:

- ✓ VES methods accurately resolved subsurface conditions
- ✓ Aquifer characteristics are reliably captured.
- ✓ Borehole lithology validates VES interpretations.

This demonstrates high interpretive confidence in the hydrogeological models generated.

> *Conclusion on the Correlations*

A holistic comparison of Tables 4–7 with the lithological profile in Table 8 shows excellent agreement between geophysical parameters and actual subsurface geology in AMAC. The area is predominantly controlled by weathered and fractured basement aquifers, characterized by moderate resistivity, substantial aquifer thickness, and suitable overburden structure. The congruence between VES data and borehole evidence confirms the reliability of VES for aquifer delineation and groundwater potential mapping in

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crystalline basement terrains. Overall, this integrated analysis provides a robust foundation for groundwater exploration, development, and sustainable resource management in AMAC.

## IV. DISCUSSIONS

The identification of major aquifer sites dominated by thick weathered or fractured basement zones aligns with previous findings that emphasize the importance of these geological settings for groundwater occurrence and storage [15]; [16].

The research of [15] found that high-yield aquifers are typically located in areas of deep weathering or significant fracturing, which increase the porosity and permeability of basement rocks. Similarly, [16] noted that the most productive boreholes are usually drilled where geophysical surveys reveal thick weathered horizons, as observed at the major aquifer sites in this study.

In another study, [17] emphasized that identifying thick aquifer zones in weathered and fractured bedrock is essential for successful groundwater development in basement complex regions. This study's findings, which align with observations from other parts of Nigeria, further support the use of integrated geoelectrical methods for aquifer characterization [18].

This study shows that the uppermost topsoil and laterite layers form an unsaturated overburden with limited groundwater significance, while the underlying saprolite and partially weathered basement horizons are more porous due to rock decomposition. This agrees with previous studies, which found that groundwater storage is generally limited in the overlying lateritic and topsoil units because of their unsaturated nature and low retention capacity [18]; [15]. The saprolite and partially weathered basement zones serve as the main pathways for groundwater recharge. In addition [17], also noted that weathered and fractured basement layers are vital for groundwater movement and storage, as their increased porosity and permeability support infiltration and aquifer recharge.

Resistivity variations in these horizons are mainly due to differences in clay content, weathering, and moisture saturation. Resistivity values in saprolite and weathered basement are reliable indicators of aquifer potential, depending on weathering and the presence of conductive materials such as clay [16]. The observed range in thickness—from as little as 3 meters to over 80 meters—highlights the heterogeneity typical of basement complex terrains. Site-specific geophysical investigations is emphasized to ensure accurate groundwater assessment in these settings [15].

Correlation of Vertical Electrical Sounding (VES) data with borehole lithology in this study confirms that the primary groundwater-bearing horizons are located within the fractured basement zone, typically at depths of 38-70 meters. This finding aligns with the work of [15], who reported that significant groundwater reserves in basement complex terrains are often confined to zones of intense fracturing and weathering at similar depths.

At sites such as AMAC03, AMAC09, AMAC17, and AMAC20, thicker weathered profiles have been observed to enhance both recharge and storage capacity. This observation is consistent with the conclusions of [16], who found that a thick, conductive weathered layer overlying fractured basement rock provides favorable conditions for groundwater accumulation and movement. The increased thickness of the weathered zone not only facilitates higher recharge rates but also improves the sustainability of well yields [17].

In contrast, sites such as AMAC18 and AMAC19, which show low deep resistivity, indicate pronounced basement fracturing that supports higher-yielding aquifers. [18] also observed that low resistivity at depth is typically linked to extensive fracturing and increased groundwater potential in basement rocks.

Although secondary groundwater storage is present in the saprolite and weathered transition zones, overall aquifer productivity depends mainly on the density and connectivity of deep basement fractures. The study by [17] also emphasized that the most productive groundwater zones in basement terrains have deep, interconnected fractures that allow greater storage and transmissivity.

The integration of Vertical Electrical Sounding (VES) data with lithologic information in this study reveals strong spatial consistency, confirming the reliability of resistivity sounding for delineating aquifer layers in basement complex terrains. This outcome is consistent with previous studies, which have demonstrated that VES is a valuable tool for mapping subsurface hydrogeological features and identifying groundwater-bearing horizons, especially when combined with borehole data [15]; [18].

This study demonstrates that groundwater potential in the AMAC area is primarily governed by the degree of basement fracturing, the extent of rock weathering, and associated lithological variations. These findings are consistent with established literature on basement complex terrains, where groundwater occurrence is largely controlled by the presence and connectivity of weathered and fractured zones [15]; [16].

The results further highlight the value of integrating geoelectrical and geological data as a robust approach for aquifer assessment. Previous studies have shown that such integrated methods significantly improve the accuracy of subsurface characterization, enabling better delineation of groundwater-bearing horizons and reducing the uncertainty associated with reliance on a single dataset [18]; [17]. This approach not only supports the identification of promising aquifer zones but also informs targeted drilling and sustainable groundwater development strategies.

The holistic comparison between VES-derived aquifer characteristics and the lithological profiles presented in Table 8 demonstrates a strong concordance between geophysical

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parameters and the actual subsurface geology in the Abuja Municipal Area Council (AMAC). This observation is consistent with the findings of [19], who reported that VES techniques reliably delineate aquifer zones in crystalline basement terrains, especially when corroborated by lithological and borehole data.

The predominance of weathered and fractured basement aquifers in the study area, as indicated by moderate resistivity values and substantial aquifer thicknesses, aligns with recent studies by [20], which highlight the hydrogeological significance of weathered/fractured zones in basement complexes across Nigeria. The overburden structure observed in AMAC is also favorable for groundwater storage and transmission, further supporting the area's suitability for groundwater development [21].

The congruence between VES interpretations and borehole lithology confirms the reliability of VES for aquifer delineation and groundwater potential mapping, as also emphasized by [22]. Such an agreement not only validates the use of VES in initial groundwater investigations but also minimizes the risk and cost associated with exploratory drilling in similar geological settings.

Overall, the results reinforce the importance of targeting thick weathered and fractured basement zones for groundwater exploration, as these settings are most likely to yield sustainable aquifers in basement complex terrains. This integrated approach provides a robust framework for groundwater exploration, development, and sustainable resource management in AMAC. Recent studies, such as those by [23], advocate for such multidisciplinary methodologies to enhance the accuracy of groundwater resource assessments and to inform evidence-based decision-making for water resource management in crystalline basement terrains.

## V. CONCLUSION

This study has demonstrated the effectiveness of integrating Vertical Electrical Sounding (VES) with borehole lithological data for a comprehensive hydrogeological evaluation of the Abuja Municipal Area Council (AMAC), situated within the crystalline basement complex terrain. The correlation of twenty VES soundings with available borehole logs consistently delineates a characteristic subsurface sequence comprising a thin topsoil layer, an overlying resistive lateritic horizon, a moderately conductive weathered basement (saprolite), a partially weathered gneissic unit, and a fractured crystalline basement that forms the principal aquifer zone. The weathered and partially weathered layers enhance secondary porosity and permit significant groundwater recharge, while groundwater storage and yield are mainly controlled by the extent, thickness, and interconnectivity of fracture systems within the underlying basement rocks.

The diversity of geoelectric curve types observed (KQ, HQ, QH, KA, KAQ, and KHA) reflects the structural heterogeneity and varied hydrostratigraphic conditions across AMAC. Locations characterized by thicker saprolite and partially weathered horizons—such as AMAC03, AMAC09, AMAC17, and AMAC20—demonstrate superior groundwater potential due to enhanced recharge and storage capacity. Conversely, sites with shallow basement or minimally developed weathered profiles exhibit lower groundwater prospects, with productivity largely dependent on the presence of localized fracture zones. Areas with deep-seated fracturing, evident from lower basement resistivity signatures (e.g., AMAC18 and AMAC19), correspond to zones of higher expected yield and should therefore be prioritized for groundwater development.

The strong spatial agreement between VES-derived geoelectric parameters and borehole lithological evidence confirms the reliability of this integrated geophysical approach for aquifer delineation and groundwater assessment in basement complex environments. The findings affirm that productive aquifers in AMAC are predominantly associated with thick, weathered, and fractured basement units that provide both substantial storage and effective recharge pathways. This integrated method significantly improves the accuracy of subsurface characterization, reduces uncertainty in aquifer identification, and supports evidence-based planning for sustainable groundwater development.

Future studies should consider expanding the spatial coverage of geophysical surveys, employing advanced imaging techniques (such as 2D or 3D resistivity tomography), and integrating hydrogeological modeling with long-term water demand projections. Such efforts will enhance the resolution of subsurface models, improve groundwater sustainability planning, and support long-term water security in the region.

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## REFERENCES

[1]. Oke, S. A., & Adetola, B. A. (2017). Application of Vertical Electrical Sounding (VES) technique to groundwater exploration in Nigeria: A review. *Applied Water Science*, 7, 1559–1569. https://doi.org/10.1007/s13201-015-0360-yOpens a new window

[2]. Mukherjee, A., Jha, M. K., Kim, K., & Pacheco, F. A. L. (2024). Groundwater resources: challenges and future opportunities. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-79936-5

[3]. Ojo, E. O., Adelowo, A., & Enock, A. (2015). *Determination of Groundwater Potential in the Permanent site of University of Abuja, FCT, Nigeria*. *16*(2), 313.

[4]. Xue, Y., Niu, Z., Zhang, R., Jia, L., & Guo, S. (2024). Current Status and Future Research of Groundwater Under Climate Change: A Bibliometric Analysis. *Water*, *16*(23), 3438. https://doi.org/10.3390/w16233438

[5]. Polemio, M., & Voudouris, K. (2022). Groundwater Resources Management: Reconciling Demand, High Quality Resources and Sustainability. *Water*, *14*(13), 2107. https://doi.org/10.3390/w14132107

[6]. Dhapre, M., Jadhav, S., Das, D., Khan, J., Kim, Y.-S., Chiao, S., & Danielson, T. (2025). A Systematic Review of Machine Learning in Groundwater Monitoring [Review of *A Systematic Review of Machine Learning in Groundwater Monitoring*]. *Environmental Modelling & Software*, 106549. Elsevier BV. https://doi.org/10.1016/j.envsoft.2025.106549

[7]. Adiat, K. A. N., Adelusi, A. O., & Ayuk, M. A. (2019). Hydrogeophysical investigation and mapping of groundwater potential in crystalline basement terrain using VES and VLF-EM methods. *Journal of African Earth Sciences*, 157, 103516. https://doi.org/10.1016/j.jafrearsci.2019.103516Opens a new window

[8]. Olorunfemi, M. O., Fasunwon, O. O., & Ojo, J. S. (2021). Geoelectric investigation for groundwater potential evaluation in basement complex terrain: Case study of Ibadan, southwestern Nigeria. *Water Resources Management*, 35(7), 2071–2085. https://doi.org/10.1007/s11269-021-02821-8

[9]. Abdullahi, M. G., Olorunfemi, M. O., & Afolayan, J. F. (2022). Application of integrated geophysical methods in groundwater exploration in crystalline basement terrain of northern Nigeria. *Environmental Earth Sciences*, 81(9), 221. https://doi.org/10.1007/s12665-022-10431-6Opens a new window

[10]. Olayinka, A. I., & Yaramanci, U. (2022). Advances in geophysical methods for groundwater exploration and aquifer characterization in crystalline basement terrain. *Surveys in Geophysics*, 43(1), 1–32. https://doi.org/10.1007/s10712-021-09652-1Opens a new window

[11]. Fashae, O. A., Tijani, M. N., Talabi, A. O., & Adedeji, O. H. (2020). Groundwater exploration and aquifer characterization in basement complex terrain: advances, challenges, and prospects. *Geosciences*, 10(12), 488. https://doi.org/10.3390/geosciences10120488Opens a new window

[12]. Olusola, O., Olorunfemi, M. O., & Adeyemo, A. (2023). Integration of VES and borehole data for aquifer characterization in crystalline basement terrain, southwestern Nigeria. *Journal of Hydrology: Regional Studies*, 48, 101334. https://doi.org/10.1016/j.ejrh.2023.101334Opens a new window

[13]. Olaojo, A. A., Olayinka, A. I., & Amadi, A. N. (2021). Integrated geoelectrical and hydrogeological evaluation of groundwater potentials in a fractured basement area, southwestern Nigeria. *Groundwater for Sustainable Development*, 14, 100634. https://doi.org/10.1016/j.gsd.2021.100634Opens a new window

[14]. Afolayan, J. F., Olorunfemi, M. O., & Ajayi, T. R. (2022). Delineation of groundwater potential zones using integrated geophysical and GIS techniques in a basement complex terrain. *Hydrogeology Journal*, 30(8), 2147–2163. https://doi.org/10.1007/s10040-022-02513-2Opens a new window

[15]. Olayinka, A.I., & Olorunfemi, M.O. (1992). Determination of geoelectrical characteristics in Okene area and implications for borehole siting. *Journal of Mining and Geology*, 28(2), 403-412.

[16]. Dan-Hassan, M.A., & Olorunfemi, M.O. (1999). Hydrogeophysical investigation of a basement terrain in the north central part of Kaduna State, Nigeria. *Journal of Mining and Geology*, 35(2), 189-206.

[17]. Ayolabi, E.A., Folorunso, A.F., & Oloruntola, M.O. (2009). Geoelectrical and hydrogeological evaluation of the groundwater potential of parts of the basement complex terrain of southwestern Nigeria. *Journal of Applied Sciences and Environmental Management*, 13(3), 71-74.

[18]. Olorunfemi, M.O., & Okhue, E.T. (1992). Hydrogeophysical and hydrogeological parameters from electrical sounding at Ile-Ife, Nigeria. *Journal of Mining and Geology*, 28(2), 221-229.

[19]. Olayinka, A.I., & Adia, B.U. (2023). Assessment of VES and borehole data for aquifer characterization in crystalline basement terrain. *Water Resources Management*, 37(2), 441-457. https://doi.org/10.1007/s11269-023-03256-9Opens a new window

[20]. Yusuf, A.O., Adeyemo, A.A., & Balogun, A.O. (2022). Hydrogeophysical investigation of basement aquifers in northern Nigeria. *Groundwater for Sustainable Development*, 18, 100770. https://doi.org/10.1016/j.gsd.2022.100770

[21]. Ehirim, C.N., Nwankwo, C.N., & Onu, N.N. (2021). Application of VES for groundwater exploration in basement terrains of Nigeria. *Journal of African Earth Sciences*, 180,

104227. https://doi.org/10.1016/j.jafrearsci.2021.104227Opens a new window

[22]. Ibuot, J.C., George, N.J., & Akpabio, I.O. (2021). Reliability of VES in groundwater studies: A case study from southeastern Nigeria. *Environmental Earth Sciences*, 80(11), 470. https://doi.org/10.1007/s12665-021-09763-5Opens a new window

[23]. Chukwuma, E.C., Onwuemesi, A.G., & Ehirim, C.N. (2024). Integrated geophysical and hydrogeological evaluation of basement complex aquifers in North-central Nigeria. *Hydrogeology Journal*, 32(1), 75-89. https://doi.org/10.1007/s10040-023-02567-5Opens a new window