GROUNDWATER POTENTIAL DELINEATION IN ZARIA: AN APPLICATION OF VERTICAL ELECTRICAL SOUNDING (VES) AND WATER SAFETY PLANNING

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ABSTRACT
This study presents a geophysical investigation to delineate groundwater potential and assess aquifer vulnerability within the ICSA/Rahmat Hostel area at Ahmadu Bello University, Zaria, Nigeria. In this crystalline basement complex, groundwater occurrence is primarily controlled by the thickness of the weathered overburden and secondary fracture zones. Four Vertical Electrical Sounding (VES) stations were established using the Schlumberger array, with electrode spacing (AB/2) extending to 100 m to ensure sufficient depth of investigation. Data were processed using IP2WIN software to produce geoelectric models. The results identified varying curve types (KH, HKH, and A), reflecting distinct weathering profiles. VES 3 was identified as the most viable location for groundwater development, exhibiting an HKH-type curve with a five-layer model and a weathered overburden of approximately 10.5 m. VES 1 and VES 2 showed moderate potential, characterized by KH-type curves and aquiferous layers exceeding 9 m in thickness. Conversely, VES 4 displayed an A-type curve, indicating a low potential due to the absence of significant fracturing. To evaluate environmental safety, the Total Longitudinal Conductance (G) was calculated. Stations VES 1, 2, and 3 were rated as Moderate, with G values ranging from 0.3370 to 0.3973 S, suggesting the clay-rich overburden acts as a natural filter. VES 4 was rated Poor, offering limited protection. The study recommends prioritizing borehole construction at VES 3 for a sustainable water supply. The paper recommends mandatory hydrochemical screening before water point commissioning, enforcement of borehole construction standards aligned with Nigeria's National Water Policy, and establishment of a formal ABU Campus Water Safety Planning framework aligned with WHO guidelines and SDG 6 commitments.

Keywords*: Groundwater Potential, Vertical Electrical Sounding, Longitudinal Conductance, Aquifer Protective Capacity, Zaria.*

INTRODUCTION
Water is essential to people, and the largest available source of fresh water lies underground. Increased demand for water has spurred the development of underground water resources, leading to improved techniques for investigating the occurrence and movement of groundwater (Bassey et al., 2023). In crystalline basement complex terrains, such as those found in Zaria, Nigeria, groundwater is not uniformly distributed; instead, its occurrence is primarily controlled by the thickness of the weathered overburden (regolith) and the presence of secondary features such as joints and fractured zones in the underlying bedrock (Sikah et al., 2016; Popoola et al., 2020).

Geophysical principles have been successfully used in solving groundwater, mining, civil engineering, and pollution problems (Sikah et al., 2016). The role of geophysics in groundwater exploration is attributed to the fact that water is a necessity, with 95% of the earth's fresh water found in voids in soil and permeable geologic formations. Among several geophysical methods, the electrical resistivity method is often preferred because it is the quickest and most economical technique for groundwater exploitation (Ogungbemi et al., 2013). Specifically, Vertical Electrical Sounding (VES) is employed to characterize the subsurface geoelectric properties and identify the fractured-to-fresh bedrock interface (Ige et al., 2022).

Beyond exploration, evaluating the overburden's Aquifer Protective Capacity is a critical environmental consideration. This assessment utilizes geoelectric parameters, such as Total Longitudinal Conductance (G), to measure the ability of the geological layers overlying the aquifer to retard and filter infiltrating contaminants from the surface (Oladapo & Akintorinwa, 2007; Aizebeokhai et al., 2018). This study aims to identify suitable sites for borehole construction to provide a sustainable water supply for the ICSA/Rahmat Hostel environs, while assessing the natural vulnerability of the local aquifer system.

MATERIALS AND METHODS
Study Area
The study area is located within the Ahmadu Bello University campus, Zaria, Kaduna State, Northwest Nigeria (Figure 1). Zaria lies approximately between latitudes 11.0°N–11.3°N and longitudes 7.6°E–7.9°E, at an elevation of approximately 670 m above mean sea level. The ICSA/Rahmat Hostel precinct occupies a gently undulating terrain typical of the Sudan Savanna zone, with local relief influenced by weathering intensity and drainage incision. The study site spans approximately 0.5 km², with four VES stations distributed to capture spatial variability in the weathering profile across the precinct. The area is characterised by moderate to sparse vegetation cover, lateritic surface soils, and seasonally active drainage channels that indicate shallow groundwater connectivity.

Field Instrumentation and Data Collection
The primary geophysical method used was Vertical Electrical Sounding (VES), which measures the vertical variation of electrical resistivity with depth (Ige et al., 2022). The survey was conducted using a standard resistivity meter capable of measuring resistance with high precision (ABEM Terrameter SAS 300). The Schlumberger array was utilized for all soundings (Adeyeye et al., 2021). This configuration is favored in basement terrains for its

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depth of penetration and superior sensitivity to vertical changes in subsurface layers compared to other arrays. Four (4) VES stations were established at strategic points within and around the ICSA/Rahmat Hostel to ensure a representative coverage of the area's hydrogeological characteristics. The current electrode spacing (AB/2) was progressively expanded from a minimum of 1.0 m to a maximum spread of 100 m (total AB = 200 m). This expansion was calculated to ensure sufficient depth of investigation to encounter the competent basement rock (Bassey et al., 2023)

Data Processing and Interpretation

The field data, consisting of measured resistance (R) and electrode spacing, underwent a multi-stage processing procedure to produce final geoelectric models. The measured resistance was converted to apparent resistivity (ρ_a) by multiplying by the geometric factor (K) specific to the Schlumberger array:

$\rho_a = KR$,
$$(1)$$

where $K = \pi \frac{a^2 - b^2}{2b}$, (2)

where a is half the current electrode spacing $AB/2$, and b is half the potential electrode spacing.

The data were plotted on log-log scales to identify resistivity curve types (e.g., KH, H, K, and A types). These curves provide an initial indication of the subsurface layering sequence and the nature of the weathering profile (Sikah et al., 2016). The field curves were subjected to computer-aided iterative inversion using the IP2WIN software program developed by Moscow State University. This process refined the resistivity (ρ), thickness (h), and depth (d) of the individual geoelectric layers until the Root Mean Square (RMS) error between the field data and the synthetic model was minimized (Bassey et al., 2023).

Evaluation of Aquifer Protective Capacity

To assess the vulnerability of the aquifer to surface contamination, the total Longitudinal Conductance (G) was calculated for each station using the Dar-Zarrouk parameters (Oladapo & Akintorinwa, 2007):

$G = \sum_{i=1}^{n} \frac{h_i}{\rho_i}$, (3)

where h_i and ρ_i are the thickness and resistivity of the i-th overburden layer, respectively. The resulting values were compared against established classification scales (Oladapo & Akintorinwa, 2007) to rate the protective capacity of the overburden at each station.

Table 1 below presents the protective capacity based on the standard classification scale for the Nigerian Basement Complex (Oladapo & Akintorinwa, 2007).

Table 1. The protective capacity rating (Oladapo & Akintorinwa, 2007).

Longitudinal Conductance G (S)	Protective Capacity Rating
> 10	Excellent
5.0 - 10	Very Good
0.7 - 4.9	Good
0.2 - 0.69	Moderate
0.1 - 0.19	Weak
< 0.1	Poor

FINDINGS AND DISCUSSION

VES station 1 delineated four distinct geoelectric layers (Figure 1). Layer 1 (topsoil) has a resistivity value of 53.5 Ωm and a thickness of 1.51 m. It is characterized as a sandy/clayey topsoil typical of the area. The resistivity of layer 2 (laterite/weathered Layer) increases to 92.2 Ωm with a thickness of 3.01 m. This indicates a more resistive, possibly lateritic or slightly dry weathered zone. For the aquiferous layer (layer 3), resistivity decreases significantly to 32.8 Ωm from 4.52 m to 13.6 m. This low-resistivity layer, with a substantial thickness of 9.06 m, represents the primary saturated aquiferous zone at this station. The final layer, the basement, shows a sharp increase in resistivity to 604 Ωm. This high value signifies the presence of a relatively fresh or partially fractured basement rock at a total depth of 13.6 m. VES station 1 follows a KH-type curve ($\rho_1 < \rho_2 > \rho_3 < \rho_4$), which is often associated with productive groundwater zones in basement terrains. The thick weathered layer (9.06 m) with a relatively conductive resistivity (32.8 Ωm) suggests that this location has moderate to high groundwater potential. The depth to the basement is sufficient to accommodate a sustainable borehole, provided the yield is tested across seasonal variations. The geoelectric layer breakdown for VES station 1 is as shown in Table 2. To determine the protective capacity of the overburden (layers 1, 2, and 3), the total longitudinal conductance (G) is calculated as:

- Layer 1 (G_1) = 1.5 / 53.5 = 0.0282 S
- Layer 2 (G_2) = 3.01 / 92.2 = 0.0326 S
- Layer 3 (G_3) = 9.06 / 32.8 = 0.2762 S

$Total\ G = 0.0282 + 0.0326 + 0.2762 = 0.3370\ S$

According to standard classifications (e.g., Oladapo and Akintorinwa, 2007), a G value of 0.3370 falls within the moderate protective capacity range (0.2–0.69 S). This indicates that the clayey materials within the overburden at this station provide a reasonable natural filter against surface-derived contaminants.
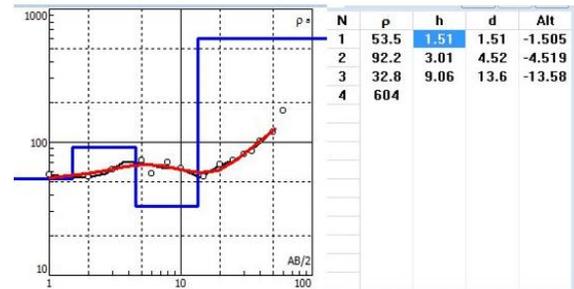

Figure 1. The digitized model of the interpreted VES station 1.

Table 2. Summary of Geoelectric Parameters and Inferred Lithology for VES 1.

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology
1	53.5	1.51	1.51	Topsoil
2	92.2	3.01	4.52	Laterite/weathered layer
3	32.8	9.06	13.6	Aquiferous layer
4	604	∞	∞	Basement

For VES Station 2 (Figure 2), the geoelectric investigation reveals a distinct four-layer subsurface model. This station is characterized by a high-resistivity terminal layer, indicating a massive, non-

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porous bedrock at depth. The third layer, with a resistivity of 31.1 Ωm, represents the weathered basement or saprolite zone. With a thickness of 10.3 m, this unit serves as the primary groundwater reservoir at this location. The terminal layer shows an exceptionally high resistivity of 14655 Ωm, indicating fresh, unweathered, and non-fractured crystalline basement rock that acts as an impermeable barrier to further downward percolation. VES Station 2 exhibits a KH-type curve ($\rho_1 < \rho_2 > \rho_3 < \rho_4$), a configuration that highlights a conductive weathered zone beneath a more resistive overburden. Due to the substantial thickness of this weathered saprolite, VES 5 is considered a viable location for groundwater development and is likely suitable for a moderate-yield borehole. The geoelectric layer breakdown for VES station 2 is shown in Table 3. The protective capacity of the aquifer is:

- Layer 1 (G_1) = 1.94 / 152 = 0.0128 S
- Layer 2 (G_2) = 3.62 / 732 = 0.0049 S
- Layer 3 (G_3) = 10.3 / 31.1 = 0.3312 S

$Total\ G = 0.0128 + 0.0049 + 0.3312 = 0.3489\ S$

Based on the classification scale established for Nigerian basement terrains, the protective capacity is rated as moderate (e.g., Oladapo & Akintorinwa, 2007); that is, the overburden at this station provides moderate protection. This suggests that the thick, clay-rich saprolite layer (layer 3) acts as a natural geoelectric barrier that can retard and filter surface contaminants before they reach the water-saturated horizons (Bahri et al., 2023; de Almeida et al., 2021).
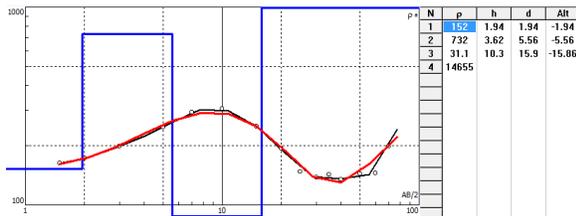

Figure 2. The digitized model of the interpreted VES station 2.

Table 3. Summary of Geoelectric Parameters and Inferred Lithology for VES 2.

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology
1	152	1.94	1.94	Topsoil
2	732	3.62	5.56	Laterite/weathered layer
3	31.1	10.3	15.9	Aquiferous layer
4	14655	∞	∞	Basement

For VES Station 3 (Figure 3), the geoelectric investigation reveals a more complex five-layer subsurface model. This station is characterized by alternating resistivity phases, indicating a highly heterogeneous subsurface. The second layer (17.2 Ωm) and fourth layer (19.3 Ωm) represent weathered or fractured zones. Specifically, the fourth layer, with a thickness of 6.94 m, represents a significant potential groundwater reservoir. The terminal layer shows a high resistivity of 8,427 Ωm, representing the fresh crystalline basement. VES Station 6 exhibits an HKH-type curve ($\rho_1 > \rho_2 < \rho_3 > \rho_4 < \rho_5$). This configuration is particularly favorable for groundwater exploration in basement terrains as it suggests multiple horizons of weathering or fracturing. With a cumulative thickness of weathered overburden reaching

approximately 10.5 m, this station is considered a very viable location for groundwater development. The geoelectric layer breakdown for VES station 3 is presented in Table 4. The total longitudinal conductance (G) is:

- Layer 1 (G_1) = 0.75 / 147 = 0.0051 S
- Layer 2 (G_2) = 0.531 / 17.2 = 0.0309 S
- Layer 3 (G_3) = 2.3 / 1714 = 0.0013 S
- Layer 4 (G_4) = 6.94 / 19.3 = 0.3600 S

$Total\ G = 0.0051 + 0.0309 + 0.0013 + 0.3600$
$= 0.3973\ S$

According to established classification scales for Nigerian basement terrains, the protective capacity is rated as moderate. The presence of these conductive layers suggests that the overburden provides a natural filter, protecting the underlying aquifer from surface-derived contamination.
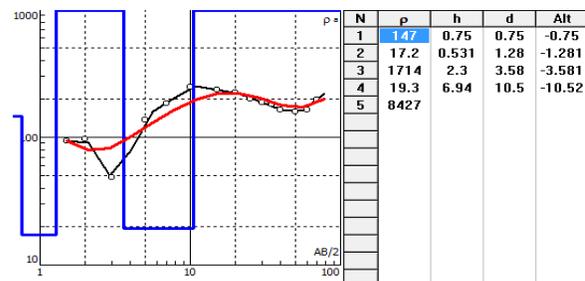

Figure 3. The digitized model of the interpreted VES station 3

Table 4. Summary of Geoelectric Parameters and Inferred Lithology for VES 3.

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology
1	147	0.75	0.75	Topsoil
2	17.2	0.531	1.28	Topsoil
3	1714	2.3	3.58	Laterite/weathered layer
4	19.3	6.94	10.5	Aquiferous layer
5	8427	∞	∞	Basement

For VES Station 4 (Figure 4), the geoelectric investigation reveals a simpler three-layer subsurface model. Unlike the previous stations, this location shows a steady increase in resistivity with depth, starting from 190 Ωm in the topsoil to 510 Ωm in the third layer. This profile indicates the absence of a distinct, highly conductive weathered aquifer unit at the measured depths.

VES station 4 exhibits an A-type curve ($\rho_1 < \rho_2 < \rho_3$). This type of curve is generally associated with areas of low groundwater potential because it reflects a lack of significant weathering or fracturing above the deeper rock units.

The protective capacity of the overburden is calculated as:

- Layer 1 (G_1) = 5.98 / 190 = 0.0315 S
- Layer 2 (G_2) = 10.9 / 297 = 0.0367 S

$Total\ G = 0.0315 + 0.0367 = 0.0682\ S$

The Total Longitudinal Conductance is relatively low at 0.0682 S, which corresponds to a poor to weak protective capacity. Consequently, the overburden at this station provides limited natural protection for potential groundwater resources. It suggests that the area is less suitable for high-yield borehole development than at Stations 5 and 6.
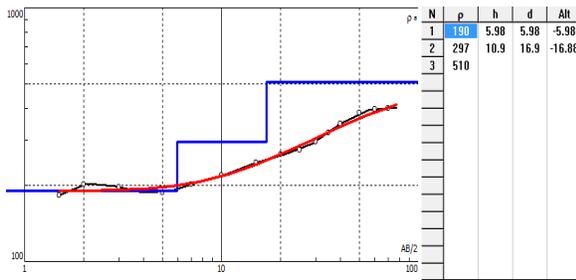
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Figure 4. The digitized model of interpreted VES station 4.

Table 5. Summary of Geoelectric Parameters and Inferred Lithology for VES 4.

Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology
1	190	5.98	5.98	Topsoil/weathered layer
2	297	10.9	16.9	Aquiferous layer
3	510	∞	∞	Basement rock

Table 6. Summary of Protective Capacity Rating for each VES Station.

Station	Total S (S)	Protective Capacity Rating
VES 1	0.3370	Moderate
VES 2	0.3489	Moderate
VES 3	0.3973	Moderate
VES 4	0.0682	Poor

The geophysical assessment of the ICSA/Rahmat Hostel area in Zaria identifies a complex crystalline basement terrain in which groundwater potential is primarily governed by the thickness of the weathered overburden and bedrock fracturing. The study successfully utilized Vertical Electrical Sounding (VES) to delineate subsurface layers and assess their ability to protect groundwater from surface contamination. Analysis of the four VES stations revealed varying degrees of groundwater viability. VES 3 is the most promising site, featuring a complex five-layer model with an HKH-type curve. It boasts a cumulative weathered overburden of approximately 10.5 m, suggesting multiple productive horizons. VES 1 and VES 2 both exhibit KH-type curves, which are typical of productive zones in basement terrains. These stations feature substantial aquiferous layers (9.06 m and 10.3 m, respectively). VES 4 displayed an A-type curve, indicating a steady increase in resistivity with depth and a lack of significant weathering, making it the least suitable for borehole development. The Total Longitudinal Conductance *(G)* was used to rate the protective capacity of the overburden against contaminants. VES 1, 2, and 3 all fall within the Moderate range (0.3370 to 0.3973 *S*), indicating that their clay-rich layers provide a reasonable natural filter. VES 4 is rated as Poor (0.0682 *S*), offering limited natural protection.

Conclusion and Recommendations
The study successfully identified variations in groundwater potential across the four VES stations. The subsurface is characterized by a crystalline basement complex, in which water retention depends on the thickness of the weathered regolith and fractured bedrock. VES 3 is the most viable location for groundwater development due to its complex five-layer HKH-type

curve and a significant weathered overburden of approximately 10.5 m. VES 1 and VES 2 also show moderate to high potential with substantial aquiferous layers exceeding 9 meters in thickness. VES 1, 2, and 3 exhibit a moderate protective capacity (*G* values between 0.3370 and 0.3973 *S*), suggesting that the clayey overburden acts as a natural filter against surface contaminants. VES 4 is considered unsuitable for high-yield development due to its A-type curve, the absence of a distinct conductive aquifer unit, and a poor protective capacity rating. This work recommends mandatory hydrochemical screening prior to water point commissioning, enforcement of borehole construction standards aligned with Nigeria's National Water Policy, and establishment of a formal ABU Campus Water Safety Planning framework aligned with WHO guidelines and SDG 6 commitments.

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