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Assessment of Aquifer Protective Capacity and Groundwater Vulnerability Using VES-Derived Longitudinal Conductance in Iwo, Southwestern Nigeria

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ABSTRACT
Investigation of groundwater vulnerability is indispensable for sustainable aquifer management, principally in areas experiencing rapid population growth and increasing anthropogenic pressure on water resources. This study employs the vertical electrical sounding (VES) method to investigate aquifer protective capacity using longitudinal conductance, a geoelectrical parameter that serves as a quantitative indicator of groundwater vulnerability investigation. In this study, six VES stations were acquired across the study area and interpreted using one-dimensional layered-earth inversion to determine subsurface resistivity distribution and the thickness of overlying lithologic units. The longitudinal conductance (S) was calculated as the sum of the ratios of layer thickness to resistivity for all layers. The results revealed that the overburden thickness ranges from 3.8 to 35.1 m, the bedrock resistivity ranges from 545.3 to 3353.4 Ωm, and the calculated longitudinal conductance values vary from (0.13345 to 0.250887 S), indicating principally weak to moderate protective capacity, which suggest varying degree of groundwater vulnerability across the investigated VES stations. The results showed that in terms of aquifer vulnerability, low values suggest more vulnerability to surface contamination, whereas higher longitudinal conductance and thicker overburden suggest enhanced protective capacity. Therefore, the study emphasized that the VES-derived longitudinal conductance offers a vital background data for groundwater protection and management; however, they represent a preliminary vulnerability assessment.

Keywords:
Geophysical method,
Longitudinal conductance,
Groundwater investigation,
Protective capacity.

INTRODUCTION

In Nigeria, groundwater is a crucial freshwater resource that meets the household, agricultural, and industrial water needs, especially in areas where surface water is insufficient, unpredictable, or seasonal (Egbueri et al., 2025). Groundwater is the primary source of drinkable water for both rural and quickly growing urban communities in Southwestern Nigeria, including Osun State (Elujoba et al., 2025). In the Nigerian Basement Complex, where surface water bodies are few and groundwater availability is regulated by weathered and fractured crystalline rocks, this dependence is particularly visible (Akinwumiju, 2020). Despite the significances of groundwater resource in basement complex formations, they are fundamentally vulnerable to contamination because of thin regolith cover, strong anthropogenic pressures and shallow aquifer systems (Egbueri et al., 2025). For sustainable water management in these environments, a systematic evaluation of groundwater vulnerability has become crucial and essential (Plummer et al., 2012).

The inherent sensitivity of groundwater systems to contamination due to the subsurface's natural hydrogeological features is known as groundwater vulnerability (Jain, 2023). The degree of fracturing, depth to groundwater, permeability differences across subsurface layers, and the thickness and composition of the regolith all have a substantial impact on vulnerability in basement complex terrains (Pradhan et al., 2022). Because of this, contaminants can move quickly from the surface to the groundwater system, especially in places where the overburden is thin, sandy, or fractured (Maurya et al., 2025). Hydrogeological data, including borehole logs, pumping test results, soil maps, and groundwater quality evaluations, are commonly used in conventional groundwater vulnerability assessment method9s (Ahmed et al., 2025; Hasan and Su, 2026). Even though these methods offer insightful information, they are often constrained by restricted data availability, high prices, and insufficient spatial coverage, especially in basement complexes. Furthermore, the significant lateral variability typical of crystalline basement terrains might not be sufficiently captured by point-based data (Choudhury et al., 2026). These difficulties underscore the need for new methods that are affordable, widely distributed geographically, and able to characterize subsurface protective capacity.

In basement complex terrains, geophysical methods, especially the electrical resistivity geophysical method have become effective instruments for investigating groundwater (Adeniji et al., 2024). Changes in lithology, degree of weathering, fracture density, moisture content, and clay mineralogy are all important factors influencing groundwater occurrence and vulnerability, and electrical resistivity techniques are vulnerable to these changes (Adiat et al., 2024). In Southwestern Nigeria, vertical electrical sounding (VES), which is commonly carried out using the Schlumberger array, has been widely used to identify groundwater-bearing zones, to estimate overburden thickness, and to delineate subsurface layers (Adagunodo et al., 2023; Akiang et al., 2025). Also, Dar Zarrouk characteristics, which offer hydrogeophysical significant indicators for aquifer characterization, may be obtained quantitatively from VES data in addition to qualitatively interpreting resistivity profiles (Aladeboyeje et al., 2024). Adeniji et al., (2022) carried out a study to evaluate the groundwater protective capacity of a crystalline basement complex terrain in southwestern Nigeria using Dar-Zarrouk parameters. Twenty Vertical Electrical Sounding (VES) stations were occupied with the Schlumberger electrode configuration to obtain subsurface resistivity and layer thickness information. The protective capacity of the subsurface layers was assessed and categorized into low, weak, moderate, and good classes. The results revealed that approximately 70% of the area possesses poor to weak protective capacity, suggesting that the underlying aquifers are highly susceptible to contamination from surface and near-surface sources. These findings underscore the importance of continuous groundwater quality monitoring and proper environmental management practices to safeguard groundwater resources and ensure their sustainable use.

For assessing aquifer protective capacity and intrinsic groundwater vulnerability, longitudinal conductance has found to be especially helpful among these metrics. Longitudinal conductance is a reliable measure of the overburden's capacity to reduce the contaminants migration since it incorporates both the thickness and resistivity of subsurface layers covering the aquifer (Adeniji et al., 2022). George, (2021) examined the geoelectrical properties and contamination susceptibility of an alluvial environment using fourteen Vertical Electrical Soundings (VES) conducted with the Schlumberger electrode configuration. The acquired data were interpreted to obtain primary geoelectrical parameters and subsequently used to derive secondary parameters, namely longitudinal conductance and longitudinal resistance. Four distinct sedimentary layers characterized by varying resistivity values were delineated, indicating differences in subsurface lithology. Reflection coefficient analysis showed an alternating sequence of argillite and arenite formations. The calculated longitudinal conductance and resistance values suggest that the subsurface offers relatively weak protection against contaminant infiltration and is therefore vulnerable to pollution. The study highlights the effectiveness of geoelectrical indices in evaluating groundwater vulnerability and characterizing subsurface geological conditions.

This research however investigates the increasing strain that urbanization, the increased land use, and population development are placing on groundwater supplies in the Iwo region in Southwestern Nigeria. Discovery high-vulnerability areas is crucial for sustainable water management, since rising groundwater abstraction raises the danger of contamination, especially in places with poor natural protection. Therefore, this work offers an economical and scientifically sound way to investigate aquifer protective capacity by using VES-derived longitudinal conductance. Thus, by highlighting characteristic aquifer vulnerability, this study emphasized the function of weathered regolith and evidence-based sustainable groundwater management in the Iwo environment and other basement complex areas where groundwater dependency is rising.

Study Area

The study area covers selected area in Iwo town, Osun State, Southwestern Nigeria, within the Nigerian Basement Complex (Obaje, 2009; Tijani, 2023). It is approximately located between latitudes 7°38′ N and 7°42′ N (DMS) and longitudes 4°08′ E and 4°12′ E (DMS). The area experiences a humid tropical climate with distinct wet and dry seasons. The dry season runs from November to February, while the wet season is from March to October. Furthermore, the average annual rainfall falls between 1000 and 2000 mm, which encourages groundwater recharging but also raises the possibility of pollutant penetration in areas with poor overburden protection (Ogunbode et al., 2025). Mean annual temperatures range from 22 °C to 32 °C, which favors intense chemical weathering of basement rocks (Laniyan et al., 2025).

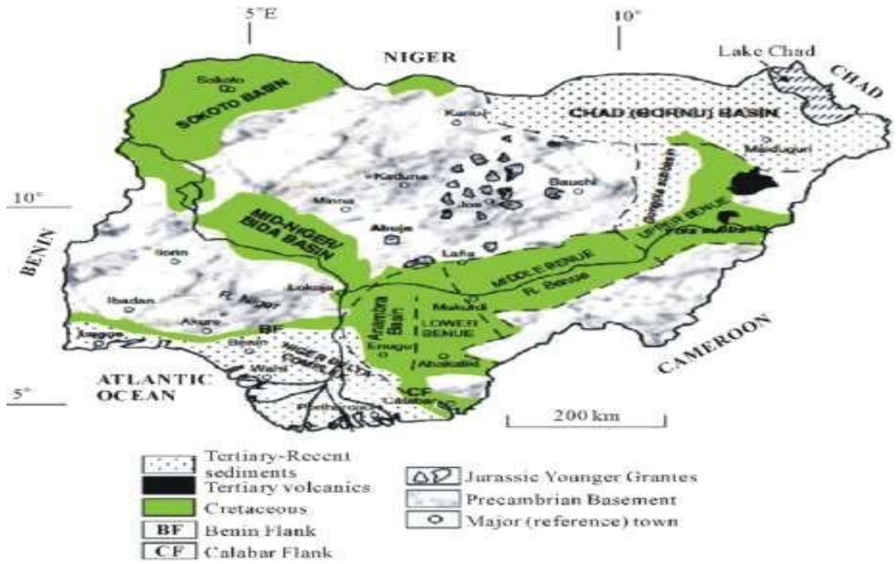

Figure 1: Geological map of Nigeria (after Obaje, 2009)

Geologically, the area is underlain by Precambrian crystalline basement rocks typical of southwestern Nigeria, including migmatite–gneiss complexes, banded gneisses, schists, and granitic intrusions (Obaje, 2009). These rocks have negligible primary porosity, and groundwater occurrence depends mainly on secondary porosity developed through weathering and fracturing (Egbueri et al., 2025). Groundwater occurs predominantly within the weathered overburden and fractured basement zones (Adiat et al., 2024). Groundwater is mostly abstracted through hand-dug wells and boreholes, often without prior assessment of aquifer vulnerability. Potential sources of groundwater contamination include septic systems, indiscriminate waste disposal, agricultural inputs, and surface runoff, necessitating groundwater vulnerability assessment in the area.

MATERIALS AND METHODS

Groundwater vulnerability assessment was carried out using the electrical resistivity method (Grant and West 1965). The principle behind electrical resistivity is based on Ohm's Law, which explains how electric current behaves in a conductor (Heaney, 2003). It states that the amount of current flowing through a metallic conductor is directly proportional to the voltage (potential difference) applied across its ends, as long as factors like temperature and other physical conditions remain constant (Grant and West, 1965). Mathematically, it is expressed as:

$$I = \frac{V}{R} \quad (1)$$

Where I is the current, measured in ampere (A), V is the potential difference measured in Volt (V), and R is the resistance measure in (Ω). From the measured current and voltage, the apparent resistivity of the subsurface can be determined. The arrangement of the four electrodes during the field-survey determines the geometric factor, (k), that is used for this (Omolaiye et al., 2025). The resistivity meters often offer the resistance value (R) rather than resistivity directly in field measurements. Therefore, the apparent resistivity is calculated by multiplying the measured resistance by the geometric factor (Grant and West, 1965; Loke et al., 2020 and Singh and Sharma (2022), expressed as:

$$\rho_a = kR \quad (2)$$

This relationship makes it possible to convert field resistance measurements into meaningful resistivity values for geophysical interpretation. Six vertical electrical sounding measurements were acquired at locations within the research area using the Omega-Resistivity meter for the field survey in order to provide sufficient spatial coverage, as indicated by the base map (Figure 2).

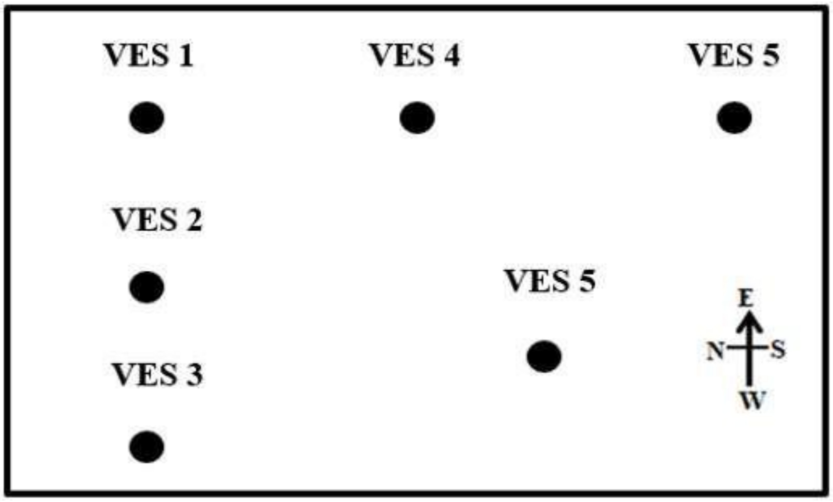

Figure 2: Schematic layout of the VES stations from the study area

The Schlumberger electrode arrangement was utilized, where the potential electrodes stayed practically near to one another but the current electrodes gradually extended symmetrically about a central point (Bakhtiar, 2010; Okolie, 2010).

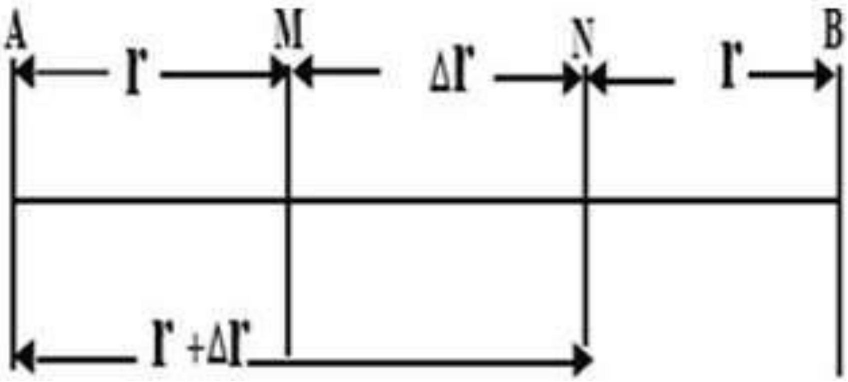

Figure 3: Schlumberger electrode configuration (Bakhtiar, 2010)

The electrical resistivity investigation was conducted using a maximum current electrode half-spacing (AB/2) ranging from 65 m to 100 m which depends on the available spread length and the estimated depth to the basement rock (Bakhtiar, 2010). Measurements were obtained by gradually increasing the separation between the current electrodes, thereby allowing the injected current to penetrate deeper subsurface layers and explore varying depth intervals (Telford et al., 1976). The acquired vertical electrical sounding (VES) data were originally interpreted through automatic curve matching using theoretical and auxiliary master curves (Keller and Frischknecht, 1966; Koefoed, 1979). This method enabled the determination of the resistivity values, layer thicknesses, and depths of the various subsurface geoelectric units (Keller and Frischknecht, 1966; Koefoed, 1979). Also, the derived geoelectrical parameters were further refined through forward modelling using the computer-based inversion software WinResist Version 1.0 (Vander Velpen, 1988). The iterative modelling process was carried out to complete the best fit between the observed and calculated field curves, resulting in a low Root Mean Square (RMS) error and a more reliable subsurface model. Subsurface layers were categorized as topsoil, weathered layer, fractured basement, and fresh basement based on resistivity differences and known basement complex correlations. The weathered overburden, which regulates the aquifer's protective capacity, was emphasized.

Theory of Longitudinal Conductance

The longitudinal conductance is theoretically based on classical electrical sounding theory (Niwas et al. 2011). It is described as the total of all layers above the aquifer's thickness to resistivity ratios (Fajana, 2020). In basement complex environments, high longitudinal conductance values are typically related with thick, clay-rich weathered layers that exhibit low resistivity and low hydraulic conductivity, thereby offering effective protection to underlying aquifers (Adabanija, et al., 2021; Ogungbemi, 2025). Conversely, low longitudinal conductance values indicate thin, resistive, sandy, or fractured layers that provide minimal protection and correspond to high groundwater vulnerability (Ajani et al., 2021; Akingboye, 2022). The longitudinal conductance (S) Was calculated as:

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

Where h_i is the thickness of the ith layer, ρi is the true resistivity of the ith layer, and the summation includes all layers overlying the aquifer. Groundwater vulnerability was evaluated by classifying longitudinal conductance values into aquifer protective capacity categories ranging from excellent to poor as shown in Table 1.

Table 1: Showing the Longitudinal Conductance Classification (Oladapo et al., 2007)

LC Rating S (Siemens)	Protective Capacity	Implications
> 10	Excellent	Thick, Clayey layers; very low contamination risk
5 – 10	Good	Moderately thick, conductive overburden
0.2 – 4.9	Moderate	Moderate protection; some contamination risk
0.1 – 0.19	Weak	Thin or resistive overburden, high vulnerability
< 0.1	Poor/Negligible	Very little to no protection; aquifer highly

RESULTS AND DISCUSSION

The resistivity sounding results can be explained clearly by investigative each subsurface layer in a more natural and related way. The topmost portion of the curve is formed by the first layer, or topsoil, which represents surface elements like laterite, clay, or sand. Compaction and moisture content have an important impact on its resistance. While lower values about 60 Ωm (VES 1) imply clay-rich environments, high values like approximately 1216 Ωm (VES 5) suggest a laterite (Sunmonu et al., 2018). The topsoil is usually thin and lies above the water table, so it has little relevance for groundwater supply. The weathered basement, which is the primary aquifer zone, is represented by the second layer. Qualitatively, it seems like a downward dip but statistically, resistivity decreases dramatically at this location, reaching around 45 Ωm in VES 5 with a discernible thickness.

This decrease suggests that weathering and water saturation have enhanced conductivity. Although very low readings may indicate clay rather than productive water-bearing material, a thick, somewhat low resistivity layer usually indicates high groundwater potential. A transition zone, the third layer is frequently partially fractured or weathered. In this layer, the resistivity starts to increase as the curve starts to rise. Fractured bedrock, which can efficiently store and transfer groundwater, is suggested by moderate values. Sharp spikes indicate limited fracture, whereas gradual increases are advantageous. Lastly, a sharp upward trend and extremely high resistivity readings (typically beyond 1000 Ωm, such as 3353 Ωm in VES 3) indicate the fourth layer, which is the fresh basement.

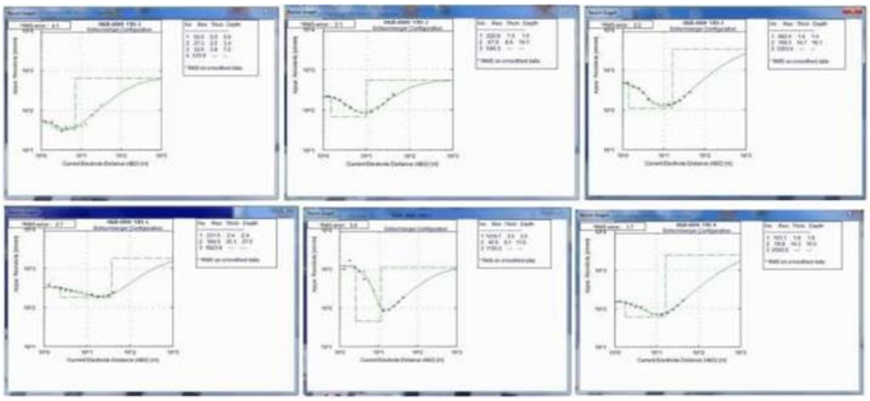

Figure 4: The Resist Graph of VES 1 to VES 6

2D Geo-Section of the Subsurface

The 2D geoelectrical sections can be understood as a straightforward account about the movement of water and, unfortunately, contaminants from the surface into the subsurface. Four primary layers comprise the subsurface in both profiles: the topsoil, the weathered layer, the fractured zone, and the fresh basement rock. Each of them contributes differently to the protection and storage of groundwater. The topsoil (Layer 1) is rather shallow, spanning from around 1.3 to 2.5 m, starting at the top. This is significant because topsoil often serves as an organic filter. In this instance, it provides relatively little protection due to its thinness. It offers little resistance to any surface contaminants, including garbage and chemicals used in agriculture. The weathered layer (Layer 2) and the fractured zone (Layer 3), which together make up the primary water-bearing zones, are located underneath this.

These layers can efficiently store and transfer groundwater because they are more porous and permeable. Around VES 3 in the first portion, the weathered layer thickens significantly, reaching a height of around 16.1 meters. Although the fractured zone underneath it is still rather shallow, this indicates a considerable groundwater potential in that location. The predicament becomes much more apparent in the second section. There is a deep basement depression at VES 4 where the cracked and corroded layers reach a depth of around 45 meters. Because these zones can hold more groundwater, they are likely to produce vast amounts of water. There is a drawback to this benefit, though. The aquifer is extremely susceptible because to the scant topsoil and these deep, porous layers. There isn't a significant layer of poor permeability or clay to serve as a barrier Because of this, contaminants can swiftly enter the groundwater system from the surface. The aquifer system is therefore extremely susceptible to surface-derived contaminants, even if the geological picture promotes high groundwater yield and raises the danger of contamination.

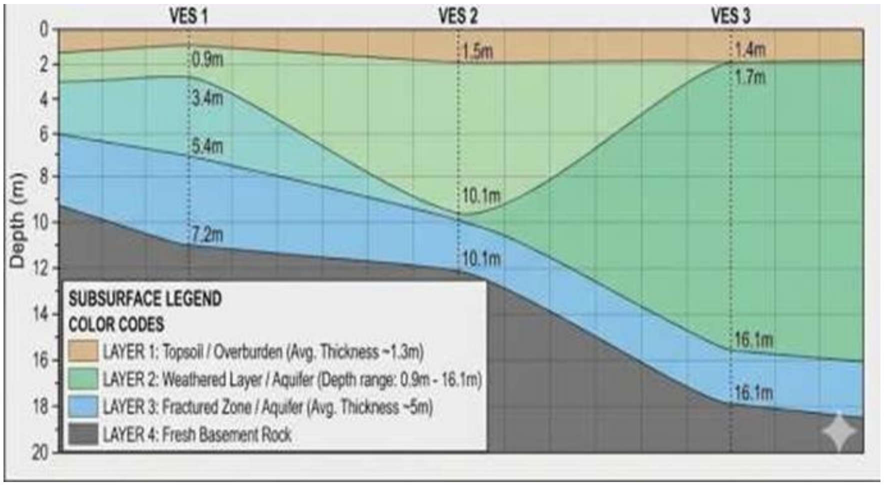

Figure 5: The 2D Geo-electrical Section along VES 1, 2, 3

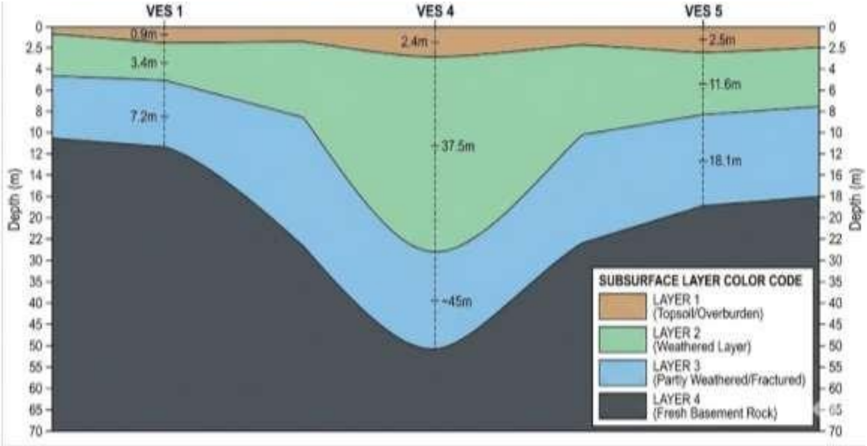

Figure 6: The Geo-electrical Section along VES 1, 4, 5

Groundwater Vulnerability Assessment

Table 2 shows the longitudinal conductance (LC), overburden thickness (OT), and basement resistivity (BR) obtained from VES data. Together, these factors provide an integrated geo-electrical basis for investigating groundwater potential and contamination susceptibility throughout the research area. They also define subsurface lithology, aquifer protective capacity, and groundwater vulnerability.

Table 2: The BR, OT and LC Distribution cross the VES stations

VES Stations	BR (Ωm)	OT (m)	LC (S)
VES 1	635.9	3.8	0.225177
VES 2	545.3	8.6	0.13345
VES 3	3353.4	14.7	0.137394
VES 4	1823.8	35.1	0.197999
VES 5	1105.2	9.1	0.200745
VES 6	2502.6	14.3	0.250887

Note: VES is vertical electrical sounding; BR is basement resistivity; OT is overburden thickness and LC is the longitudinal conductance

When assessing groundwater vulnerability, the link between basement resistivity and overburden thickness is crucial and vital, as illustrated in Figure 6 (Olomo, 2021). Low bedrock resistivity commonly indicates weathered or fractured basement characteristics that improve groundwater storage, although a thin overburden layer may make the area more vulnerable (Pradhan et al., 2022). On the other hand, by reducing contaminant movement, thick overburden with moderate to low resistivity, which is frequently clay-rich, offers an excellent protective capacity (Dongel et al., 2025). Groundwater occurrence is controlled by bedrock resistivity linked to fractured basement, but when paired with thin overburden, it enhances vulnerability because of inadequate filtration (Elshalkany et al., 2025). Therefore, the best way to evaluate groundwater vulnerability is to interpret bedrock resistivity and overburden thickness together rather than just one of them.

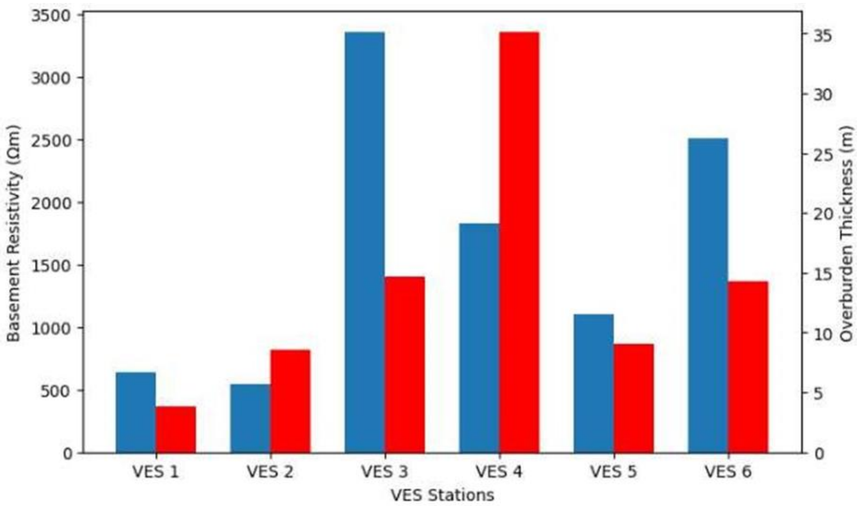

Figure 6: Relationship between Basement Resistivity and Overburden Thickness

Subsurface Vulnerability Section

The longitudinal conductance (LC) values derived from the VES data range between 0.13345 S and 0.250887 S, indicate predominantly weak to moderate aquifer protective capacity, suggesting varying levels of groundwater vulnerability throughout the study area. It also reflects variations in the thickness and electrical properties of the overburden materials that serve as protective layers above the aquifer. These variations indicate differences in the ability of the subsurface materials to safeguard groundwater from surface contaminants. The results show that VES 1, VES 5, and VES 6 possess relatively higher LC values, placing them within the moderate to good protective capacity category. This suggests the presence of thicker weathered layers with higher clay content, which enhance groundwater protection by limiting the movement of contaminants. Conversely, VES 2, VES 3, and VES 4 exhibit lower LC values and are classified as having weak to moderate protective capacity, indicating thinner overburden materials and a lower degree of natural protection. Although VES 4 is characterized by a relatively thick overburden and the resistivity properties of the overlying materials result in a lower conductance value. The, overburden thickness alone is not a reliable indicator of aquifer protective capacity and longitudinal conductance which is controlled by the combined influence of layer thickness and resistivity is important. Therefore, areas characterized by higher LC values are less vulnerable to contamination, whereas locations with lower LC values are more prone to pollutant infiltration and potential groundwater quality degradation.

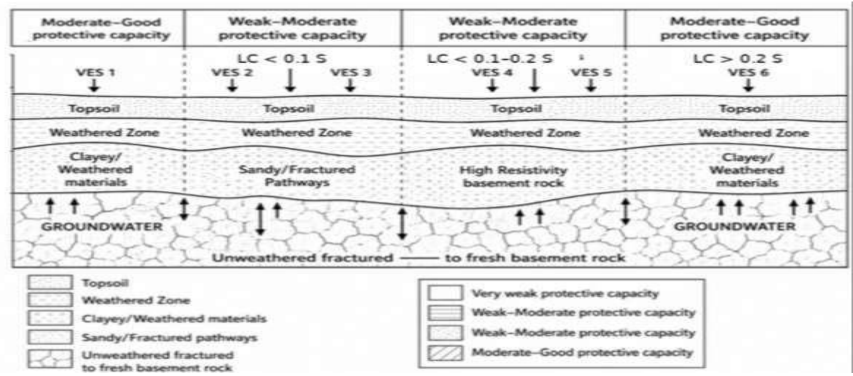

Figure 8: Subsurface Schematic Diagram of Groundwater Vulnerability

CONCLUSION

Groundwater potential and vulnerability in the research area may be clearly and practically understood by the combined analysis of geoelectrical characteristics, such as resistivity, overburden thickness, and longitudinal conductance (LC). Four primary layers comprise the subsurface: fresh basement rock, weathered layer, fractured zone, and topsoil. The primary water-bearing zones (aquifers) among them are the weathered and fractured strata. These strata are comparatively thick in areas such as VES 3 and VES 4, indicating excellent groundwater supply potential. However, because the topsoil in the region is typically thin (between 1.3 and 2.5 m), it offers very little natural defense against contaminants that come from the surface. The groundwater system is therefore more vulnerable to contamination. The study also demonstrates that vulnerability is influenced by a variety of factors rather than just one. For example, low basement resistivity, which is frequently associated with fractures, can hold more water but also facilitates the faster movement of contaminants, particularly in areas where the overburden is thin or porous. Conversely, heavier, clay-rich strata slow down the flow of contaminants, protecting the aquifer. The longitudinal conductance values (0.13345–0.250887 S) provide additional insight into the disparities in the protection of various study area. VES 2, 3, and 4 are in weaker zones, but VES 1, 5, and 6 typically provide moderate to high protection. Therefore, these findings highlight the need for careful, vulnerability-based groundwater management, careful siting of boreholes and septic systems and proper waste disposal, to ensure long-term sustainability and protection.

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