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Assessment of Groundwater Potential and Aquifer Vulnerability Using Dar Zarrouk Parameters in Erin-Ile, Kwara State, Nigeria

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Abstract

Groundwater constitutes the principal source of potable water in Erin-Ile, Kwara State, Nigeria, making a comprehensive assessment of aquifer characteristics essential for sustainable groundwater development and effective resource management. This study integrated Vertical Electrical Sounding (VES) employing the Schlumberger electrode configuration with Dar Zarrouk parameter analysis to evaluate groundwater potential and aquifer vulnerability across the study area. Eight VES stations were acquired and quantitatively interpreted to delineate subsurface lithological units and determine key hydrogeophysical parameters, including aquifer resistivity, thickness, depth, hydraulic conductivity, transmissivity, permeability, transverse resistance, and longitudinal conductance. The interpreted aquifer resistivity values range from 98.8 to 710.3 Ωm, while aquifer thickness varies between 7.03 and 37.87 m, reflecting significant spatial variability in aquifer properties. Estimated hydraulic conductivity ranges from 0.85 to 8.16 m/day, transmissivity from 5.94 to 282.15 m^2/day, and permeability from 1010.79 to 9757.11 mD, indicating moderate to high groundwater potential, particularly within the central and southern sectors of the study area where aquifer productivity is expected to be highest. Dar Zarrouk analysis further revealed longitudinal conductance values ranging from 0.0767 to 0.5774 mhos, suggesting that the aquifers possess predominantly moderate protective capacity against near-surface contamination. The integration of geoelectrical interpretation with derived hydrogeophysical parameters enabled the delineation of groundwater prospective zones and provided a reliable framework for evaluating aquifer productivity and vulnerability. Overall, the hydrogeophysical assessment identified the central-southern corridor of Erin-Ile as the most favourable zone for groundwater exploration, borehole development, and long-term sustainable groundwater exploitation, thereby providing valuable information for water resource planning and management in the area.

Keywords

Vertical Electrical Sounding (VES);
Groundwater potential;
Hydraulic conductivity;
Transmissivity;
Dar Zarrouk parameters;
Aquifer vulnerability;
Erin-Ile;
Nigeria.

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1.0 Introduction

Groundwater is one of the most important sources of freshwater for domestic, agricultural, and industrial purposes, particularly in developing countries where surface water supplies are often inadequate or seasonal. In Nigeria, groundwater constitutes the primary source of potable water for many rural and urban communities, especially within the Precambrian Basement Complex terrain where reliable surface water resources are limited (Adelana & MacDonald, 2008). The increasing demand for groundwater, coupled with rapid population growth, urbanization, and changing land-use practices, has heightened the need for effective groundwater exploration and protection.

In Basement Complex terrains, groundwater occurrence is controlled mainly by weathered overburden and fractured bedrock because the crystalline rocks possess negligible primary porosity (Rahaman, 1976). Consequently, identifying productive aquifer zones and evaluating their vulnerability to contamination require detailed subsurface characterization. Electrical resistivity methods, particularly Vertical Electrical Sounding (VES), have proven to be reliable, cost-effective, and non-invasive techniques for groundwater investigations. Beyond estimating layer resistivity and thickness, VES data can be used to derive the Dar Zarrouk parameters, namely transverse resistance and longitudinal conductance, which provide valuable information on aquifer potential and protective capacity (Maillet, 1947; Henriet, 1976).

Transverse resistance has been widely correlated with aquifer transmissivity and groundwater yield, while longitudinal conductance serves as an indicator of the ability of the overburden to protect underlying aquifers from surface-derived contaminants (Oladapo et al., 2004; Ibanga & George, 2016). These parameters therefore provide an effective means of simultaneously assessing groundwater potential and aquifer vulnerability, particularly in heterogeneous Basement Complex environments.

Erin-Ile, located in Oyun Local Government Area of Kwara State, is underlain by granites, migmatites, and augen gneisses of the Nigerian Basement Complex. The community depends largely on groundwater abstracted from boreholes and hand-dug wells for domestic and agricultural use. However, the complex geological setting and increasing anthropogenic activities necessitate a comprehensive evaluation of groundwater resources and the protective capacity of the aquifer system (Olasunkanmi et al., 2025).

This study therefore applies Dar Zarrouk parameters derived from Vertical Electrical Sounding data to assess groundwater potential and aquifer vulnerability in Erin-Ile, Kwara State. The findings are expected to provide a scientific basis for groundwater exploration, optimal borehole siting, aquifer protection, and sustainable groundwater resource management in the Basement Complex terrain.

2.0 Location of the Study Area

The study was conducted in Erin-Ile, the largest community in Oyun Local Government Area of Kwara State, north-central Nigeria. Erin-Ile is situated within the Nigerian Precambrian Basement Complex and lies between latitudes 8.091535°N and 8.124083°N and longitudes 4.696150°E and 4.710770°E (Figure 1.1). The town occupies a strategic location along the transitional corridor linking northern and southern Nigeria and is well connected by road to neighbouring towns such as Offa, Ijagbo, Ilemona, and Ilorin, the Kwara State capital (Olasunkanmi et al., 2025).

The study area experiences a tropical wet-and-dry climate characterized by distinct rainy and dry seasons. The rainy season extends from April to October, while the dry season lasts from November to March under the influence of the north-easterly Harmattan winds. Annual rainfall generally ranges between 1,000 and 1,300 mm, whereas mean annual temperatures vary from 25 to 34°C. Relative humidity is highest during the wet season, creating favourable conditions for groundwater recharge through infiltration and percolation into the weathered regolith (Olasunkanmi et al., 2025).

Topographically, Erin-Ile is characterized by gently undulating terrain with elevations generally ranging between 300 and 450 m above mean sea level. The drainage system is predominantly dendritic and is controlled by the underlying crystalline Basement Complex rocks and associated structural features. Seasonal streams and minor tributaries enhance groundwater recharge through stream infiltration and subsurface percolation, while the topography promotes localized accumulation of weathered materials that serve as groundwater reservoirs in the Basement Complex terrain (Rahaman, 1976; Olasunkanmi et al., 2025).

Groundwater constitutes the principal source of potable water for domestic, agricultural, and commercial activities in Erin-Ile. Water supply is obtained mainly from hand-dug wells and boreholes completed within the weathered and fractured Basement Complex aquifers. However, increasing population growth, urban expansion, agricultural practices, and indiscriminate waste disposal have intensified pressure on the available groundwater resources, raising concerns about borehole productivity and groundwater quality. Consequently, detailed hydrogeophysical investigations are required to evaluate groundwater potential and aquifer vulnerability for sustainable groundwater development and effective environmental management (Olasunkanmi et al., 2025; Adesola et al., 2020).

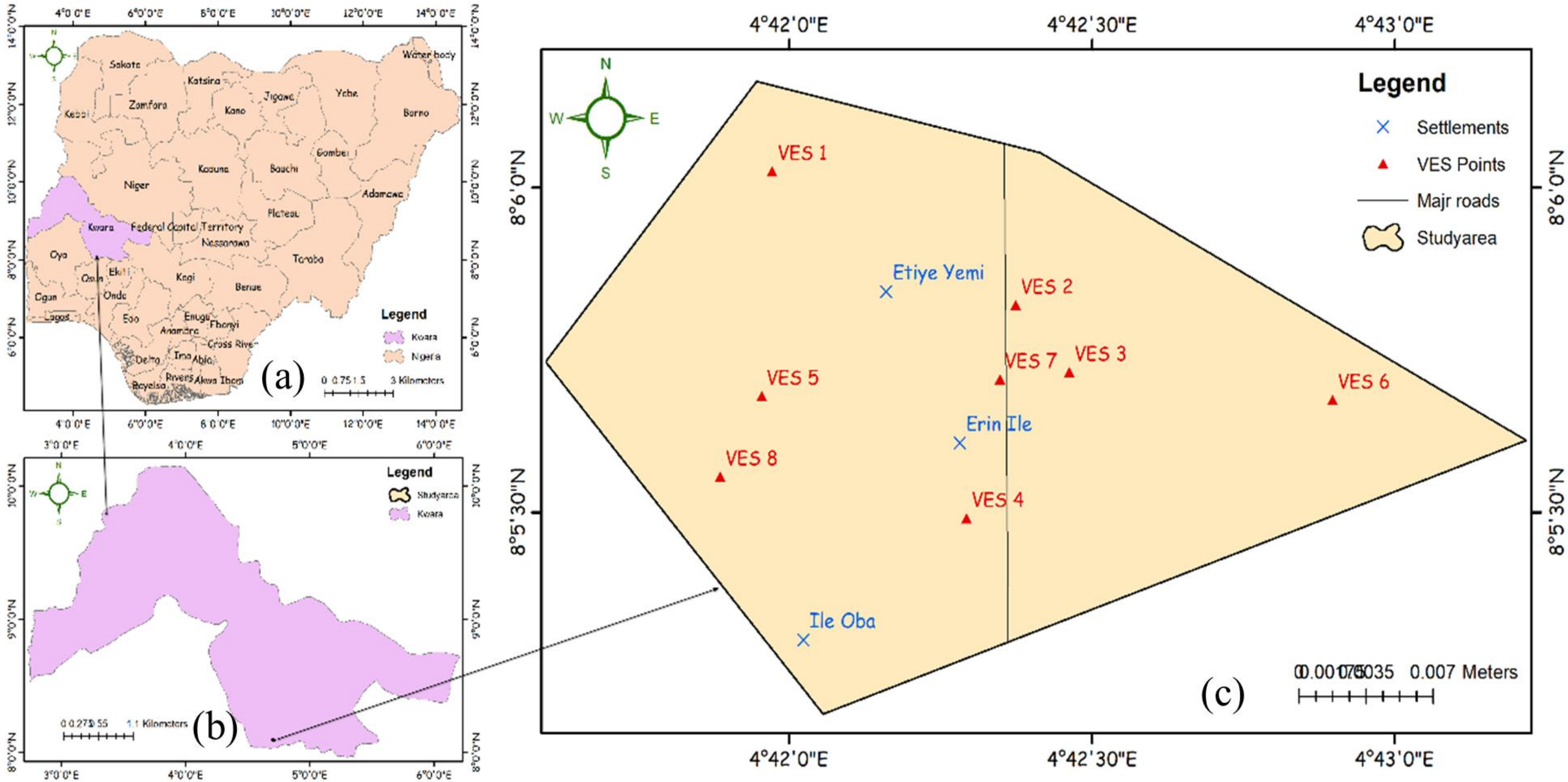

Figure 1. Location of the study area: (a) Map of Nigeria showing Kwara State, (b) Map of Kwara State showing Oyun Local Government Area, and (c) Spatial distribution of the Vertical Electrical Sounding (VES) survey locations in Erin-Ile, Oyun Local Government Area, Kwara State, Nigeria.

3.0 Materials and Methods

3.1 Materials

The study was made feasible by a number of important materials and devices carefully chosen to ensure effective data collection and analysis. These included software applications like ArcGIS for map contouring and IPI2Win for VES inversion. Accurate coordinate and elevation measurements were made using a Global Positioning System (GPS) radar, while precise VES measurements were made using ABEM Terrameter SAS 1000 and its accessories. The research also gave a lot of attention to comprehending the geology and position of Erin-Ile, Oyun Local Government Area, which provided a fundamental understanding that was essential for the interpretation of the data that was gathered. The careful selection and use of these instruments and materials, together with a practical interpretational method, were crucial in guaranteeing the effectiveness and precision of the data collection process and subsequent analysis.

3.2 VES Technique

The geo-sounding procedure, which included a 1-D vertical electrical sounding (VES), was carried out in Erin-Ile, Oyun Local Government Area, Kwara State, Nigeria with an ABEM Terrameter SAS 300 B resistivity meter and accessories. Ten (8) VES stations were sounded in accordance with the area's infrastructure (Fig. 1). The VES approach used a Schlumberger array with a maximum current electrode spread (AB) of 400 m. Taking all the essential safeguards, according to Zohdy et al. (1974) and Akpan et al. (2013), earth apparent resistance R_{app}, were measured in each VES. For the VES approach, the apparent resistivities ρ_{app} were assessed using the formulae presented below in equation 1.

$$\rho_{app} = \pi \cdot \left[\frac{(AB/2)^2 - (AB/2)^2}{MN} \right] \cdot R_{app} \quad (1)$$

where AB and MN are respectively current electrode separation and potential electrode separation. The entire term multiplied by R_{app} in Schlumberger in order to obtain the apparent resistivities ρ_{app} in equation 1 represents the configuration geometric factor. The dataset was manually smoothed to remove erroneous readings that deviated from the overall curve trend, which was accomplished by drawing a graph of apparent resistivities on a logarithmic scale against half of the current electrode separations. The IPI2Win Version 3.0 program, a 1-D least square computer-assisted forward modeling tool, was then used to quantitatively evaluate the curves. The software program defined key geoelectric indices such as layer resistivity, thickness, and depth, as well as the root-mean square (which was less than 5%), which served as an indicator of the degree of goodness of fit between the theoretical and field-derived curves, providing detailed insights into the interpreted curve. Table 1 displays the geographic data alongside measured and predicted hydrokinetic parameters pertaining to the shallowest aquifer, positioned atop the deeper aquifers within the unconfined aquifer system.

3.3 Determination of Secondary Geo-Electric Parameters

The secondary geo-electric characteristics are shown by equations 2, 3, 4, and 5. These include the transmissivity (T) and hydraulic conductivity of the aquifer, as well as the Dar Zarrouk parameters (transverse resistance (Tr) and longitudinal conductance (S). The capacity of a rock or sediment to allow water to pass through it or the ease with which groundwater may travel within an aquifer is known as hydraulic conductivity. Hydraulic conductivity and groundwater reservoir risk are positively correlated (Ekanem et al., 2019; George, 2020). The velocity at which water may cross an aquifer's unit width at a given hydraulic gradient is known as transmissivity, or T. The amount of resistance to the flow of electrical current through underground formations is measured by transverse resistance. Longitudinal conductance in the context of groundwater studies refers to the layer thickness to resistivity ratio.

$$S_L = \sum_i^n \frac{h_i}{\rho_i} \quad (2)$$

$$T_R = \sum_i^n \rho_b . h \quad (3)$$

$$T = K_h b \quad (4)$$

$$K_h = \frac{T}{h} \quad (5)$$

where S_L is the longitudinal conductance, h is the thickness of the layer (in the direction of current flow), and ρ_b is the bulk resistivity of the layer, T_R is Transverse Resistance, T is the transmissivity, K_h is the hydraulic conductivity of the aquifer.

4.0 Results and Discussions

4.1 Quantitative Interpretation of Vertical Electrical Sounding (VES) Data

The apparent resistivity data acquired from the Vertical Electrical Sounding (VES) survey were initially plotted on a logarithmic scale as apparent resistivity (ρ_a) versus half-current electrode spacing (AB/2) to obtain the characteristic sounding curves and identify possible noisy measurements or outliers. The field curves were subsequently interpreted quantitatively using the one-dimensional (1-D) least-squares inversion program IPI2WIN (Vander Velpen & Sporry, 1993). To improve the geological consistency of the inversion results, available borehole lithologic information was incorporated as constraints during the interpretation.

The inversion algorithm iteratively adjusted the layer resistivities and thicknesses until the calculated theoretical curves closely matched the observed field data. The quality of the inversion was assessed using the Root Mean Square (RMS) error, which quantifies the difference between the observed and computed apparent resistivity values. The interpreted models yielded RMS errors ranging from 0.94% to 2.52%, with values of 1.17%, 2.21%, 2.52%, 1.05%, 2.02%, 1.58%, 1.49%, and 0.94% for VES 1 to VES 8, respectively. These errors are considerably lower than the generally accepted threshold of 10%, indicating excellent agreement between the measured and theoretical curves and confirming the reliability of the interpreted geo-electrical models.

The representative interpreted VES curves for the eight sounding locations are presented in Figure 2, while the corresponding interpreted geo-electrical parameters, including layer resistivities, layer thicknesses, cumulative depths, RMS errors, and curve types, are summarized in Table 1. The close agreement between the observed field curves and the computed theoretical responses (Figure 2) demonstrates the robustness of the inversion procedure and validates the derived geo-electrical parameters presented in Table 1 for subsequent hydrogeological interpretation.

As shown in Table 1, the interpreted models reveal predominantly four-layer geo-electrical successions across the study area. However, VES 1 and VES 4 exhibit five-layer geo-electrical sequences, reflecting localized variations in subsurface lithology. The first-layer resistivity ranges from 21.3 to 843.0 Ωm, with corresponding thicknesses varying between 0.42 and 1.28 m, representing the topsoil. The second layer exhibits resistivity values ranging from 17.4 to 1,639.0 Ωm and thicknesses between 1.90 and 8.57 m, corresponding to the weathered horizon. The third layer, interpreted as the principal aquifer unit, records resistivity values between 62.5 and 710.3 Ωm and thicknesses ranging from 7.03 to 52.62 m, indicating considerable lateral variability in aquifer characteristics. Where present, the fourth layer exhibits resistivities ranging from 114.8 to 5,368.0 Ωm, while a fifth geo-electrical layer with a resistivity of 2,164.0 Ωm was identified only at VES 4, representing the fresh crystalline basement.

Furthermore, the interpreted curve types presented in Table 1 comprise one A-type curve (VES 2) and seven H-type curves (VES 1 and VES 3–VES 8), indicating that H-type resistivity layering predominates within the study area. The spatial variations in layer resistivity, thickness, and curve type reflect the heterogeneous nature of the Basement Complex terrain, with differences in weathering intensity, degree of fracturing, and groundwater occurrence. These interpreted geo-electrical parameters provide the basis for the subsequent evaluation of Dar Zarrouk parameters, groundwater potential, and aquifer vulnerability in the study area.

4.2 Measured and Estimated Hydraulic Properties associated with the Aquifer System. The measured and estimated hydraulic properties of the aquifer system derived from the interpreted VES data are presented in Table 2. The results indicate considerable spatial variability in aquifer characteristics, reflecting the heterogeneous nature of the subsurface geology.

Aquifer resistivity ranges from 62.5 to 710.3 Ωm, with a mean of 276.74 Ωm, suggesting variations in lithology, groundwater saturation, and clay content across the study area. Aquifer thickness varies between 7.03 and 52.62 m, averaging 32.40 m, indicating that relatively thick saturated zones capable of storing appreciable groundwater occur in several locations. The depth to the aquifer ranges from 16.12 to 55.62 m, with an average of 39.07 m, implying that the aquifers are generally shallow to moderately deep and suitable for groundwater development.

The derived Dar Zarrouk parameters show transverse resistance values ranging from 1235.00 to 29,934.70 Ωm² (mean 8387.89 Ωm²) and longitudinal conductance values of 0.0767–0.5774 mhos (mean 0.2512 mhos). The relatively high transverse resistance observed at some VES locations suggests appreciable aquifer storage capacity, whereas the predominantly low to moderate longitudinal conductance indicates moderate protective capacity of the overburden against surface-derived contaminants (Henriet, 1976).

Estimated hydraulic conductivity ranges from 0.8455 to 8.1618 m/day, with a mean value of 3.8094 m/day, indicating low to moderately high groundwater transmission characteristics. Correspondingly, transmissivity varies from 5.94 to 282.15 m²/day, averaging 122.52 m²/day, suggesting that the aquifer system is capable of supporting moderate to high groundwater yields, particularly at VES 7 and VES 8. Permeability values range between 1010.79 and 9757.12 mD, with a mean of 4553.95 mD, further confirming significant differences in pore connectivity and groundwater flow capacity within the aquifer.

Overall, the hydraulic properties indicate that the aquifer system possesses moderate to good groundwater potential, with the highest productivity associated with locations exhibiting high hydraulic conductivity, transmissivity, and permeability. These findings demonstrate that variations in groundwater potential are primarily controlled by aquifer thickness, lithology, and pore structure, consistent with previous hydrogeophysical studies (Freeze & Cherry, 1979; Todd & Mays, 2005).

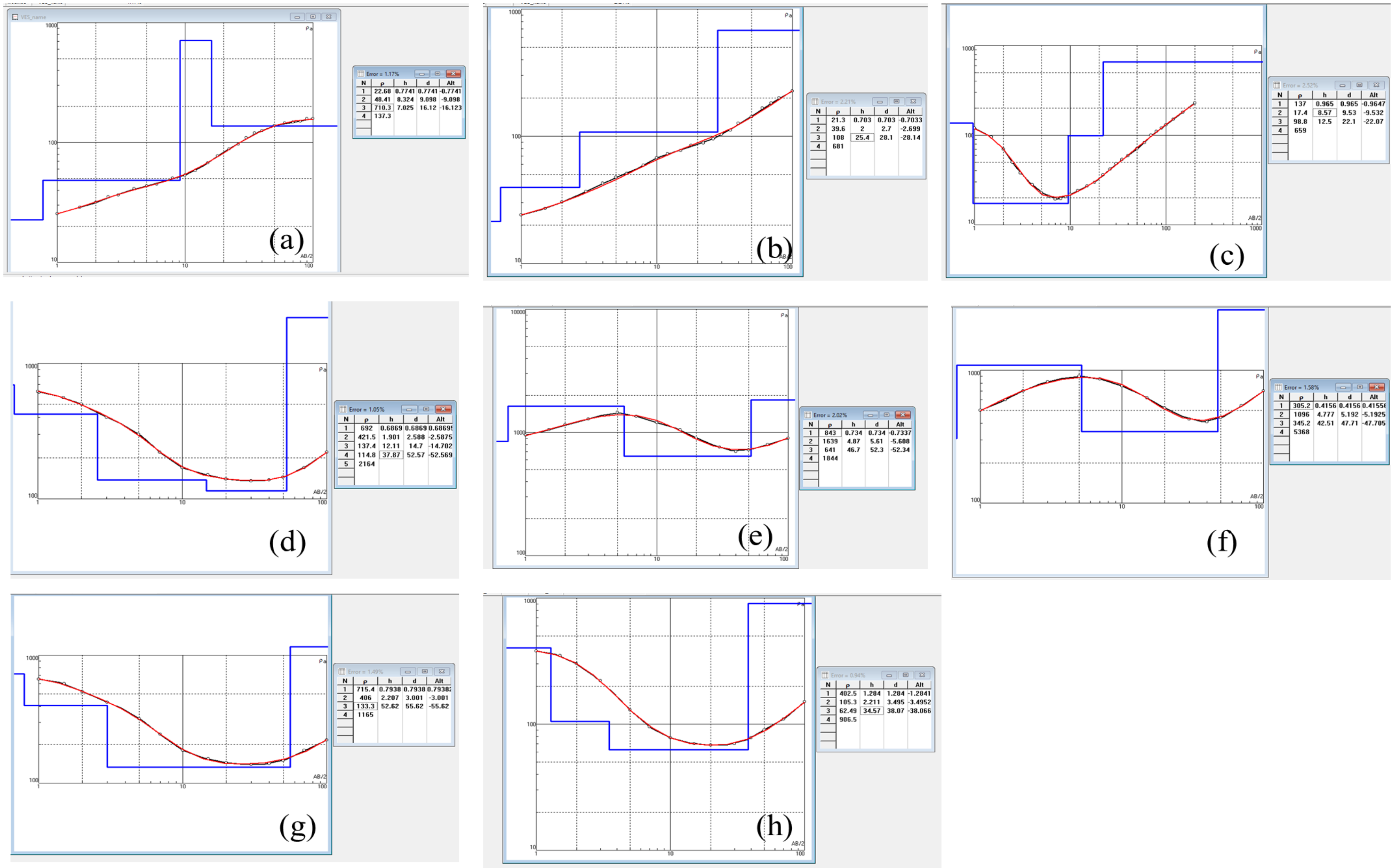

Figure 2. Representative interpreted Vertical Electrical Sounding (VES) curves showing the geoelectrical layer models at (a) VES 1, (b) VES 2, (c) VES 3, (d) VES 4, (e) VES 5, (f) VES 6, (g) VES 7, and (h) VES 8 in the study area, Oyun Local Government Area, Kwara State, Nigeria.

Table 1. Summary of VES results in the Study Locations from VES 1 to 8

VES	Long	Lat	Layer Resistivity Ωm)					Layer thickness (m)				Depth (m)				RMS Error
No	(Degrees)	(degrees)	ρ_1	ρ_2	ρ_3	ρ_4	P_5	h_1	h_2	h3	h4	d_1	d_2	d_3	d4	
VES 1	8.100413	4.699535	22.7	48.4	710.3	137.3	-	0.77	8.32	7.03	-	0.77	9.10	16.12	-	1.17%
VES 2	8.096979	4.706237	21.3	39.6	108.0	681.0	-	0.70	2.00	25.40	-	0.70	2.70	28.10	-	2.21%
VES 3	8.095253	4.707704	137.0	17.4	98.8	659.0	-	0.81	2.28	4.23	-	0.81	3.09	7.32	-	3.08%
VES 4	8.106499	4.713882	692.0	421.5	137.4	114.8	2164	0.69	1.90	12.11	37.87	0.69	2.59	14.70	52.5679	1.05%
VES 5	8.094644	4.699240	843.0	1639.0	641.0	1844.0	-	0.73	4.87	46.70	-	0.73	5.60	52.30	-	2.02%
VES 6	8.094544	4.714950	305.2	1096.0	345.2	5368.0	-	0.42	4.78	42.51	-	0.42	5.19	47.70	-	1.58%
VES 7	8.095073	4.705796	715.4	406.0	133.3	1165.0	-	0.79	2.21	52.62	-	0.79	3.00	55.62	-	1.49%
VES 8	8.092579	4.698097	402.5	105.3	62.5	906.5	-	1.28	2.21	34.57	-	1.28	3.50	38.07	-	0.94%

Table 2. Measured and Estimated Hydraulic Properties associated with the Aquifer System

VES No.	Aquifer Resistivity (Ωm)	Aquifer Thickness (m)	Depth (m)	Transverse resistance r (Ωm^2)	Longitudinal conductance s (mhos)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Permeability
V 1	710.3	7.03	16.12	4993.41	0.2160	0.8455	5.94	1010.79
V 2	108.0	25.40	28.10	2743.20	0.3187	4.9000	124.46	5857.79
V 3	98.8	12.5	22.1	1235.00	0.1798	5.3244	66.55	6365.07
V 4	114.8	37.87	52.57	4347.48	0.1111	4.6287	175.29	5533.46
V 5	641.0	46.70	52.30	29934.70	0.0767	0.9305	43.45	1112.37
V 6	345.2	42.51	47.70	14674.45	0.1289	1.6575	70.46	1981.45
V 7	133.3	52.62	55.62	7014.25	0.4013	4.0265	211.88	4813.57
V 8	62.5	34.57	38.07	2160.63	0.5774	8.1618	282.15	9757.12
Mean	**276.74**	**32.40**	**39.07**	**8387.89**	**0.2512**	**3.8094**	**122.52**	**4553.95**
Min	**62.50**	**7.03**	**16.12**	**1235.00**	**0.0767**	**0.8455**	**5.94**	**1010.79**
Max	**710.30**	**52.62**	**55.62**	**29934.70**	**0.5774**	**8.1618**	**282.15**	**9757.12**

4.3 Aquifer Potential and Protective Capacity

The groundwater development potential of an aquifer depends not only on its hydraulic characteristics but also on the degree of natural protection afforded by the overlying geologic materials. In this study, aquifer potential was evaluated using transmissivity values, while aquifer protective capacity was assessed using longitudinal conductance derived from the Dar Zarrouk parameters. The protective capacity classification adopted follows the modified scheme of Oladapo et al. (2004) and Ibanga and George (2016), in which longitudinal conductance serves as a reliable indicator of the ability of the overburden to attenuate the downward migration of contaminants.

Similarly, the groundwater potential of the aquifer was evaluated using the transmissivity classification proposed by Krasny (1993) (Table 3), which classifies aquifers into impermeable, very low, low, intermediate, high, and very high transmissivity categories based on their groundwater production capability. According to this classification, aquifers with transmissivity values between 100 and 1000 m^2/day are considered to possess high groundwater potential, values between 10 and 100 m^2/day indicate intermediate potential, while values between 1 and 10 m^2/day represent low groundwater potential. This classification provides a practical framework for evaluating the suitability of aquifers for domestic, municipal, agricultural, and regional groundwater supply.

The results presented in Table 4.4 indicate that longitudinal conductance values range from 0.0767 to 0.5774 mhos, corresponding to poor, weak, and moderate protective capacity classes. Four VES locations (V1, V2, V7, and V8), representing 50% of the investigated sites, fall within the moderate protective capacity category. These locations are characterized by moderately conductive overburden materials capable of providing a reasonable degree of natural filtration and attenuation of contaminants before they reach the aquifer. Nevertheless, the protection offered remains moderate and may not adequately prevent contaminant migration where pollution sources are persistent or highly concentrated.

Three locations (V3, V4, and V6), accounting for 37.5% of the study area, exhibit weak protective capacity. The relatively low longitudinal conductance values suggest the presence of thin overburden or predominantly sandy, permeable lithologic units with limited ability to retard contaminant transport. Consequently, groundwater within these areas is more susceptible to contamination from anthropogenic activities such as indiscriminate waste disposal, agricultural chemicals, leaking septic systems, and hydrocarbon spills.

Only one location (V5), representing 12.5% of the surveyed area, falls within the poor protective capacity class, with a longitudinal conductance value of 0.0767 mhos. This indicates that the overburden provides minimal natural protection, allowing contaminants introduced at the surface to migrate relatively rapidly into the groundwater system. Such areas are therefore considered highly vulnerable and require stringent groundwater protection strategies, including proper land-use regulation, continuous groundwater quality monitoring, and the establishment of sanitary protection zones around water supply facilities.

Aquifer productivity was evaluated using transmissivity values, which range from 5.94 to 282.15 m^2/day. Based on the Krasny (1993) transmissivity classification, four locations (V2, V4, V7, and V8) fall within the high transmissivity class (100–1000 m^2/day), indicating aquifers capable of supporting groundwater withdrawals of regional significance. Three locations (V3, V5, and V6) belong to the intermediate transmissivity class (10–100 m^2/day), suggesting groundwater resources adequate for supplying nearby communities, small towns, irrigation, and other local demands. In contrast, V1, with a transmissivity of 5.94 m^2/day, falls within the low transmissivity class (1–10 m^2/day), indicating that groundwater abstraction should be limited primarily to private or small-scale domestic water supply.

An integrated assessment of aquifer potential and protective capacity reveals that high groundwater productivity does not necessarily correspond to high aquifer protection. For example, V4 exhibits a high transmissivity (175.29 m^2/day) but only weak protective capacity, indicating that although the aquifer can sustain relatively large groundwater withdrawals, it remains susceptible to contamination due to inadequate overburden protection. Conversely, V7 and V8 combine high transmissivity with moderate protective capacity, making them the most suitable locations for sustainable groundwater development, provided adequate groundwater protection measures are implemented. V5, despite exhibiting intermediate transmissivity, possesses poor protective capacity, highlighting its vulnerability to contamination and the need for careful groundwater management.

Overall, the integrated evaluation demonstrates that the aquifer system possesses moderate to high groundwater development potential, with 87.5% of the investigated locations falling within the intermediate and high transmissivity categories of Krasny (1993). However, the protective capacity is generally weak to moderate, with no location attaining good, very good, or excellent protective ratings. This indicates that while the aquifer can supply appreciable quantities of groundwater across much of the study area, sustainable utilization depends on effective groundwater protection practices, including continuous groundwater quality monitoring, proper waste management, regulated land-use planning, and the establishment of groundwater protection zones.

Table 3: Longitudinal Conductance Values and Aquifer Protective Capacity Ratings for the Study Area

VES No.	Longitudinal Conductance (mhos)	Protective Capacity Rating	Transmissivity (m^2/day)	Transmissivity Class	Groundwater Supply Potential
V1	0.2160	Moderate	5.94	Low	Reduced extraction for private use of nearby water supply
V2	0.3187	Moderate	124.46	High	Withdrawal of less significant regional significance
V3	0.1798	Weak	66.55	Intermediate	Withdrawal of nearby water source for plants, small towns, etc.
V4	0.1111	Weak	175.29	High	Withdrawal of less significant regional significance
V5	0.0767	Poor	43.45	Intermediate	Withdrawal of nearby water source for plants, small towns, etc.
V6	0.1289	Weak	70.46	Intermediate	Withdrawal of nearby water source for plants, small towns, etc.
V7	0.4013	Moderate	211.88	High	Withdrawal of less significant regional significance
V8	0.5774	Moderate	282.15	High	Withdrawal of less significant regional significance

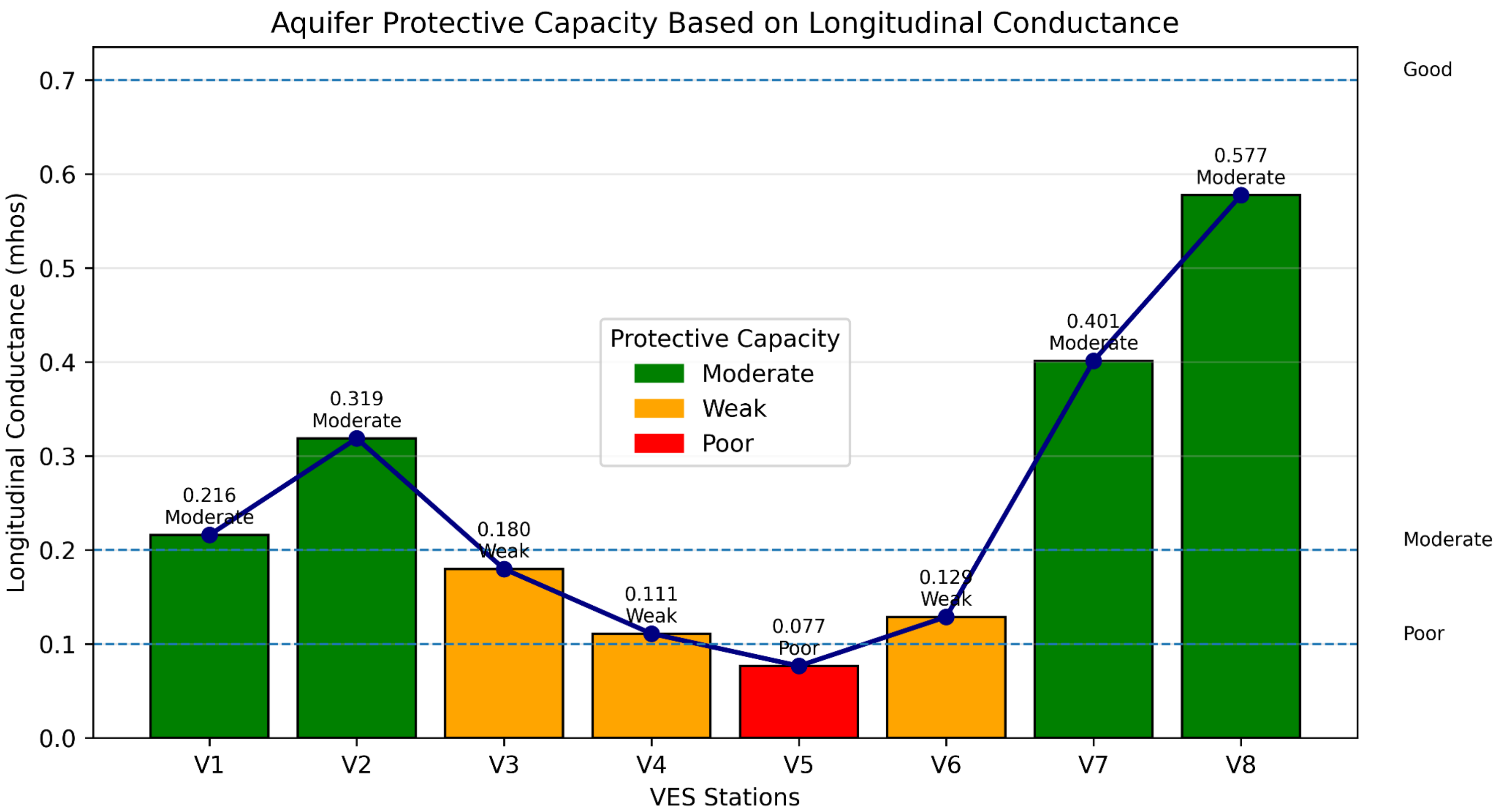

Figure 3. Spatial variation of longitudinal conductance and corresponding aquifer protective capacity across the VES stations. Green bars indicate moderate protective capacity, orange bars represent weak protective capacity, and the red bar denotes poor protective capacity based on the classification of Oladapo et al. (2004) and Ibanga and George (2016).

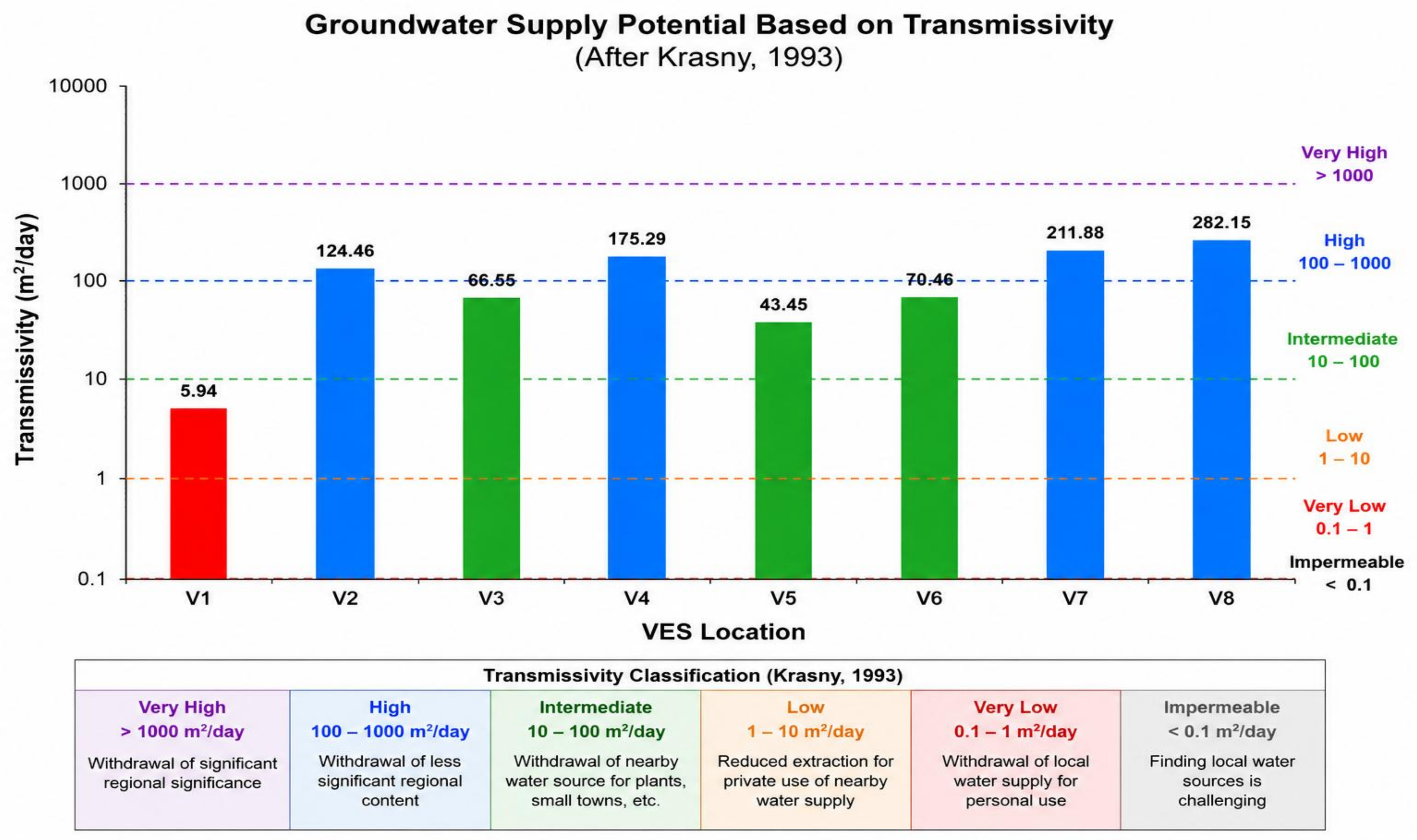

Figure 4. Groundwater Supply Potential of the Aquifer System Based on Transmissivity (After Krasny, 1993)

4.4 Overburden Thickness and Overburden Resistivity

Overburden thickness and overburden resistivity are important geoelectrical parameters widely employed in evaluating the intrinsic vulnerability of aquifers to surface-derived contamination. The overburden thickness represents the vertical distance from the ground surface to the top of the identified aquifer, while the overburden resistivity reflects the overall electrical characteristics of the materials overlying the aquifer. These parameters provide valuable information on the degree of natural protection afforded by the overburden. Generally, thick overburden composed of low-resistivity, clay-rich materials provides effective attenuation of contaminants, whereas thin overburden and highly resistive sandy materials offer relatively poor protection.

Based on the interpreted geo-electric models (Table 4), the depth to the selected aquifer, which represents the overburden thickness, ranges from 16.12 m at VES 1 to 55.62 m at VES 7. Intermediate overburden thicknesses of 22.10 m (VES 3), 28.10 m (VES 2), 38.07 m (VES 8), 47.70 m (VES 6), 52.30 m (VES 5) and 52.57 m (VES 4) were also obtained. The relatively greater overburden thicknesses encountered at VES 4, VES 5, VES 6, VES 7, and VES 8 suggest enhanced natural protection of the underlying aquifers because infiltrating contaminants would require a longer travel path before reaching the groundwater reservoir. Conversely, the relatively shallow aquifers at VES 1, VES 2, and VES 3 are likely to be more susceptible to contamination due to their comparatively thin protective cover.

The resistivity distribution of the overburden indicates considerable lithological variation across the study area. At VES 1, VES 2, and VES 3, the overburden is dominated by relatively low-resistivity materials (approximately 17–137 Ωm), suggesting the presence of clayey and silty sediments with appreciable moisture content. Such materials generally possess low hydraulic conductivity and are capable of retarding the downward migration of contaminants. In contrast, the overburden at VES 5 and VES 6 is characterized by relatively high resistivity values (up to 1,639 Ωm and 1,096 Ωm, respectively), indicative of predominantly sandy or lateritic materials with relatively higher permeability. Although these locations possess thick overburden, the coarse-grained nature of the materials may reduce their effectiveness as protective barriers compared with clay-rich sediments. The overburden at VES 4, VES 7, and VES 8 exhibits intermediate resistivity characteristics, reflecting variations in sediment composition and moisture conditions.

The selected aquifer resistivities also vary considerably, ranging from 62.5 Ωm at VES 8 to 710.3 Ωm at VES 1. The relatively low aquifer resistivities observed at VES 2, VES 3, VES 4, VES 7, and VES 8 are indicative of saturated sandy formations containing relatively fresh groundwater, whereas the higher resistivities recorded at VES 1, VES 5, and VES 6 may reflect coarser sediments, lower pore-water conductivity, or reduced clay content within the aquifer matrix.

Overall, the combined evaluation of overburden thickness and overburden resistivity demonstrates significant spatial variability in the protective characteristics of the study area. While the relatively thick overburden observed in several VES locations enhances the natural protection of the aquifers, the effectiveness of this protection is strongly influenced by the lithological composition of the overlying materials. Consequently, areas characterized by thin overburden and relatively permeable overlying formations are expected to exhibit greater groundwater vulnerability, whereas thick overburden containing conductive clay-rich materials provides more effective protection against contaminant infiltration. For this reason, overburden thickness and resistivity should be interpreted together with longitudinal conductance and other hydraulic parameters to provide a more reliable assessment of aquifer vulnerability.

Table 4: Overburden Thickness, Overburden Characteristics and Aquifer Vulnerability

VES No.	Overburden Thickness (m)	Overburden Resistivity (Ωm)	Overburden Characteristics	Expected Protective Capacity	Inferred Aquifer Vulnerability
VES 1	16.12	250.18	Low resistivity (clayey/silty)	Moderate	Moderate
VES 2	28.10	28.61	Low resistivity (clayey/silty)	Good	Low
VES 3	22.10	53.46	Low resistivity (clayey/silty)	Moderate to Good	Low to Moderate
VES 4	52.57	190.16	Moderate resistivity (mixed sandy/clayey)	Good	Low
VES 5	52.30	709.48	High resistivity (predominantly sandy)	Moderate	Moderate
VES 6	47.70	386.94	High resistivity (predominantly sandy)	Moderate	Moderate
VES 7	55.62	162.50	Moderate resistivity (mixed sediments)	Good	Low
VES 8	38.07	91.65	Moderate resistivity (mixed sandy/clayey)	Moderate to Good	Low to Moderate

4.5 Spatial Distribution and Hydrogeological Assessment of Aquifer Parameters

The spatial distribution of hydraulic conductivity, longitudinal conductance, permeability, transmissivity, and transverse resistance (Figures 4a–4e) reveals marked lateral variations in the hydrogeological characteristics of the study area, reflecting differences in lithology, weathering intensity, aquifer thickness, and pore connectivity. Collectively, these parameters indicate that groundwater potential improves from the northern and western sectors toward the central and southern parts of the study area.

The hydraulic conductivity map (Figure 4a) shows values ranging from 0.8455 to 8.1618 m/day, with the highest values concentrated around VES 2, VES 3, VES 4, VES 7, and VES 8. These zones are characterized by enhanced permeability and groundwater flow, whereas the northern and western sectors exhibit relatively low hydraulic conductivity, indicating compact or clay-rich formations with limited groundwater transmission (Todd & Mays, 2005).

Longitudinal conductance (Figure 4b) varies between 0.0767 and 0.5774 mhos, indicating predominantly moderate aquifer protective capacity. Higher conductance values observed in the southern sector suggest thicker conductive overburden capable of attenuating contaminant migration, while lower values in the western and eastern portions imply greater groundwater vulnerability (Henriet, 1976; Oladapo et al., 2004).

The permeability distribution (Figure 4c) closely follows the hydraulic conductivity pattern, with values ranging from 1010.79 to 9757.11 mD. High-permeability zones occurring within the central and southern sectors indicate well-connected pore networks and favourable groundwater circulation, whereas lower permeability in the northern and western areas reflects poorer aquifer quality (Freeze & Cherry, 1979).

Similarly, transmissivity (Figure 4d) ranges from 5.94 to 282.15 m^2/day, with the highest values concentrated around VES 4, VES 7, and VES 8. These areas combine appreciable saturated thickness with high hydraulic conductivity, making them the most productive groundwater zones within the study area (Krasny, 1993).

Transverse resistance (Figure 4e) ranges from 1235 to 29,934.7 Ωm^2, reflecting spatial variations in aquifer thickness and resistivity. Although high transverse resistance values indicate greater groundwater storage capacity, the coincidence of moderate transverse resistance with high transmissivity and hydraulic conductivity in the central and southern sectors suggests that groundwater productivity is controlled more by hydraulic efficiency than storage alone (Henriet, 1976). The integrated spatial analysis identifies the central and southern portions of the study area as the most favourable zones for groundwater development, owing to their high hydraulic conductivity, permeability, and transmissivity, coupled with moderate to good aquifer protective capacity.

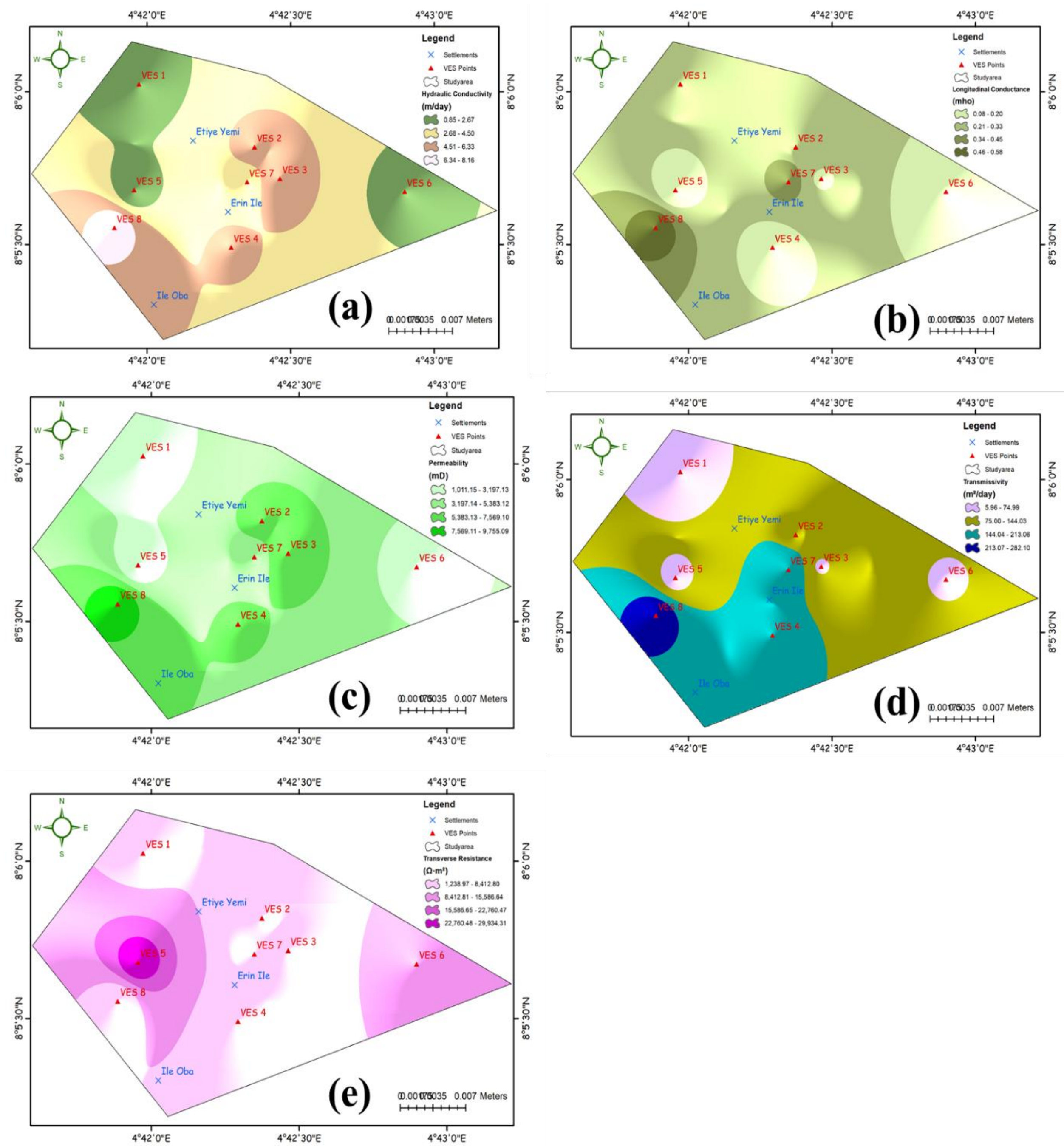

Figure 5. Spatial distribution of the hydrogeological parameters derived from Vertical Electrical Sounding (VES): (a) hydraulic conductivity, (b) longitudinal conductance, (c) permeability, (d) transmissivity, and (e) transverse resistance across the study area.

5.0 Concluding Remarks

This study demonstrates the effectiveness of integrating Vertical Electrical Sounding (VES) with Dar Zarrouk parameters for evaluating groundwater potential and aquifer vulnerability in Erin-Ile, Kwara State, Nigeria. The results revealed considerable spatial variability in aquifer characteristics, with hydraulic conductivity, transmissivity, and permeability indicating moderate to high groundwater potential across the study area. The central and southern sectors exhibited the most favourable hydrogeological conditions due to their relatively high transmissivity, hydraulic conductivity, and permeability, making them suitable locations for sustainable groundwater development.

In contrast, the northern and western sectors showed comparatively lower groundwater potential because of reduced hydraulic properties. Longitudinal conductance values indicate predominantly moderate aquifer protective capacity, suggesting that while the aquifers are generally protected, appropriate groundwater management measures are necessary to minimize contamination risks (Olasunkanmi et al., 2025; Yusuf et al., 2025). Overall, the study confirms that the integration of geoelectrical and hydrogeophysical parameters provides a reliable basis for groundwater exploration, aquifer characterization, and informed water resource management in crystalline basement terrains.

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