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Geoelectrical Assessment of Groundwater Potential and Aquifer Protective Capacity Using Vertical Electrical Sounding in Osin-Ekiti, Southwestern Nigeria

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ABSTRACT
Adequate supply of potable water is needed for domestic and agricultural uses, and groundwater is a significant source of fresh water that needs to be protected to safeguard its future sustainability. This study utilized the geoelectrical parameters obtained from Vertical Electrical Sounding (VES) to assess groundwater potential and protective capacity of aquifers in parts of Osin-Ekiti, Southwest Nigeria. Sixteen (16) VES points were occupied using the Schlumberger electrode array, with current electrode separation (AB/2) between 1 and 100 m. The geoelectric interpretation identified three to six subsurface layers, comprising topsoil, clay, weathered layer, partly weathered layer, and fresh basement. The resistivity data were interpreted to produce isopach, isoresistivity, and Dar-Zarrouk parameter maps, including longitudinal conductance (S), and transverse resistance (T). Results show that overburden thickness ranges between 1 and 29.1 m, while resistivity values vary from <100 to >19,000 Ωm. The longitudinal conductance values (0.0001–1.6 S) classify the aquifer protective capacity from highly protected to poorly protected, whereas transverse resistance values (<100 to >3000 Ωm²) reveal low to high groundwater potential. The north-central and parts of the central region of the study area exhibit the most favorable conditions with T > 500 Ωm², S ≥ 0.1 S, and appreciable overburden thickness (> 12 m) that indicates a combination of adequate groundwater storage, moderate to high transmissivity, and fair to high aquifer protective capacity.

Keywords:
Groundwater potential,
Aquifer protective capacity,
Geoelectric properties,
Aquifer vulnerability.

INTRODUCTION

Groundwater is a major source of freshwater worldwide (Apostolaki et al., 2020), especially in areas where surface water is seasonal, unreliable, or threatened by human activities and climate change. It serves as the main supply of water for domestic, agricultural, and industrial uses, making its quality and protection critical for sustainable water supply systems (Oyelakin et al., 2021; Zacchaeus et al., 2020; Olusola et al., 2017). Nevertheless, the heterogeneous subsurface geology, limited hydrogeological information, and increasing susceptibility to contamination constrain the sustainable development and management of this resource. These challenges are more pronounced in Basement Complex environments, where weathering and fracturing processes dominate the occurrence of groundwater as secondary porosity rather than primary pore spaces (Idris et al., 2018; Wali et al., 2024; Egbueri et al., 2025). Precambrian crystalline rocks in the Basement Complex of Southwestern Nigeria, including migmatites, gneisses, schists, and granites, have negligible primary porosity and permeability (Tijani et al., 2023). As a result, groundwater storage and movement are limited to the weathered regolith and fractured bedrock. The spatial variability of these features leads to considerable diversity in aquifer characteristics, making groundwater exploration and development a complex task. The crucial requirements for successful groundwater exploitation under these conditions are the proper delineation of subsurface layers, identification of weathered and fractured zones, and assessment of their hydrogeophysical properties (Alao and Abubakar, 2025; Shailaja et al., 2019).

Near-surface geophysical methods have, over the last decades, been shown to be an essential tool in environmental, engineering, and groundwater exploration (Ali et al., 2025; Ademolaa et al., 2024; Goldman and Neubauer, 1994; Robinson et al., 2008). Electrical resistivity methods, including the Vertical Electrical Sounding (VES), have been widely adopted because they are cost-effective, simple, and can detect variations in lithology and the fluid content of the underlying rock. The basic principle of resistivity techniques is the difference in electrical conductivity of earth materials, which depends on mineral composition, porosity, saturation level, and fluid conductivity (Parkhomenko, 1982; Wyllie and Spangler, 1952; Glover, 2015). Therefore, resistivity data can be used to characterize the subsurface, and delineate geologic structures that can house groundwater. Geoelectric properties derived from resistivity survey analysis provide important information regarding the nature of the aquifers, including thickness, depth, transmissivity, and protective capacity. Assessing the protective capacity of the overburden is fundamental to understand how effectively it can prevent contaminants from reaching the underlying aquifer (Henriet, 1976; Olorunfemi and Fasuyi, 1993). This evaluation is commonly achieved using Dar Zarrouk parameters, which include the longitudinal conductance (S), and transverse resistance (T) derived from Vertical Electrical Sounding (VES) data (Maillet, 1947; Niwas and Singhal, 1981).

Longitudinal conductance (S) is a measure of the overburden's ability to protect an aquifer. Higher values indicate the presence of more conductive materials, such as clay, which can inhibit the downward movement of contaminants (Olorunfemi and Fasuyi, 1993; Adiat et al., 2009). In contrast, low conductance values indicate a weak protective cover and may increase aquifer vulnerability (Adepelumi et al., 2009). The transverse resistance (T) is complementary to longitudinal conductance and can be used to understand the transmissive properties of aquifer units. While longitudinal conductance focuses on protective ability, transverse resistance is directly proportional to the aquifer's transmissivity and hydraulic conductivity. Transverse resistance values are typically high, and high values in aquifer layers signify thick, less resistive layers that can store and conduct large amounts of groundwater, and thus represent areas of high groundwater potential. Integrating both parameters enables a comprehensive evaluation of subsurface conditions prior to groundwater exploration.

Osin Ekiti, the study area, continues to face a major problem of sustainability and safety of groundwater resources, which is mostly facilitated by the growing population and other anthropogenic factors, including poor disposal of waste products, defecation, agricultural runoffs, and sinking of wells without proper consideration. These aspects have increased the threat of groundwater pollution in the area. The basis of this study is to characterize the subsurface geo-electric layers, determine the possible aquiferous zones, and assess the level of protective capacity of the overburden in order to evaluate the vulnerability of the underlying aquifers.

Description and Geology of the Study Area

The location of the study area is within Osin Ekiti, Ekiti State, southwestern Nigeria, and it is about 30 km northeast of the state capital, Ado- Ekiti. It is bounded by latitudes 7° 47' 40" N to 7° 48' 20" N and longitudes 5° 24' 20" E to 5° 25' 05" E, within Zone 31 N of the Universal Transverse Mercator (UTM) projection based on the Minna Datum (Figure. 1). The area is accessible through major and minor roads. Osin Ekiti is part of the Precambrian Basement Complex topography of Southwestern Nigeria. The main lithologic unit is the migmatite-gneiss (Figure 2), which is interspersed with instances of Pan-African granitoids and small belts of schist that can be associated to the Ife Ilesha belt. The crystalline basement rocks are covered by weathered materials, clayey and lateritic regoliths, in low-lying valleys, and gently undulating terrain (Yohe, 2024). Such weathered materials are major groundwater storage areas in the basement environment.

The Basement Complex rocks of the region are impermeable because of the lack of primary porosity. The secondary porosity characteristics like fractures, faults, joint, and the overlying weathered materials therefore control the occurrence and movement of groundwater. Factors such as mineral composition, grain size and deformation degree determine porosity and permeability of these rock unit (Obini and Omietimi, 2020). Fracturing, which may be the result of tectonic processes, improves weathering and the possibility of groundwater accumulation. The mineralogical composition is also vital in the intensity of weathering rocks that have a higher content of ferromagnesian minerals and feldspars where they break down to lower permeable clay minerals, and silica-rich rocks which break down to more permeable sandy and gravelly rocks. Groundwater in the Basement Complex terrain is usually found in the weathered regolith and the fractured bedrock aquifers.

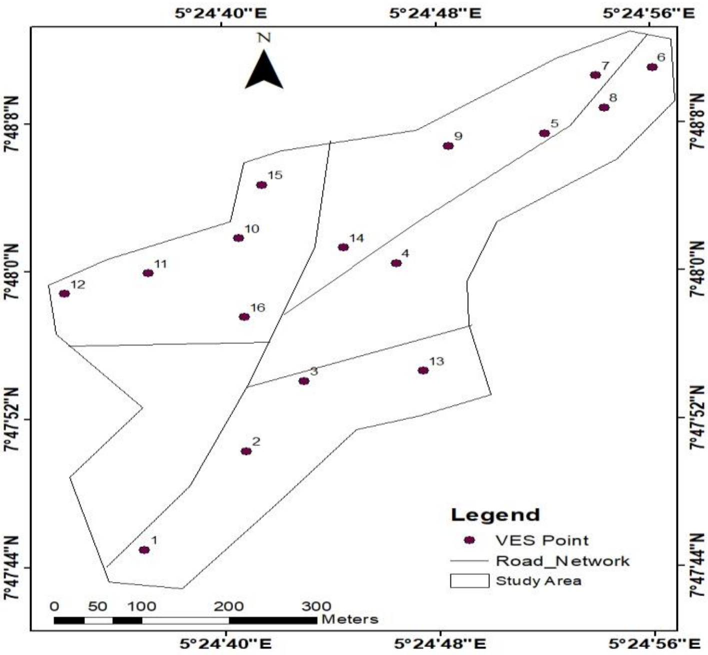

Figure 1: Base Map Showing the Occupied VES Points across the Study Area

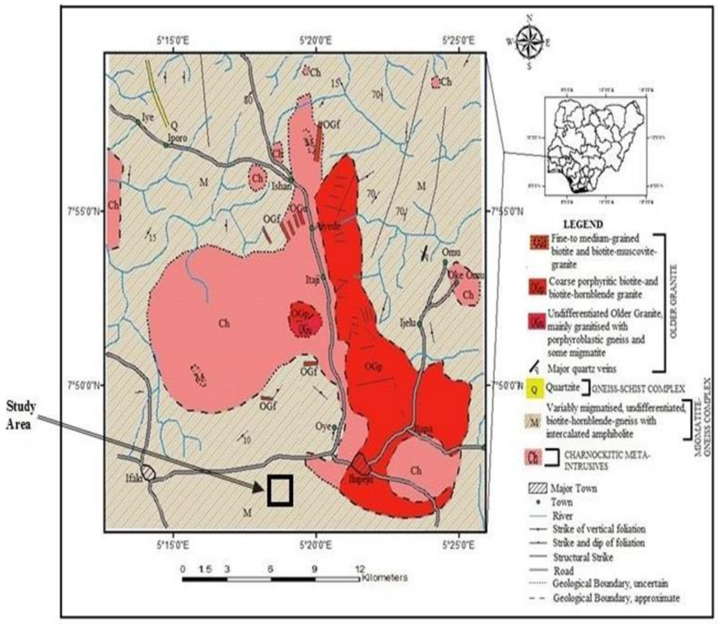

Figure 2: Geological Map of Itaji and Its Environs Showing the Area of Study (Abiye *et al.,* 2019)

MATERIALS AND METHODS

The electrical resistivity method which utilized the Vertical Electrical Sounding (VES) technique was adopted to characterize the subsurface geoelectric and hydrogeologic lithology of the study area. The ULTRA MINI-RES resistivity meter was used for data acquisition, and sixteen (16) sounding points were occupied across the study area (Figure 1), using the schlumberger electrode arrangement. The half-current electrode spacing (AB/2) varied between 65 and 100 m, in order to ensure adequate depth of penetration and resolution of subsurface layers. The geographic coordinates of each VES station were recorded using a Global Positioning System (GPS) receiver to enable spatial referencing and integration with subsequent mapping outputs. The field data, which comprises the apparent resistivity values and corresponding current electrode separations, were processed and interpreted quantitatively using the IPI2WIN software. Apparent resistivity data with respect to distance were input into the program, and one-dimensional (1D) iterative inversion was performed to generate geoelectric models. The resulting inversion models gave true resistivity values, layer thicknesses, and depth to geoelectric interfaces, which formed the basis for subsurface lithologic interpretation and groundwater potential evaluation. Further analysis of the geoelectric parameters was undertaken through the computation of the Dar Zarrouk parameters, namely longitudinal conductance (S) and transverse resistance (T), derived from the primary resistivity and thickness values of individual layers. These parameters were obtained using the relations;

Longitudinal Conductance $S = \sum \left(\frac{hi}{\rho i}\right)$

Where hi = Thickness of the i^{th} layer (m)

ρi = Resistivity of the i^{th} layer (Ωm)

Traverse Resistance $T = \sum (hi.\rho i)$

Longitudinal conductance measured in Siemens (S)

Transverse resistance is measured in Ωm²

Longitudinal conductance which is expressed in Siemens (S), reflects the current carrying capacity of the subsurface materials, whereas transverse resistance (T), measured in Ωm², indicates the resistive strength of the subsurface. These parameters combined are indicators for evaluating aquifer protective capacity and groundwater potential. The parameters were integrated in ArcGIS 10.8 through spatial interpolation and overlay analysis to produce a composite map for delineating groundwater potential zones and assessing aquifer protective capacity within the study area.

RESULTS AND DISCUSSION

Vertical Electrical Sounding

The resistivity sounding curves obtained in the study area are the K, A, H, QH, KH, HK, AA, HA, HKH, QHA, KHA, and QHKH types with three to six geoelectric layers. Figure 3 (a-c) shows typical curve types, modelled layer resistivity and thickness values obtained in the study area. The A curve type makes up about 25% of the entire curve types (Figure 4). Table 1 shows the summary of the inferred lithology according to Keary et al. (2022) classification of resistivity values of common rock types.

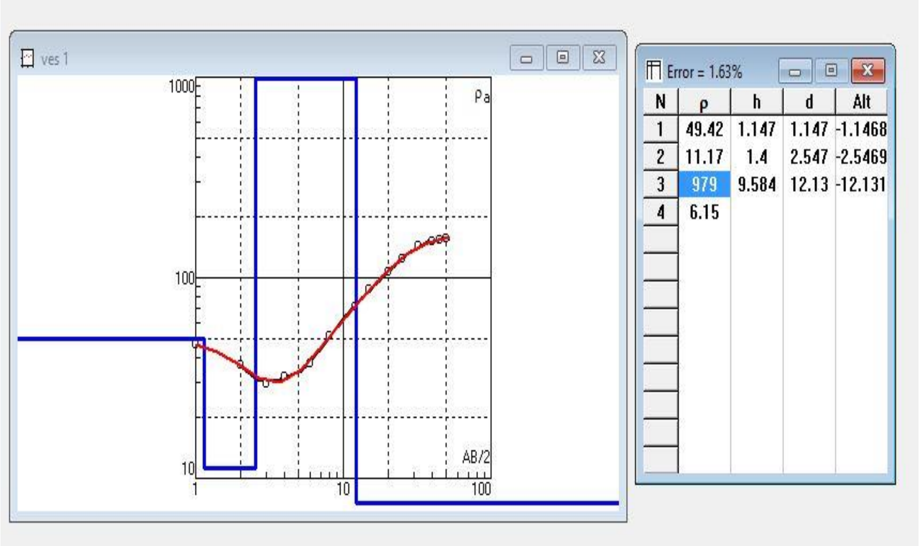

Figure 3a: Typical HK VES Curve from the Study Area

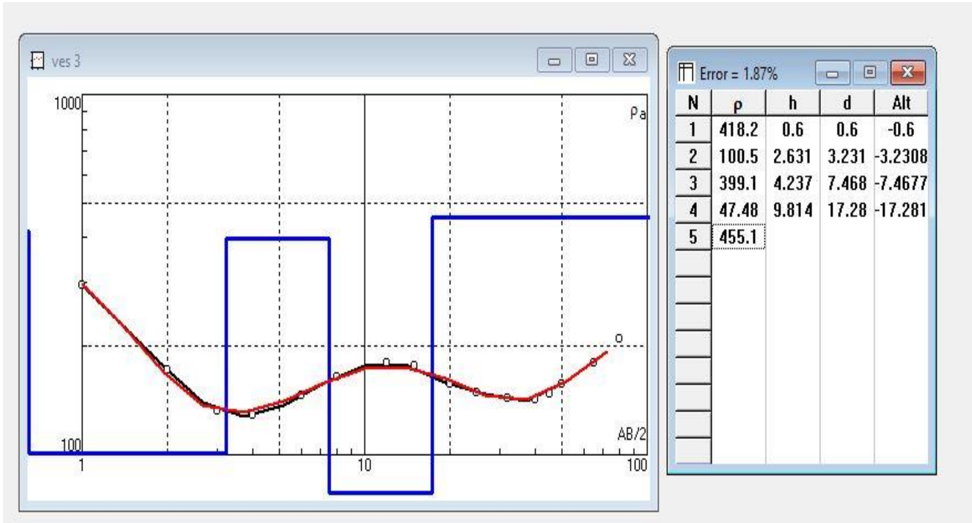

Figure 3b: Typical HKH VES Curve from the Study Area

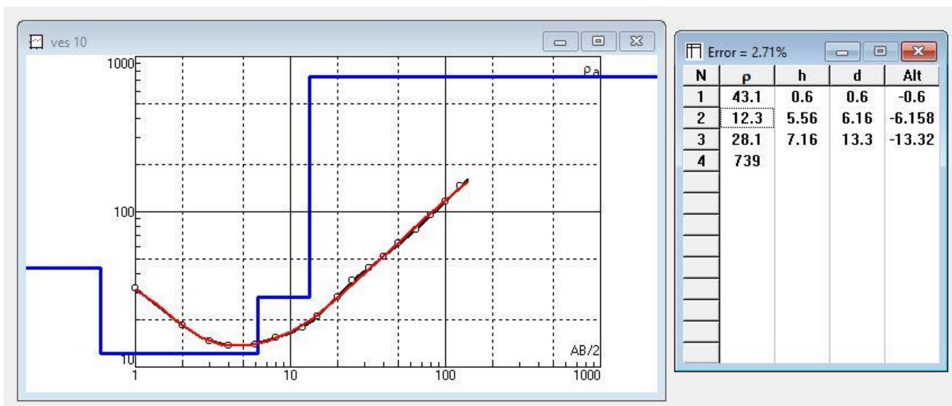

Figure 3c: Typical HA VES Curve From the Study Area

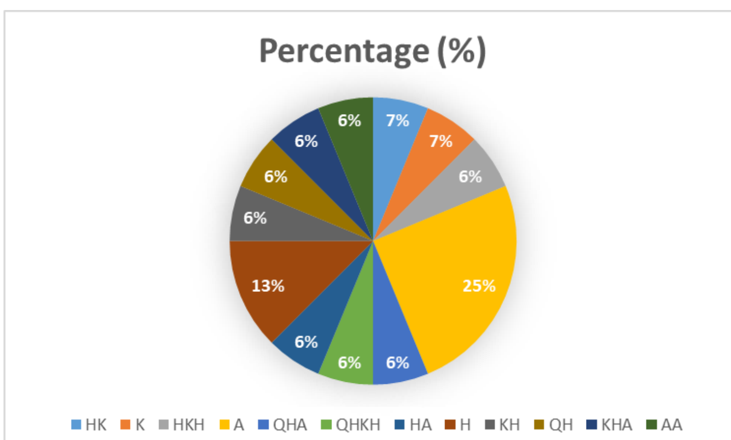

Figure 4: Pie-Chart Showing the Percentage of the Different Curve Types Obtained in the Study Area

Table 1: Summary Showing the Lithology of the VES Points Occupied in the Study Area

VES No	Curve Type	No of Layer	Resistivity Value (Ωm)	Thickness (m)	Depth (m)	Probable Lithology
1	HK	4	49	1.1	1.1	Topsoil
			11	1.4	2.5	Weathered Layer
			979	9.6	12.1	Fresh Basement
			6	-	-	Fractured Basement
2	K	3	476	2.7	2.7	Topsoil
			9680	4.1	6.8	Fresh Basement
			5	-	-	Fractured Basement
3	HKH	5	418	0.6	0.6	Topsoil
			101	2.6	3.2	Weathered Layer
			399	4.2	7.5	Partly Weathered Layer/
			47	9.8	17.3	Partly Fractured Layer
			455	-	-	Fresh Basement
4	A	3	3	0.5	0.5	Topsoil
			520	0.9	1.3	Weathered Layer
			10073	-	-	Fresh Basement
5	A	3	12	0.6	0.6	Topsoil
			125	2.5	3.1	Weathered Layer
			4066	-	-	Fresh Basement
6	A	3	11	0.5	0.5	Topsoil
			1907	1.0	1.4	Fresh Basement
			27069	-	-	Fresh Basement
7	A	3	1.2	1.6	1.6	Topsoil
			2.8	8.4	10	Weathered Layer
			84	-	-	Fresh Basement
8	QHA	5	59	0.9	0.9	Topsoil
			23	1.8	2.7	Weathered Layer
			4	2.5	5.2	Clay
			25	18	23.2	Weathered Layer
			1346	-	-	Fresh Basement
9	QHKH	6	186	0.6	0.6	Topsoil
			82	1.6	2.2	Weathered Layer
			7	2.2	4.4	Clay
			63	4.0	9.2	Weathered Layer
			16	19.9	29.1	Clay
			36	-	-	Weathered Layer
10	HA	4	43	0.6	0.6	Topsoil
			12	5.6	6.2	Weathered Layer
			28	7.2	13.3	Partly Weathered Layer
			739	-	-	Fresh Basement
11	H	3	12532	1.4	1.4	Topsoil
			230	7.1	8.5	Weathered Layer
			2132	-	-	Fresh Basement
12	KH	4	608	0.5	0.5	Topsoil
			22291	0.9	1.3	Lateritic Layer
			154	5.8	7.1	Weathered Layer
			1256	-	-	Fresh Basement
13	QH	4	3949	0.8	0.8	Topsoil
			1089	3.5	4.3	Lateritic Layer
			169	23	26.8	Weathered Layer
			4003	-	-	Fresh Basement
14	H	3	216	1.5	1.5	Topsoil
			46	9.3	10.8	Weathered Layer
			2060	-	-	Fresh Basement

15	KHA	5	495	1.4	1.4	Topsoil
			853	1.8	3.2	Lateritic Layer
			138	4.2	7.5	Weathered Layer
			381	9.8	17.3	Partly Weathered Layer
			2437	-	-	Fresh Basement
16	AA	4	19	1.3	1.3	TopsoilWeathered
			42	1.4	2.6	Layer
			146	8.8	11.5	Partly Weathered Layer
			5299	----	----	Fresh Basement

Dar-Zarrouk Parameters

Longitudinal Conductance Map

The calculated longitudinal conductance values compare favorably with the standard protective capacity rating modified after Oladapo and Akintorinwa (2007) (Table 2). The computed values in Table 2 indicate that the study area is characterized by a range of aquifer protective capacity ratings, from highly protected to fairly protected and poorly protected zones. In Figure 5, the longitudinal conductance map show that the aquifer protective capacity within the study area is highly protected in the north-central flank around VES 9, fairly protected in the northeastern and central part around VES 5, 6, 7, 8, 4, 10, 14, and 15, and fairly to poorly protected in the southwestern, southern, and southeastern regions around VES 1, 2, 3, 11, 12, 13, and 16.

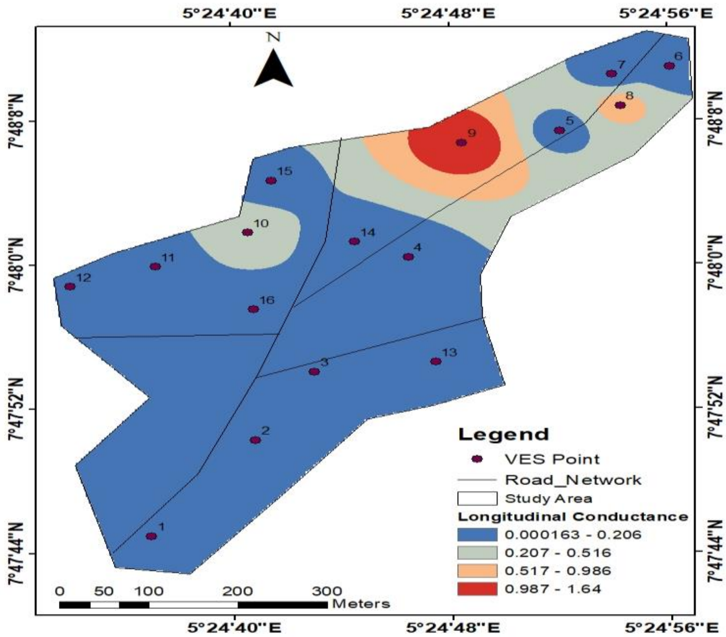

Figure 5: Longitudinal Conductance Map

Table 2: Longitudinal Unit Conductance/Protective Capacity Rating (Modified After Oladapo and Akintorinwa, 2007)

Longitudinal Unit Conductance (Ωm)	Protective Capacity Rating
> 0.5	High
0.1 – 0.5	Moderate
0.05 – 0.1	Fair
Less than 0.05	Poor

Transverse Resistance Map

The groundwater potential in the study location, as indicated by the transverse resistance map (Figure 6), varies significantly with the thickness and resistivity of the overburden materials. Transverse resistance (T) is one of the Dar-Zarrouk parameters, which is directly proportional to the transmissivity of the aquifer; therefore, areas with higher values have high groundwater potential.

In the northeastern flank, VES 5, 6, 7, and 8 are predominantly located within the cyan color band (< 503 Ωm^2), indicating less resistive, and thin aquifer layers. The central part which includes VES 4, 9, 10, 14, and 16, occupies mostly grey color band (504–1,130 Ωm^2), shows moderate transverse resistance with appreciably thick aquifer that is capable of supporting sustainable groundwater yields. High transverse resistance are apparent near VES 11, 13, and 15 in the southwestern, southeastern, and northwestern parts of the study area, represented by orange (1,140–2,260 Ωm^2) and red bands (>2,270 Ωm^2). These values denotes thick and relatively high resistivity subsurface layers. Regions with such conditions are often associated with thick and highly weathered layers or fractured basement rocks, which can store and transmit substantial amounts of groundwater. The computed values of the Dar-Zarrouk parameters used in the study is presented in Table 3.

Isopach Map of the Overburden

The isopach map (Figure 7) reveals a variable distribution of overburden thickness across the study area, ranging from about 1 m to 29.1 m. This variation reflects differences in the degree of weathering and subsurface structural controls, which are important factors that influences groundwater occurrence and aquifer protective capacity (Olorunfemi and Fasuyi, 1993; Mogaji et al., 2011). In the northeaster flank of the study area, VES 6 and 7 fall within the red color band (<4.68 m), which indicates very thin aquifer layers with limited storage capacity. VES 8, located in the adjacent yellow color band (4.69–8.78 m), represents a moderately thick aquifer, while VES 9, in the cyan color band (8.79–29.1 m), shows thick aquifer. This is an indication that VES 9 has the highest groundwater storage potential with moderate productivity. In the central part of the study area, VES 4, 11, 12, 13, 14, and 16 are located within the red color band, which indicates aquifer layers of relatively thin thickness. In contrast, the western and southwestern part, including VES 1, 2, 3, 10, and 15, show moderate variation in thickness (4.69-16.5).

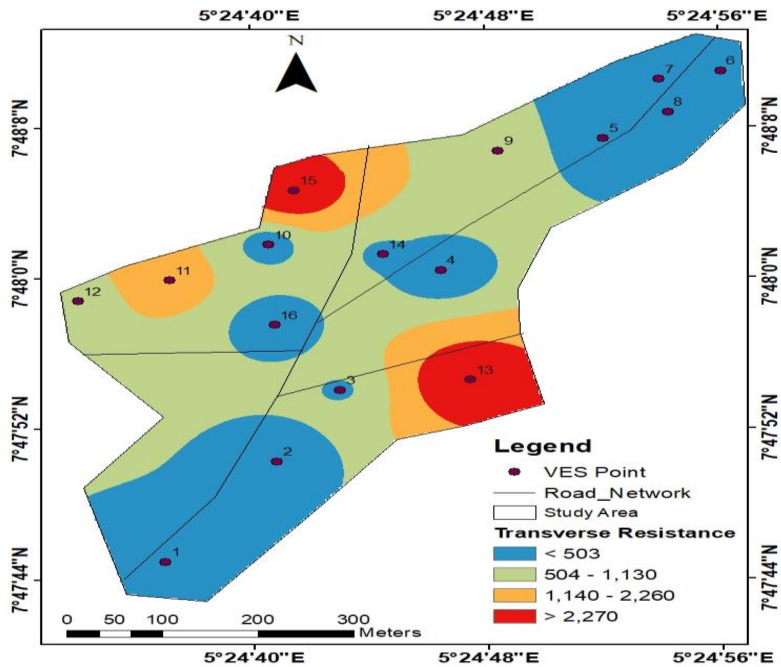

Figure 6: Transverse Resistance Map

Table 3: Summary of the Dar-Zarrouk Parameters Adopted For This Study

VES	Latitude	Longitude	Longitudinal Conductance	Transverse Resistance	Isopach value of the overburden	Isoresistivity of the Aquifer
1	765807	862484	0.159	90	12.1	6
2	765924	862648	0.006	50	6.8	5
3	765990	862765	0.038	460.6	7.5	47
4	766095	862961	-------	------	------	------
5	766265	863177	-------	------	------	------

6	766388	863287	-------	------	------	------
7	766324	863273	-------	------	------	------
8	766333	863220	0.719	452.5	5.2	25
9	766155	863156	1.644	910.8	29.1	36
10	765915	863002	0.481	201.6	6.2	28
11	765811	862944	0.0001	1633	1.4	230
12	765715	862910	0.0009	893.2	1.3	154
13	766126	862782	0.0034	3887	4.3	169
14	766035	862987	0.007	427.8	1.5	46
15	765941	863091	0.035	3733.8	7.5	381
16	765921	862871	0.1	58.8	2.6	146

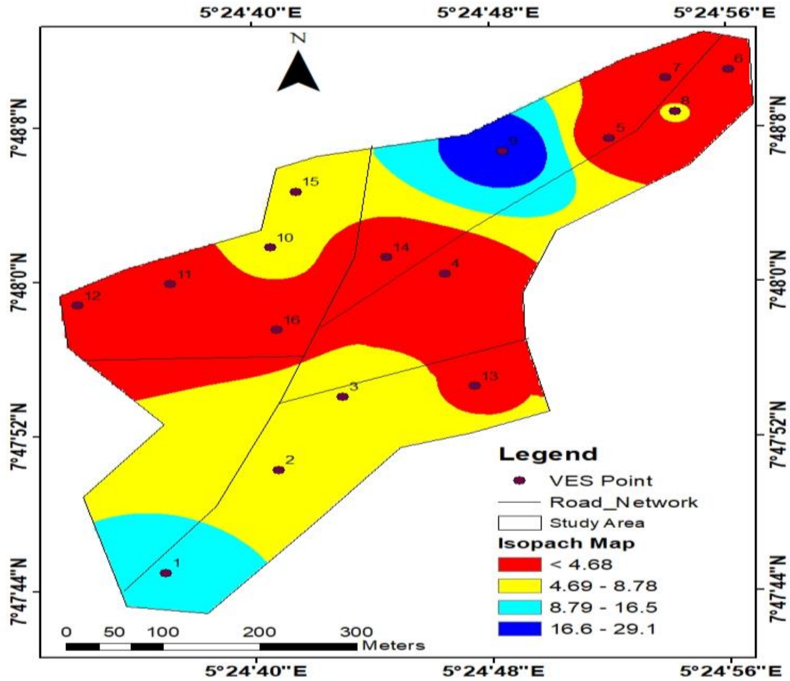

Figure 7: Isopach Map of the Overburden

The moderate thickness indicates a balanced condition where groundwater accumulation is feasible, and a reasonable degree of protection is provided through partial filtration and attenuation processes. The central, and northeastern parts of the study area are predominantly characterized by thin overburden (less than 10 m). The thin overburden reduces the capacity for contaminant attenuation and increases the vulnerability of the underlying aquifer to surface derived pollutants (Adepelumi et al., 2009; Omosuyi et al., 2008).

Isoresistivity Distribution of the Aquifer

In Figure 8, the northeastern and southwestern flanks of the study area are primarily associated with low resistivity values (< 80 Ωm), as shown by the blue color band. These areas, hosting VES 1, 2, 3, 4, 5, 6, 7,8,9, and 14 reveal the presence of highly weathered (clay-rich), or saturated formations. These formations have high porosity and permeability, which is conducive for groundwater accumulation but also increase susceptibility to contaminant infiltration. In the central part of the study area, the resistivity values change to moderate values (about 100-200 Ωm), with yellow color band. This area, which covers VES 12, 13, and 16, corresponds to a combination of weathered and partially lateritic materials. The materials have moderate permeability and better filtration properties. Thus, the central part of the study area exhibits moderate aquifer protective capacity where some degree of contaminant attenuation may take place. However, the northwestern flank is characterized by relatively moderate-to-high resistivity values (red color band). This is probably due to the occurrence of relatively denser, partly weathered, and perhaps laterite. These formations, with lower porosity and permeability, restrict the downward percolation of contaminants and increase aquifer protection. As a result, northwestern area has a moderate to high protective capacity.

Synthesis of Results

The northeastern flank, around VES 5, 6, 7, and 8 of the study area, is characterized by low transverse resistance, thin overburden, and low aquifer resistivity values. Although the low resistivity value could possibly be an indication of the presence of weathered and saturated formations, the thin aquiferous layer and low transverse resistance shows low groundwater accumulation and transmissivity. Furthermore, the relatively weak protective capacity observed within parts of this region is an indication of increased vulnerability of the aquifer to contamination. The north-central part, around VES 9 presents comparatively more favorable hydrogeological conditions. This area is made up of appreciable overburden thickness, and high aquifer protective capacity, thus, the area is considered suitable for moderate groundwater development with relatively good protection against pollutants.

In the central part of the study area which combines VES 10, 12, 13, 14, and 16, the groundwater potential appears moderate to high due to the occurrence of moderate to high transverse resistance and moderately resistive subsurface materials. The presence of weathered to partially lateritic.

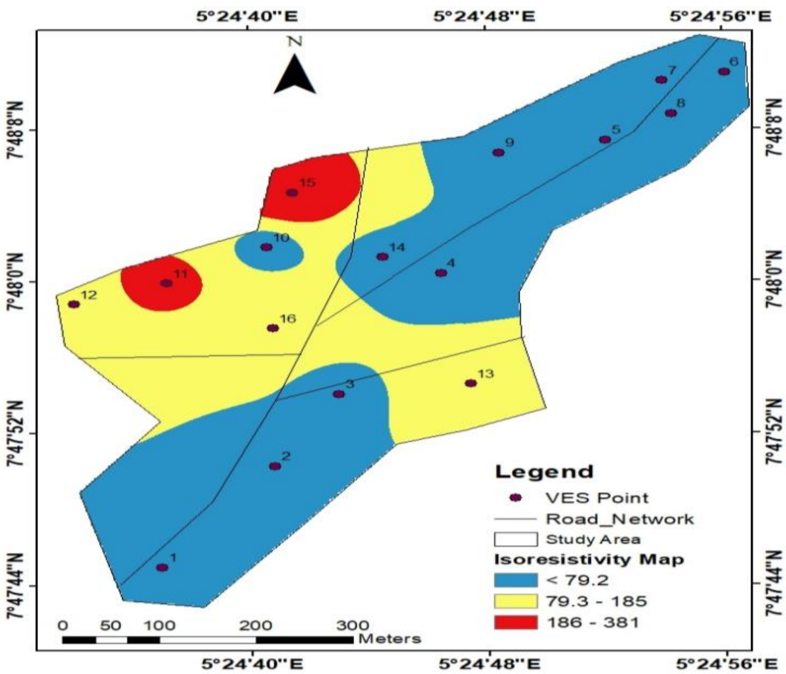

Figure 8: Isoresistivity Map of the Aquifer

Formations within this zone suggests improved transmissivity and relatively better filtration characteristics. Although some locations within the central part are associated with thin overburden, the moderate aquifer resistivity and fair protective capacity indicate that groundwater occurrence is structurally controlled and may be enhanced by localized fracturing. These conditions show that the central part is capable of supporting sustainable groundwater abstraction where adequate borehole siting is carefully carried out. In the same vein, the southwestern and southeastern parts of the study area, most especially around VES 11, 13, and 15, exhibit relatively high transverse resistance values, moderately thick and resistive subsurface layers capable of storing and transmitting groundwater. However, the protective capacity within parts of these zones ranges from fair to poor, implying that although groundwater yield may be appreciable, the aquifers remain susceptible to contamination due to insufficient overburden filtration in some locations. The northwestern flank displays relatively moderate-to-high resistivity values, which are indicative of partly weathered formations with reduced permeability.

CONCLUSION

The integration of the geo-electric parameters in the study area reveals different aquifer conditions from the interpretation of the isopach, isoresistivity, longitudinal conductance (S) and transverse resistance (T) maps of the study area. This is because of the influence of overburden thickness, and resistivity distribution of groundwater occurrence and protective capacity. The study revealed that the most favorable zones for groundwater development within the study area are concentrated around the north-central and parts of the central region, where moderate to high transverse resistance coincides with appreciable overburden thickness and fair to high aquifer protective capacity. On the other hand, the northeastern part of the study location is comparatively less favorable for groundwater abstraction owing to the presence of thin overburden and low transmissivity characteristics, while parts of the southwestern and southeastern regions require careful groundwater management because of their relatively weak protective capacity. It is recommended that groundwater development within the study area should prioritize the north-central and central zones for borehole siting due to their comparatively higher groundwater potential and better aquifer protection.

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