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Groundwater Hydraulic Characterization from Part of the Basement Area Using Vertical Electrical Sounding Data: A Case Study of Oshogbo, Southwestern Nigeria

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Abstract

Groundwater potential in basement complex terrains is primarily governed by the hydraulic properties of weathered and fractured zones, as the underlying bedrock typically exhibits low porosity and permeability. This study utilized the Vertical Electrical Sounding (VES) method with a Schlumberger array at 20 locations within Oshogbo metropolis to evaluate groundwater potential. Geophysical data were processed using WINRESIST software to interpret subsurface characteristics and estimate key aquifer parameters—hydraulic conductivity, transmissivity, and longitudinal conductance—through established empirical and interpretative models. The subsurface sequence delineated includes topsoil (resistivity: 16.1–2509.8 Ωm; thickness: 0.5–9.7 m), clay (10.5–43 Ωm; 2.8–27.7 m), sandy/clayey materials (54–133 Ωm; 6–19.8 m), weathered layers (822.6–1635.7 Ωm; 6–19.8 m), and fresh bedrock (1614.1–5679.8 Ωm). Hydraulic conductivity values ranged from 0.33 to 61.36 m/day, with a mean of 20.07 m/day, while transmissivity varied in relation to both conductivity and aquifer thickness. Longitudinal conductance values ranged from 0.002 to 0.325 Ω^{-1} (mean: 0.087 Ω^{-1}), indicating generally poor protective capacity and high vulnerability across the study area, with exceptions at Locations L01, L10, and L15, which exhibited moderate protective capacity. These three sites also demonstrated moderate hydraulic conductivity, low transmissivity, and fair groundwater potential. Overall, the integration of geoelectrical and hydrogeophysical parameters offers a reliable approach for assessing aquifer capacity and groundwater vulnerability in crystalline basement terrains.

Keywords: Vertical Electrical Sounding; Aquifer Characteristics; Hydraulic Conductivity; Transmissivity; Groundwater Potential

INTRODUCTION

Water is an important resource for human existence. Groundwater exploration in the basement complex is a difficult task due to the crystalline nature of the bedrock. Crystalline rocks have poor water bearing capacity because of their low porosity and permeability (Oladunjoye et al, 2019). Groundwater in the crystalline rocks resides in the fractured and weathered part of the underlying rocks. However, transmission and movement within the fracture is a function of the interconnectivity and degree of fracturing as a result of tectonic activities (Ebong et al., 2023). Electrical resistivity (Vertical Electrical Sounding) method have been found very useful in groundwater exploration especially in the basement. It has proved worthy in delineating sub-surface structures, characterizing aquifer properties such as porosity, permeability, specific yield and storage coefficient, also hydraulic properties such as transmissivity, hydraulic conductivity and specific storage (Oyeyemi et al., 2015). Groundwater potential in the basement complex is a function of aquifer characteristics due to low porosity and permeability of the bedrock (Ajayi and Adegoke, 1988). Therefore, exploration of groundwater in the basement should focus on thick overburden and fractured zones of the basement (Okpoli and Ozomoge, 2020). Resistivity is influenced by several factors such as water content, porosity, and degree of salinity, therefore, it can be related to hydraulic conductivity and geometry of the aquifer. For more accurate estimation of aquifer properties, integrated geophysical-hydrogeological approaches are increasingly being used. High resistivity values often indicate coarse grained soils which are generally permeable, whereas low resistivity values indicates or suggest clay or silt with low permeability (Agbodike, 2021). Archie, (1942) relates bulk resistivity to porosity and water saturation, providing a means to estimate aquifer properties from resistivity data. Similarly, the Kozeny-Carman equation links permeability with porosity and grain size, which can be inferred from geophysical survey

Oshogbo is underlain by the basement complex rock of the southwestern Nigeria, including gneiss and migmatite undifferentiated rock, schist pegmatised (NGSA, 2006). Larger percentage of the inhabitant depend on pipe borne water which is supplied by waterworks from Ede town, but for the past few years, this project has been abandoned due to lack of maintenance, vandalization of pipeline and government policies. With this, the populace depends on groundwater as a means of survival. Hence it is necessary to delineate potential zones and estimate aquifer parameters in the absence of pumping test data to facilitate groundwater exploration and resource management with Oshogbo metropolis. This study employed the use of electrical resistivity method (Vertical Electrical Sounding) to delineate subsurface geology and lithology for segmenting potential and non-potential zones. This study aimed at assessing the hydraulic properties (such as transmissivity and hydraulic conductivity) within Oshogbo metropolis using vertical electrical sounding method to unravel the aquifer yield and geometry.

Location and Geology

The study area in is bounded by longitudes E 4°30’55” and E 4°32’48” and latitudes N 7°46’52” and N 7°47’47”. It covers about 5.8459 km^2 (Figure 1). Oshogbo is located on Precambrian Basement of high grade metamorphic facie (Rahaman, 1988; Falana and Akanbi, 2023) and noted that the rock lies in the zone of Pan-African reactivation 600 ± 150 Ma. He grouped quartzite and gneisses as migmatite-gneiss complex and subscribed to the view that rocks of the migmatite-gneiss-quartzite complex comprises largely a sedimentary series with associated minor in igneous rocks which has been variably altered by metamorphic, migmatitic and granitic processes (Figure 2). The area has two climatic seasons within a year. The seasons are the hot dry season between November and April and the wet season May to October with temperature which ranges between 27°C and 35°C (WorldData.info, 2024). The area typically receives an annual rainfall of about 1500mm with a dendritic drainage pattern.

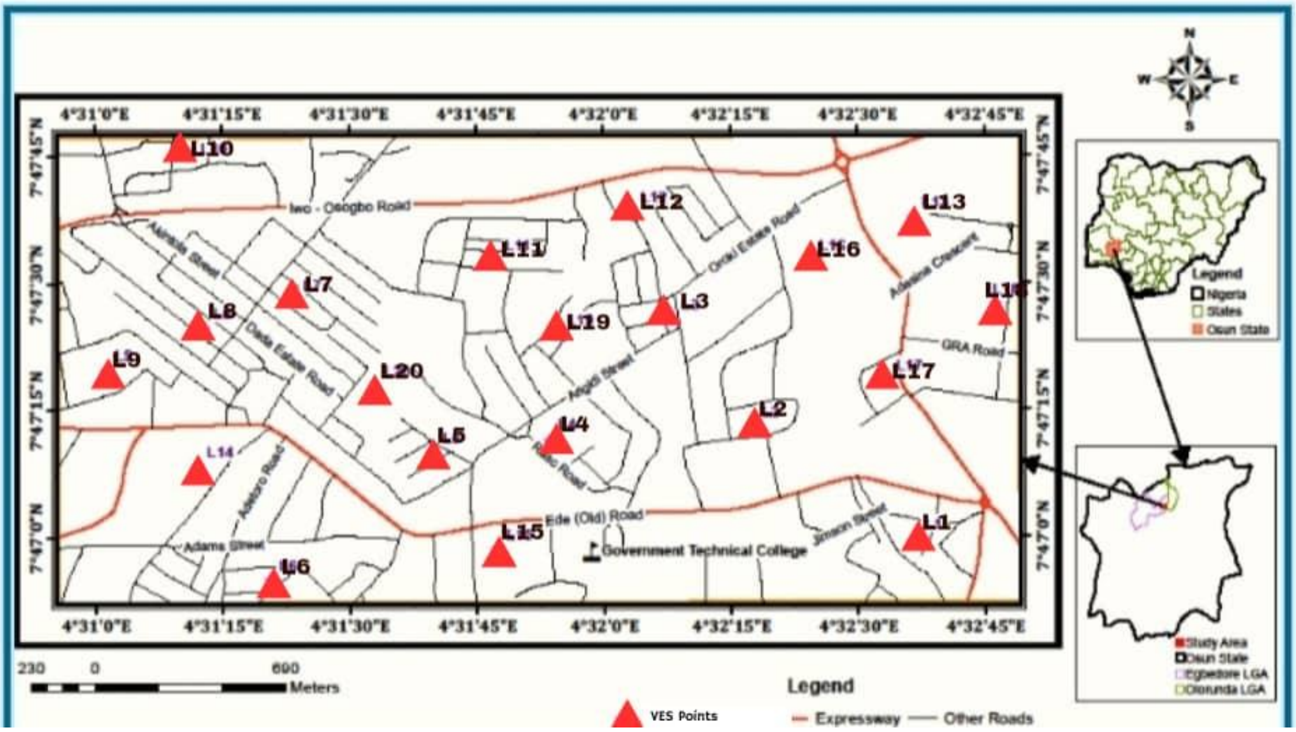


Figure 1: Location map with sampling points in the study area.

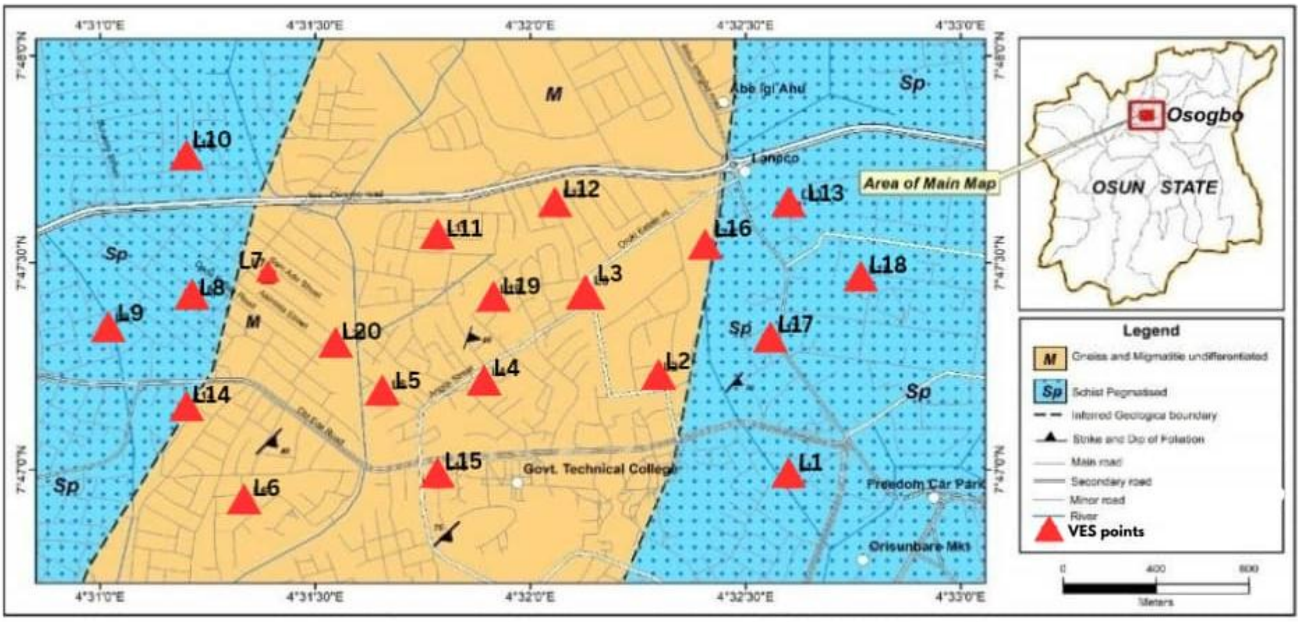


Figure 2: Geologic map with VES points across the study area.

METHODS

This study makes use of electrical resistivity method (VES) collected from 20 points for delineating groundwater potential in Oshogbo metropolis. Vertical Electrical Sounding is a geophysical method based on measuring the subsurface electrical resistivity variations with depth. The technique involves injecting current into the ground through a pair of electrodes and measuring the resulting potential difference with another pair of electrodes. The distance between the electrodes is gradually increased, allowing the current to penetrate deeper into the subsurface and providing information about the resistivity of different layers. This study employed the use of Schlumberger array because its preferred in groundwater exploration because it provides higher resolution data, particularly in detecting variations at greater depths. The maximum AB separation employed was 200m. The terrameter brand used was Omega Ohm meter. The apparent resistivity is plotted against the corresponding half electrode spacing (AB/2) on a bi-log graph to generate the sounding curves. The sounding curves were initially subjected to manual curve marching to generate the resistivity of the layers and thickness and later interpreted with WINRESIST software.

Assessment of Aquifer Characteristics from Electrical Method

Electrical resistivity survey is relevant to groundwater exploration, several authors have made use of this method in groundwater exploration in the basement complex environment (Akanbi, 2018; Oladunjoye et al., 2019; Adeeko et al., 2019; Kwami et al., 2023; Nwankwo et al., 2013 and Ige et al., 2019). The geoelectric data collected from the surface can be used to delineate aquifer properties such as hydraulic conductivity (K), transmissivity (T) and longitudinal conductance. Hydraulic conductivity is the fluid transmission ability in a porous material (Kwami et al., 2023). There are several numerical equations that correlate electrical resistivity to hydraulic conductivity. Kosinki and Kelly (1981) linked electrical resistivity with hydraulic conductivity with the equation below;

$K(m/s) = 10^{-5} X\ 97.5^{-1} X\ \varrho^{1.195}$

$K(m/d) = 60\ X\ 60\ X\ 24$

Where K = hydraulic conductivity and ϱ= aquifer resistivity

Transmissivity is defined as the rate of water flow through a unit cross sectional of the aquifer od a unit width that extends through a full saturated thickness under a unit hydraulic gradient. Thus,

$T = K X h$

Where T = Transmissivity

K = Hydraulic conductivity (m/d)

h = aquifer thickness

Longitudinal conductance can be used in evaluating the aquifer vulnerability, hence protective capacity and are derived using primary geoelectric parameters thus:

$S = h / \varrho$

RESULTS

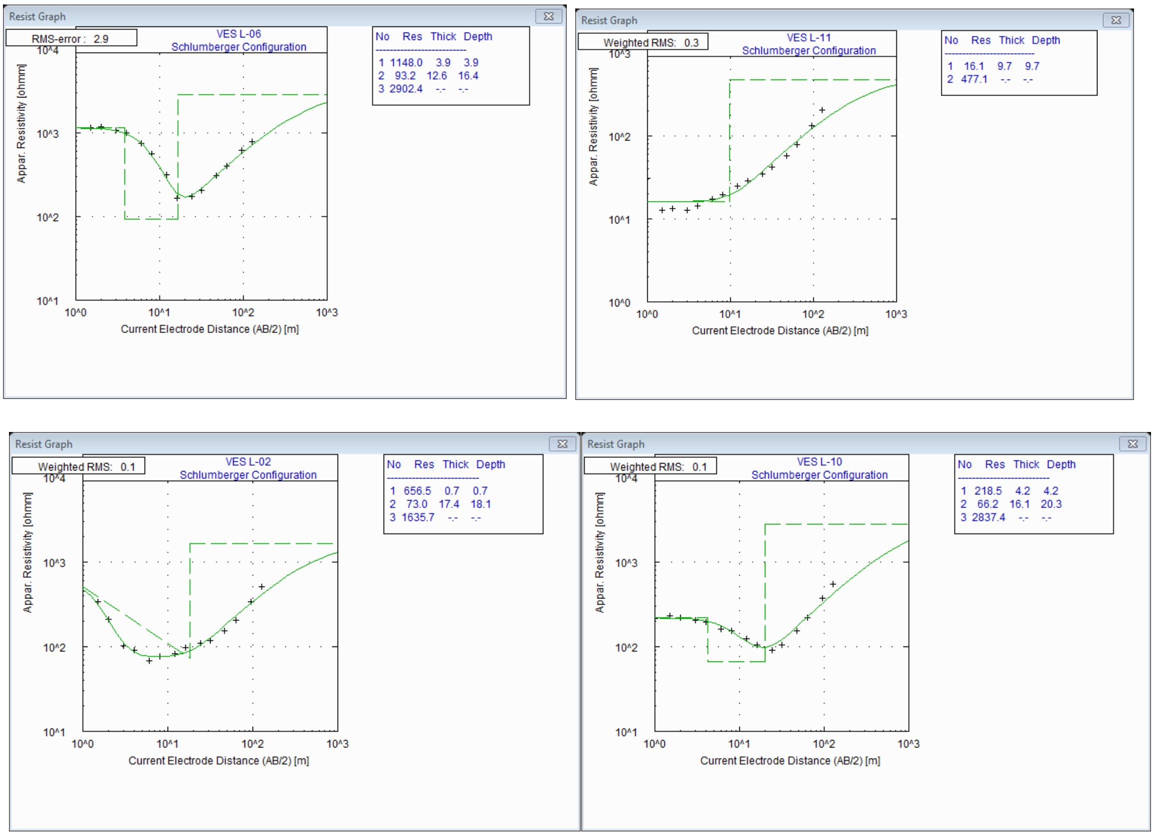
The results of the vertical electrical sounding (VES) data obtained from twenty (20) VES stations within the study area were presented in Table 1. The dominant curve type is H – curve taking 90% and A – curve taking 10% (Figure 3).

Table 1: Summary of geoelectric parameters and lithologic interpretation across the study area

VES NO	NUMBER OF GEO-ELECTRIC LAYERS	APPARENT RESISTIVITY (Ωm)	THICKNESS (m)	DEPTH (m)	INFERED LITHOLOGY	CURVE TYPE
01.	3	1913.3	1.0	1.0	Top soil	H
		39.8	9.2	10.2	Clayey	
		2005.1			Fresh Bedrock	
02.	3	656.5	0.7	0.7	Top soil	H
		73	17.4	18.1	Sandy/clayey	
		1635.7			Weak/slightly weathered	
03.	3	1906.8	1.0	1.0	Top soil	H
		29.1	9.1	10.1	Clayey	
		1571.4			Weak/slightly weathered	
04.	3	1068.2	1.6	1.6	Top soil	H
		38.6	24.6	26.2	Clayey	

VES NO	NUMBER OF GEO-ELECTRIC LAYERS	APPARENT RESISTIVITY (Ωm)	THICKNESS (m)	DEPTH (m)	INFERED LITHOLOGY	CURVE TYPE
		1033.5			Weak/slightly weathered	
05.	3	324.3	1.7	1.7	Top soil	H
		26.0	15.2	16.9	Clayey	
		1033.5			Weak/slightly weathered	
06.	3	1148.0	3.9	3.9	Top soil	H
		93.2	12.6	16.4	Sandy/clayey	
		2902.4			Fresh bedrock	
07.	3	428.0	2.9	2.9	Top soil	H
		107.9	19.8	22.7	Sandy/clayey	
		2869.4			Fresh bedrock	
08	3	545.0	2.2	2.2	Top soil	H
		54.7	6.0	8.3	Sandy/clayey	
		437.8			Compactedclay/hardpan	
09.	3	87.6	0.9	0.9	Top soil	H
		19.1	4.3	5.2	Clayey	
		133.0			Sandy/clayey	
10.	3	218.5	4.2	4.2	Top soil	
		66.2	16.1	20.3	Sandy/clayey	
		2837.4			Fresh bedrock	
11.	2	16.1	9.7	9.7	Top soil	A
		477.1			Compacted clay/hardpan	
12.	3	461.0	0.7	0.7	Top soil	H
		10.5	8.9	9.6	Clayey	
		851.1			Weak/slightly weathered	
13.	3	74.7	2.3	2.3	Top soil	H
		13.4	11.5	13.8	Clayey	
		822.6			Weak/slightly weathered	
14.	3	149.8	1.1	1.1	Top soil	H
		21.0	2.8	3.8	Clayey	

VES NO	NUMBER OF GEO-ELECTRIC LAYERS	APPARENT RESISTIVITY (Ωm)	THICKNESS (m)	DEPTH (m)	INFERED LITHOLOGY	CURVE TYPE
		5679.8			Fresh bedrock	
15.	3	828.0	1.2	1.2	Top soil	H
		20.6	6.7	7.9	Clayey	
		2508.6			Fresh bedrock	
16.	2	24.6	3.9	3.9	Top soil	A
		1614.1			Weak/slightly weathered	
17.	3	1268.4	0.9	0.9	Top soil	H
		43.8	9.7	10.6	Clayey	
		1214.7			Weak/slightly weathered	
18.	3	329.4	1.7	1.7	Top soil	H
		60.6	6.0	7.7	Sandy/clayey	
		3911.3			Fresh bedrock	
19.	3	288.4	3.2	3.2	Top soil	H
		34.9	27.7	30.9	Clayey	
		456.0			Compacted clay/hardpan	
20.	3	2509.8	0.5	0.5	Top soil	H
		38.9	6.8	7.3	Clayey	
		2069.3			Fresh bedrock	



```
RMS-error :  2.9
VES L-06
Schlumberger Configuration

No   Res   Thick  Depth
-------------------------
1  1148.0   3.9    3.9
2    93.2  12.6   16.4
3  2902.4   -.-    -.-
```

```
Weighted RMS:  0.3
VES L-11
Schlumberger Configuration

No   Res   Thick  Depth
-------------------------
1   16.1    9.7    9.7
2  477.1    -.-    -.-
```

```
Weighted RMS:  0.1
VES L-02
Schlumberger Configuration

No   Res   Thick  Depth
-------------------------
1   656.5   0.7    0.7
2    73.0  17.4   18.1
3  1635.7   -.-    -.-
```

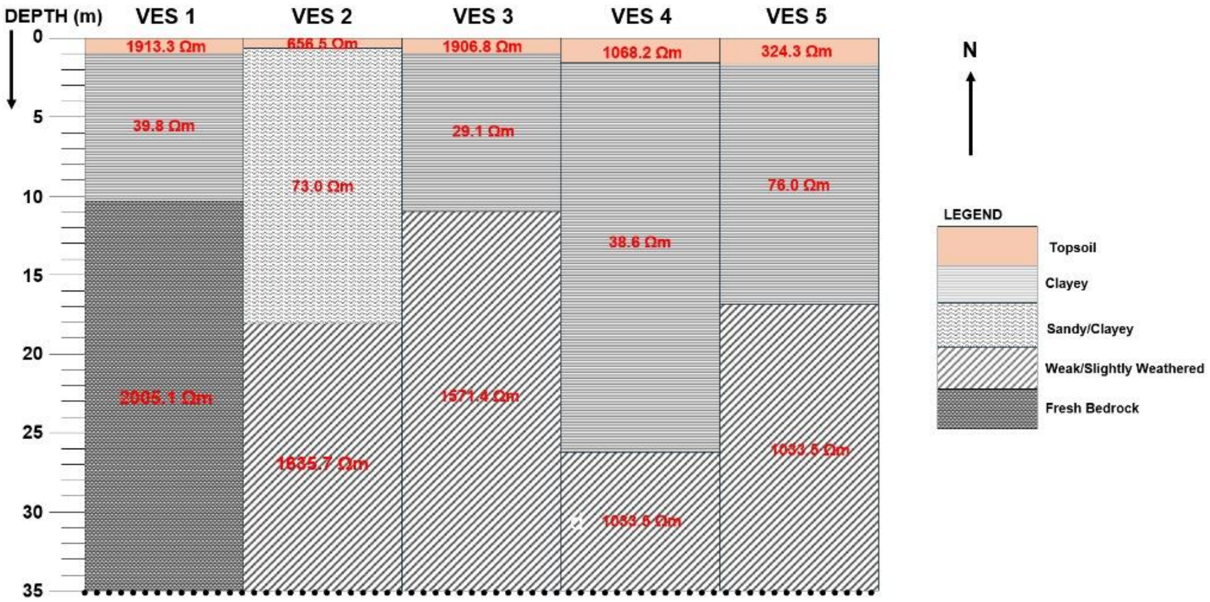
```
Weighted RMS:  0.1
VES L-10
Schlumberger Configuration

No   Res   Thick  Depth
-------------------------
1   218.5   4.2    4.2
2    66.2  16.1   20.3
3  2837.4   -.-    -.-
```

Figure 3: Representative curve type across the study area.

DISCUSSION

The analysis and interpretation of each resistivity curve across the area shows that the study area consists of two to three geoelectric layers ranging from top soil, sandy/clayey, weak/slightly weathered and fresh basement rock (Figure 4). The results of the interpretation show the top soil have resistivity and thickness ranges between 16.1Ωm – 2509.8Ωm and 0.5m – 9.7m and clay possess resistivity and thickness between 10.5Ωm - 43Ωm and 2.8m – 27.7m, sandy/clayey resistivity and thickness is between 54Ωm - 133Ωm and 6m – 19.8m, weak/slightly weathered layer is between 822.6Ωm – 1635.7Ωm and 6m – 19.8m, fresh bedrock resistivity is between 1614.1Ωm – 5679.8Ωm.


DEPTH (m)
VES 1
VES 2
VES 3
VES 4
VES 5
0
5
10
15
20
25
30
35
1913.3 Ωm
656.5 Ωm
1906.8 Ωm
1068.2 Ωm
324.3 Ωm
39.8 Ωm
73.0 Ωm
29.1 Ωm
38.6 Ωm
76.0 Ωm
2005.1 Ωm
1635.7 Ωm
1571.4 Ωm
1033.5 Ωm
1033.5 Ωm
N
LEGEND
Topsoil
Clayey
Sandy/Clayey
Weak/Slightly Weathered
Fresh Bedrock


DEPTH (m)
VES 6
VES 7
VES 8
VES 9
VES 10
0
5
10
15
20
25
30
35
1148.0 Ωm
428.0 Ωm
545.0 Ωm
87.6Ωm
218.5 Ωm
93.2Ωm
107.9Ωm
54.7Ωm
19.1Ωm
66.2 Ωm
437.8 Ωm
2902.4Ωm
2869.4Ωm
133.0Ωm
2837.4Ωm
N
LEGEND
Topsoil
Clayey
Sandy/Clayey
Compacted clay/hardpam
Fresh Bedrock

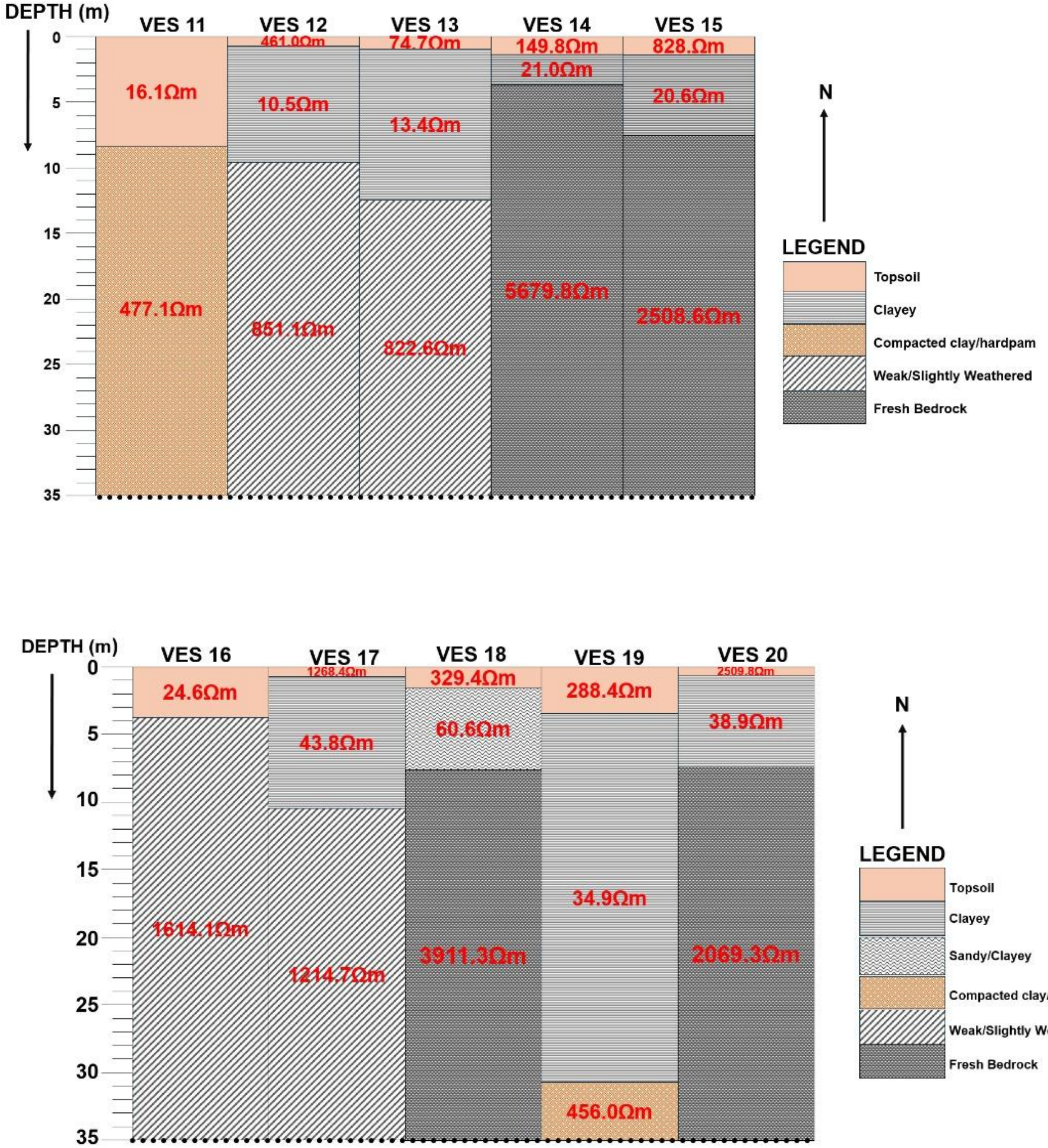


Figure 4: Geoelectric sections from VES data in the study area.

Domenico and Schwartz present typical ranges of hydraulic conductivity for various geologic materials which are mostly used as basis for classification in groundwater evaluation. The classification scheme for hydraulic characterization of groundwater in the basement complex terrain used for the interpretation is presented in the in Table 2, modified after (Domenico and Schwartz, 1990). These values are approximate and depend on local conditions such as degree of fracturing and weathering.

Table 2: Classification scheme for Hydraulic conductivity in groundwater characterization in the basement complex (Modified after Domenico and Schwartz, 1990)

Hydraulic Conductivity (m/day)	**Classification**	**Typical Geologic zone**
>8.64	High	Highly fractured/weathered rock
8.64 – 0.0864	Moderate	Moderately fractured/weathered rock
0.0864 – 0.00000864	Low	Slightly fractured/crystalline basement
<0.00000864	Negligible	Fresh/compact/unfractured

The calculated aquifer characteristics from the interpreted VES data for the study area is presented in Table 3.

Table 3: summary of aquifer characteristics from VES data obtained across the study area.

VES No	**Aquifer Resistivity (Ωm)**	**Aquifer Thickness (m)**	**Hydraulic Conductivity (m/day)**	**Transmissivity(m^2/day)**	**Longitudinal conductance (Ω^{-1})**
01	39.8	9.2	0.72	6.62	0.230
02	1635.7	17.4	61.36	1067.66	0.010
03	1571.4	9.1	58.49	532.26	0.006
04	1033.5	24.6	35.45	872.07	0.024
05	1033.5	15.2	35.45	538.84	0.015
06	93.2	12.6	1.99	25.07	0.135
07	107.9	19.8	2.38	47.12	0.184
08	437.8	6.0	12.70	76.20	0.014
09	133.0	4.3	3.06	13.16	0.032
10	66.2	16.1	1.33	21.41	0.243
11	477.1	9.7	14.07	136.48	0.020
12	851.1	8.9	28.11	250.18	0.011
13	822.6	11.5	26.99	310.39	0.014
14	21.0	2.8	0.34	0.95	0.133
15	20.6	6.7	0.33	2.21	0.325
16	1614.1	3.9	60.39	235.52	0.002

VES No	Aquifer Resistivity (Ωm)	Aquifer Thickness (m)	Hydraulic Conductivity (m/day)	Transmissivity(m^2/day)	Longitudinal conductance (Ω^{-1})
17	1214.7	9.7	42.99	417.00	0.008
18	60.6	6.0	1.19	7.14	0.099
19	456	27.7	13.33	369.24	0.061
20	38.90	6.8	0.70	4.76	0.175
Mean	586.44	11.15	20.07	246.71	0.087
Minimum	20.6	2.8	0.33	0.95	0.002
Maximum	1635.7	27.7	61.36	1067.66	0.325

The aquifer resistivity across the study are ranges from 20.6Ωm to 1635.7Ωm with an average of 586.44Ωm. thickness ranges from 2.8m to 27.7m and a mean value of 2.8m.

Hydraulic conductivity values ranges from 0.33 m/day to 61.36 m/day and mean value of 20.07 m/day. The relationship between hydraulic conductivity and transmissivity indicates that transmissivity is directly proportional to both hydraulic conductivity and aquifer thickness. A high hydraulic conductivity or thicker aquifer will result in higher transmissivity, indicating greater ability to transmit water. Therefore, areas with high hydraulic conductivity were observed in locations 02, 03, 04, 05, 08, 11, 12, 13, 16, 17 and 19 respectively. Also locations 01, 06, 07, 09, 10, 14, 15, 18 and 20 has moderate hydraulic conductivity. Hence 55% of the area coverage has high hydraulic conductivity and 45% has moderate hydraulic conductivity. From the hydraulic conductivity map (Figure 5) the brown/yellowish portion towards the western part, pockets in the southeastern part and northeastern part of the map shows the zone of low to moderate hydraulic conductivity indicating zone of low groundwater potential. Also, zones with purple/black color shows zone of high hydraulic conductivity indicating zones of high groundwater potential.

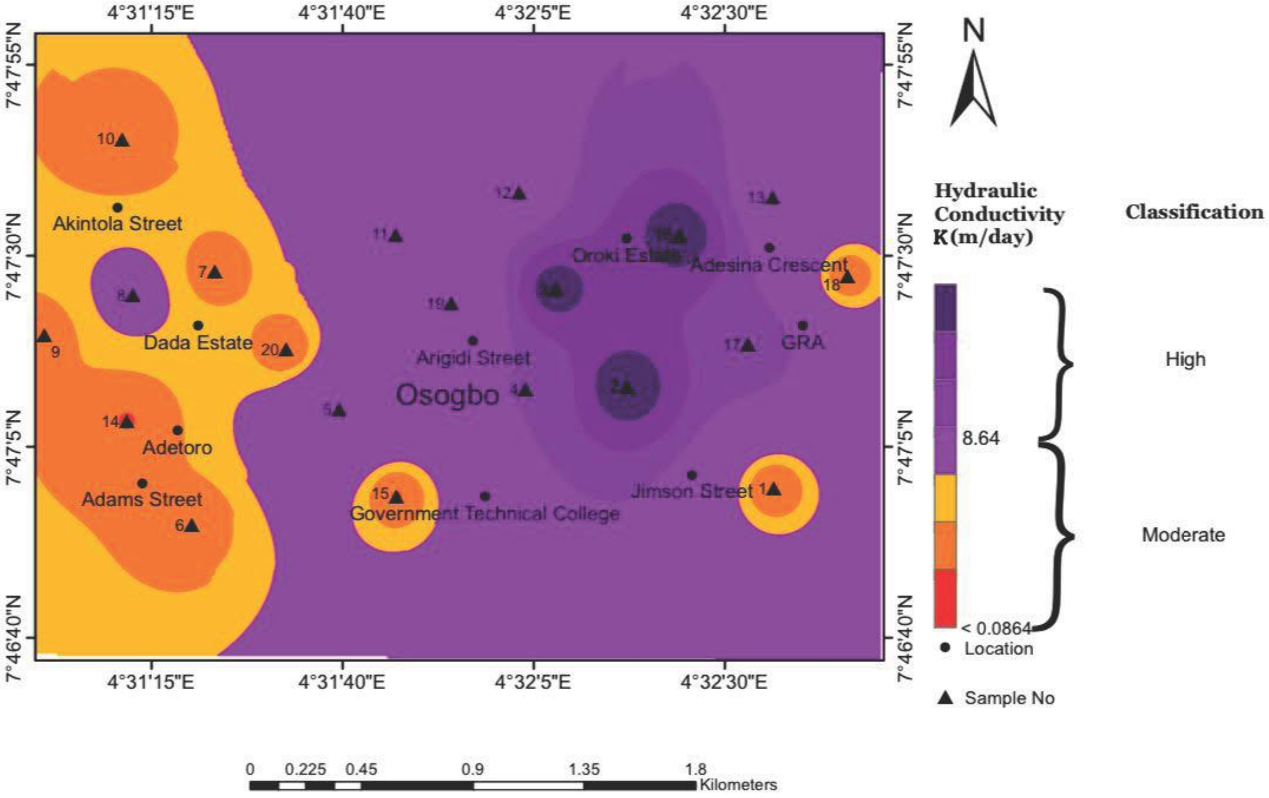


Figure 5: Hydraulic conductivity map of the study area.

The transmissivity value across the study area ranges from 0.95m^2/day to 1067.66m^2/day and a mean value of 246.71m^2/day. The interpretation of groundwater potential in the study area can be adopted from modified values of Offodile, 1983; Kwami et al., 2019b. <0.5 – 50 m^2/day indicates low potential, between 51 – 500 m^2/day indicates moderate potential and >500 m^2/day indicate high potential. Low potential can be found in locations 01, 06, 07, 09, 10, 14, 15, 18 and 20. Moderate potential is found in locations 08, 11, 12, 13, 16, 17 and 19 while high potential is found in locations 02, 03, 04 and 05 (Figure 6).

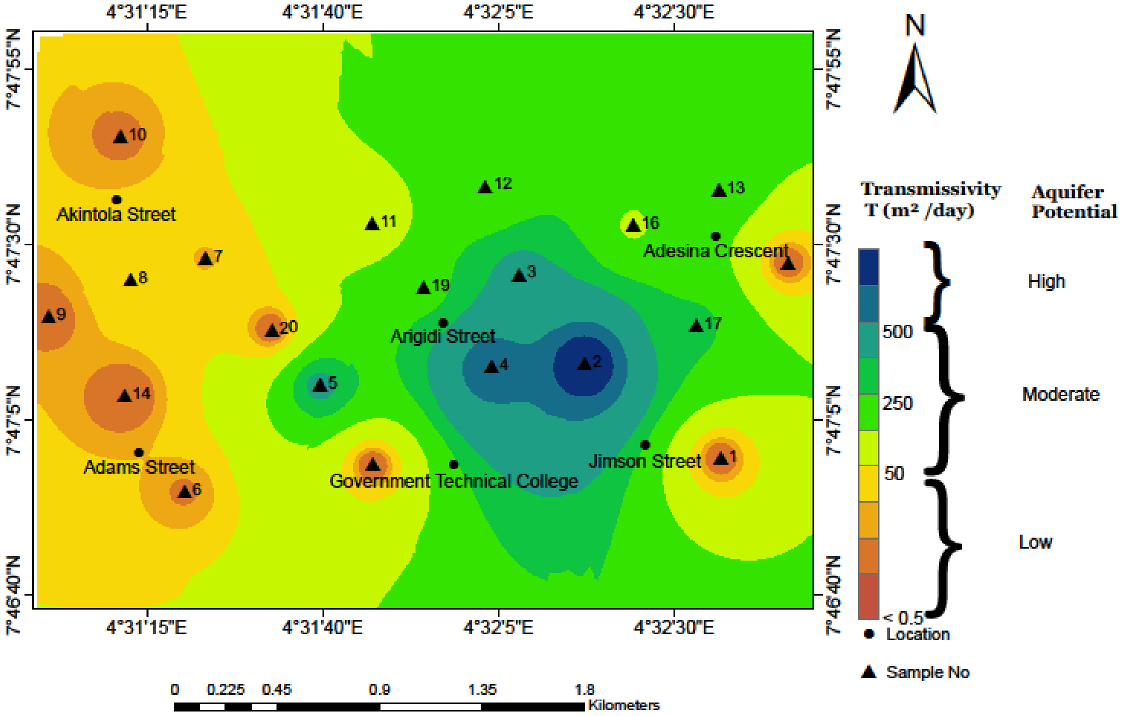


Figure 6: Transmissivity map of the study area.

Longitudinal conductance has been used as a tool by many professional and authors in the areas of groundwater potential. The variation of longitudinal conductance across the study area ranges from $0.002\Omega^{-1}$ to $0.325\Omega^{-1}$ with a mean value of 0.087 Ω^{-1}. Increase in the value of longitudinal conductance indicates high clay content of the overburden, high protective capacity against pollution from the overburden, hence low vulnerability and vice versa. Based on modified rating of Oladapo and Akintorinwa (2007), longitudinal conductance of <0.1 – 0.19 indicate poor protective capacity, between 0.2 – 0.69 indicate moderate protective capacity and between 0.7 – 10 indicate good protective capacity. All the locations have poor protective capacity/high vulnerability except for locations 01, 10 and 15 with moderate protective capacity/moderate vulnerability. Figure 7 shows the longitudinal conductance across the study area.

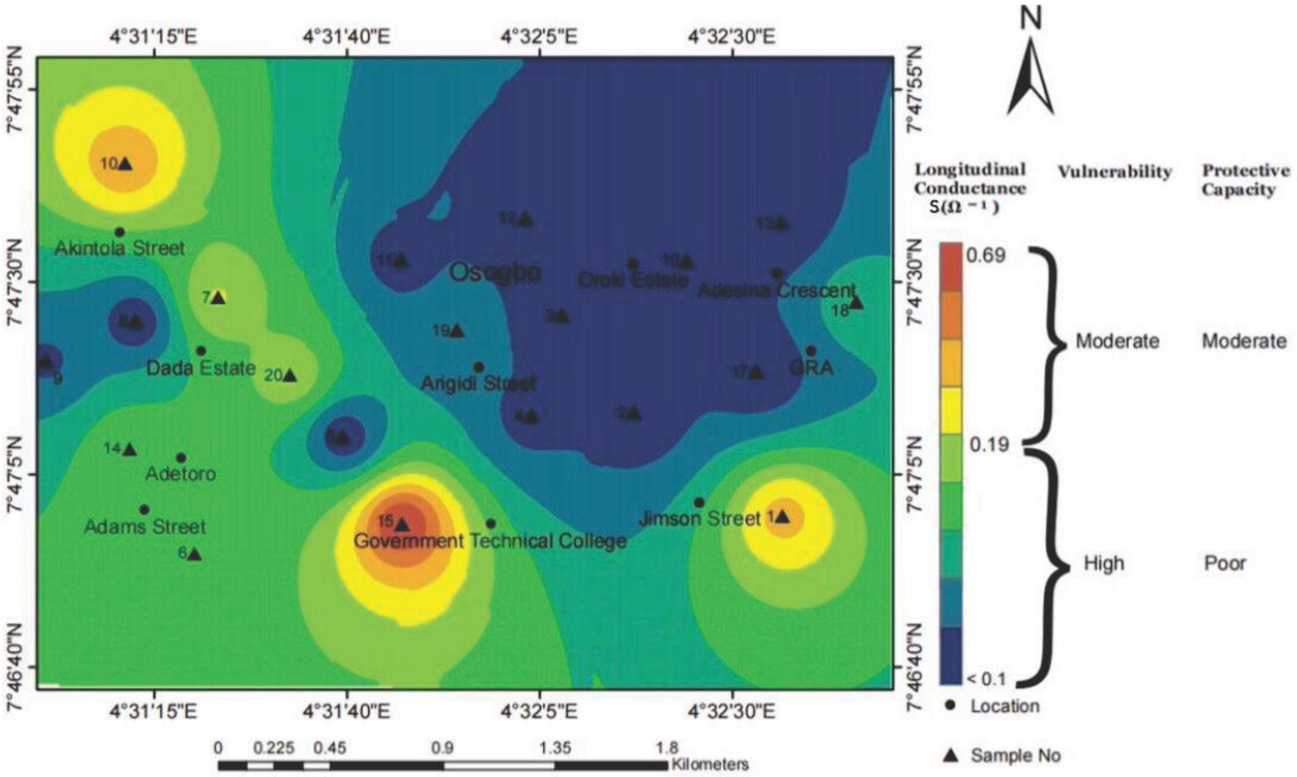


Figure 7: Longitudinal conductance map of the study area.

CONCLUSION

This study has demonstrated the effectiveness of the Vertical Electrical Sounding (VES) method using the Schlumberger array in delineating aquifer characteristics and evaluating groundwater potential in Oshogbo metropolis, a typical basement complex environment. The resistivity variations observed across the subsurface layers provided valuable insights into the lithological composition, thickness, and hydrological significance of each unit. The derived geoelectric parameters, particularly hydraulic conductivity, transmissivity, and longitudinal conductance, were instrumental in assessing the productivity and vulnerability of the aquifers. The results revealed significant heterogeneity in subsurface properties, indicating variable groundwater potential across the study area. The moderate hydraulic conductivity and low transmissivity values observed at locations L01, L10, and L15 suggest limited water yield, though with moderate protective capacity against contamination. These findings are crucial for informed decision-making in groundwater resource development, especially in urban settings with increasing water demand. The direct proportionality between hydraulic conductivity and transmissivity underscores the importance of both parameters in aquifer assessment. Moreover, the integration of geophysical data with empirical relationships has proven reliable for characterizing aquifer systems without extensive drilling. For future studies, it is recommended to combine resistivity surveys with borehole data and hydrochemical analysis for more comprehensive groundwater evaluation. Overall, this research contributes to a better understanding of groundwater distribution and supports sustainable water resource management in basement complex terrains.

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