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Geoelectric Assessment of Regolith Aquifer and Its Vulnerability, in a Typical Basement Complex Terrain, Southwestern Nigeria

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Abstract: Assessment of groundwater potential cum regolith aquifer protective strength was carried out using the electrical resistivity method at Ikole Ekiti, Southwestern Nigeria, to assess its viability and susceptibility. The Vertical Electrical Sounding (VES) technique using the Schlumberger array was adopted. The acquired data was partially curve-matched, forward-modelled, and iterated using WinResist version 1.0 software. Charts, para sections, tables, and maps were generated from the results obtained to aid interpretations. The KH curve type, which indicates good protective capacity, is more predominant in the study area than other curve types. Parasections showed four (4) geoelectric layers, i.e., topsoil, upper saprolite, lower saprolite, and sap rock. A weathered layer is the principal aquifer unit identified in the area; it is appreciably thick, and the basement is fresh. The thickness of regolith ranges from 2 to 56 m, with an appreciable thickness that can sustain moderate groundwater yield in the southern region of Ikole. The layer above the regolith aquifer has an average thickness slightly below 20 m; therefore, areas without lateritic cover will be prone to pollution. The strength of the regolith aquifer was assessed by employing longitudinal conductance (LC) and Geoelectric Layer Susceptibility Index (GLSI) ratings. The inherent weakness of the LC rating (not accounting for the lateritic nature of soil) was complemented by the GLSI rating. The southern region of the study area where groundwater is feasible is evaluated to have moderate protective capacity. Therefore, sources of pollution, such as septic tanks and dump sites, should be located far away from the area.

Keywords: *Aquifer, geoelectric, longitudinal conductance, protective capacity, susceptibility.*

1. Introduction

Geophysical methods and techniques are relevant in groundwater studies, environmental impact assessment (EIA), and engineering site investigation (Ademilua *et al*., 2014). The survey by Olorunfemi and Fasuyi (1993) has shown that geophysical explorations could be successfully applied in developing groundwater feasibility plans at both small and large scales for assessing groundwater flow path. Humans' unavoidable need for water for daily activities has led hydro scientists both in the past and present to design and develop different geophysical methods and techniques used today to explore and exploit groundwater. Examples are gravity, seismic, magnetic, electrical, electromagnetic methods, and most recently, Surface Nuclear Magnetic Resonance (SNMR).

The significance of water to human life and survival on earth cannot be evaluated. Many countries, including Nigeria, suffer from inadequate quantity and quality of fresh surface water, and therefore, the resolve to explore and exploit the abundant groundwater reserves becomes eminent. As groundwater becomes necessary for living activities and human consumption, geophysical methods and techniques are important for exploration, exploitation, and development. Integrating surface and subsurface geophysical measurements can go a long way in helping delineate groundwater occurrence, dynamics, and associated geologic formation.

Numerous researchers, such as Ademilua *et al*., 2014 Akana *et al*., 2016 Alabi *et al*., 2016 and Farid *et al*., 2017, have carried out geophysical projects and research to delineate the properties of subsurface lithological units to examine their hydrogeological significance. Authors such as Srinivasan *et al*., 2013 Akintorinwa and Olowolafe 2013; Kamlesh and Shukla (2014) have specifically conducted studies on groundwater potential and vulnerability using geoelectrical methods. This has proven to be one of the most valuable tools in delineating groundwater (Ndatuwong & Yadav, 2015). Electrical resistivity has been classified as one of the most effective and efficient methods for assessing and exploiting groundwater (Hasan *et al.,* 2018). Agbasi and Edet (2016) have determined the aquifer geometry, depth to the water table, and groundwater quality by analysing the apparent resistivity measured from the electrical survey.

The availability of potable water is a serious problem that is faced not only by rural communities but also by developing regions of the world at large today. The influx of the university community to the study area and the nonfunctional rural water schemes have limited the available water resources. Therefore, there is a need to explore the groundwater potential of the regolith aquifer using geophysical methods, as well as the

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vulnerability of the aquifer since regolith aquifers are vulnerable to pollution. The most common rating for aquifer vulnerability in Southwestern, Nigeria basement complex is the Longitudinal Conductance rating, Adebo *et al.*, (2021); Ayuk, (2019); Eyankware *et al*., 2020; Nwosu and Chinaka (2021), but the existence of resistive lateritic layer (of high protective capacity) which distort the longitudinal conductance ratings (Oni *et al.*, 2017; Ayodele *et al.*, 2022) necessitates the integration of geoelectric layer susceptibility index (GLSI) to compensate for the inherent weakness of longitudinal conductance rating in aquifer vulnerability mapping. The specific objectives of this research are to identify geoelectric layers and their thickness for regolith aquifers across the study area and to assess the vulnerability of the aquifer using LC and GLSI ratings.

2. Location and Accessibility of The Area

The study area, Odo Oro, Ikole, is in southwestern Nigeria (Figure 1). It lies within latitudes 7^0 46′16′′N to $7^0$48′43′′N and longitudes 5^0 30′ 51′′E to 5^0 32′ 29′′E. It covers 321 km^2 and is approximately 555m above sea level. The area can be accessed through main roads, minor roads, and footpaths.

Relief, Climate and Drainage

The area is located in an undulating terrain within the tropical region of southwestern Nigeria, which has two seasons: wet season (March to October) and dry season(November to February). The average monthly temperature, humidity, and annual rainfall are 28^{0}C, 70%, and 1800mm, respectively, Rahaman (1988). The dendritic study area has a drainage pattern indicating a uniform response of underlying rocks to water absorption.

Geology of the Study Area

Many great scholars have worked on the geology of Nigeria, particularly on Nigeria's basement complex; among such works are the ones of Odeyemi (1977), Grant (1978), and Bayowa *et al*., 2016. Odeyemi (1977) remarked that southwestern Nigeria lies within the basement complex and classified the rock within the region as migmatite-gneiss of Precambrian origin. Grant (1978) opined that the occurrence of geological structures is of tectonic origin. The geological fissures herein deform the caprock and create discontinuities that promote g, groundwater accumulation and storage capacity. The prominent rock types in the study area are migmatite gneiss, granite, and charnokite.

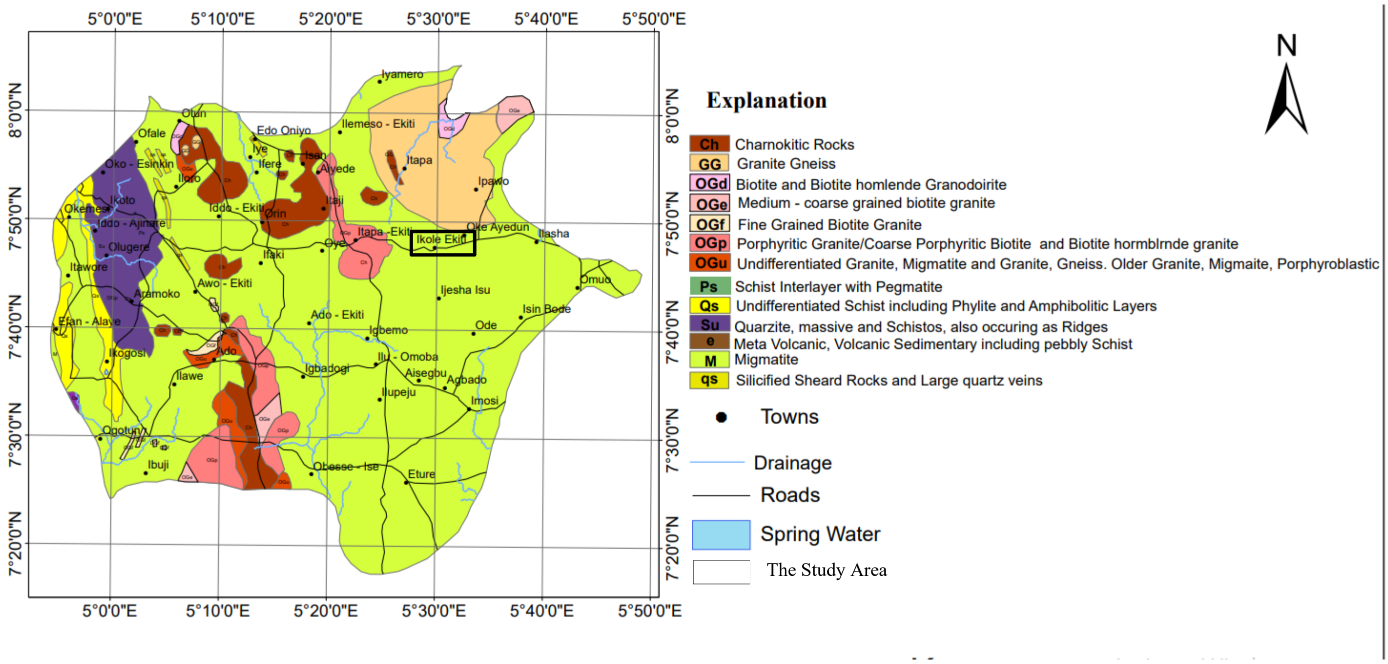

Figure 1. Geological Map of Ekiti highlighting major rock groups

3. Methodology

A Vertical Electrical Sounding (VES) technique using a Schlumberger array was adopted to investigate how resistivity varies with depth at each station point (Figure 2). The Schlumberger array was adopted for this survey because of its effectiveness in subsurface investigation and high penetration depth (Keller and Frishchncht (1996); Abudulawal *et al*., 2015; Anomohanran *et al*., 2017).

Twenty-seven (27) VES stations were equally spread across the area to map the geological sequence (Fig. 3). Half current electrode spacing (AB/2) was used and varied from 1m to 75 m. Vertical Electrical Sounding (VES) data were processed and interpreted quantitatively via partial curve matching techniques. Vander Velpen (2004) involves layer-by-layer fitting of field curves and theoretical curves starting from small electrode spacing. Geoelectric parameters obtained from the partial curve matching were employed as an initial model using WinResist version 1.0

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Malaysian Journal of Science 44(1): 42-54 (March 2025)

(Oladapo & Akintorinwa, 2007) for forward modelling. The geoelectric parameters obtained from the iteration were used to draw geoelectric parasections (Figure 3), charts, and maps. Longitudinal Conductance (LC) and Geoelectric Layers Susceptibility Index (GLSI) ratings were calculated to determine the vulnerability of the aquifer as shown in equations (1) and (2), respectively.

$$LC = \frac{h1}{\rho 1} + \frac{h2}{\rho 2} + \frac{h3}{\rho 3} + \cdots + \frac{hn}{\rho n} \ldots\ldots\ldots\ldots\ldots\ldots \quad (1),$$

Abiola et al., (2009)

Where h_i stands for the thickness of layers above the aquifer thickness and ρ_i is the resistivities of layers above the aquifer. LC of 0.7 and above indicates good to excellent protective capacity.

$$GLSI = (((\rho 1r + h1r)/2)) + ((\rho 2r + h2r)/2)) + \cdots + ((\frac{\rho nr + hnr}{2}))/2))/N))) \ldots\ldots \quad (2)$$

Ugwu *et al.*, 2016.

ρ_{1r} stands for resistivity index rating of layer 1,
h_{1r} stands for thickness index rating of layer 1,
ρ_{2r} stands for resistivity index rating of layer 2,
h_{2r} stands for thickness index rating of layer 2,
ρ_{nr} stands for the resistivity index rating of the nth layer
h_{nr} is the thickness index rating of the nth layer,
while N is the numeric value of geoelectric layers upon the aquifer. Index ratings are shown in Table 1 below.

Table 1. Geoelectric Susceptibility Index ratings (Oni *et al.*, 2017).

Lithology	Apparent Resistivity	Vulnerability Index
Laterite	>401	1
Lateritic Sand	151-400	2
Sand	101-150	4
Clayed Sand	51-100	3
Sandy Clay	20-50	2
Clay	< 20	1

Table 2. Geoelectric Susceptibility index of layer thickness (Oni *et al.*, 2017)

Thickness	Index Rating
>20	1
5 – 20	2
2 – 5	3
< 2	4

GSLI between 1.0 to 1.99 means low vulnerability; 2.0 to 2.99 indicates moderate vulnerability; 3.0 to 3.99 indicates high vulnerability, while 4.0 and above is extreme vulnerability Ugwu *et al.*, 2016.

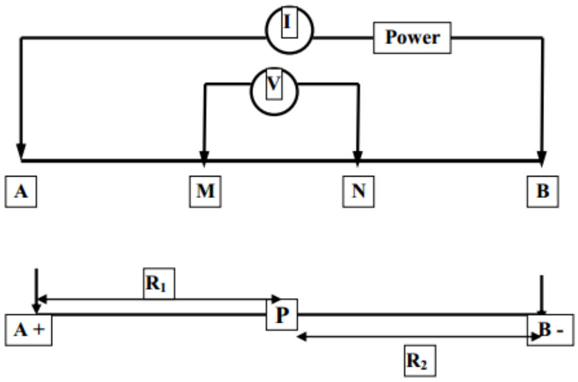

Figure 2. Vertical Electrical Sounding Diagram

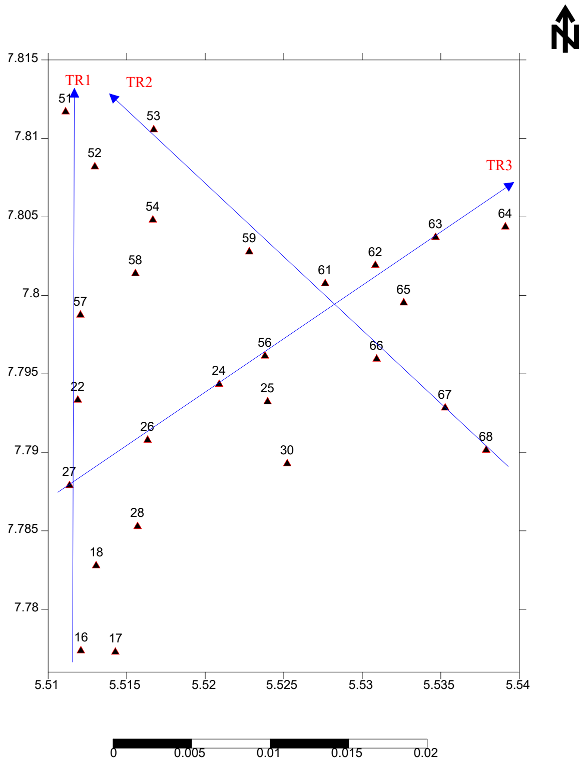

Figure 3. VES Points on the Study Area.

3. Discussion of Results

VES Curve Types

The twenty-seven (27) VES stations occupied generated resistivity sounding curves that varied from 3-layer (H and A) to 4-layers (KH, HA, and AA) as shown in Table 3, and the samples of the curve types are presented in Figures 4-8. Figure 9 shows the frequency of the occurrence of each curve type; the curves were characterised according to their signatures and mirrored the subsurface's layering. The predominant curve type is KH, as highlighted in Figure 6, which depicts a good aquifer protective capacity. KH curve type is one of the signatures of a confined weathered layer/fractured basement aquifer, Olorunfemi and Fasuyi (1993). HA and H curve types could also be suitable regolith aquifers depending on the thickness of each layer. Figure 9 shows the occurrence of each curve type across the study area, while Figure 10 shows how the curve types are distributed relative to the topography of the study area.

DOI:https//doi.org/10.22452/mjs.vol44no1.6
Malaysian Journal of Science 44(1): 42-54 (March 2025)

Table 3. Geoelectric Characteristics of VES stations

S/N	VES	Longitude	Latitude	Elevation	ρ1	ρ2	ρ3	ρ4	ρ5	h1	h2	h3	h4	Curve Type
1	15	5.509681	7.785528	578	33	199	54	180	-	0.5	4.1	9.8	-	KH
2	16	5.512083	7.777361	579	147	1079	77	936	-	0.7	2.1	15.2	-	KH
3	17	5.514278	7.777278	582	188	1005	335	1756	-	0.4	4.2	37	-	KH
4	18	5.513056	7.782778	585	146	91	218	2736	-	0.7	1.8	14.1	-	KH
5	22	5.511889	7.793333	560	53	45	147	1172	-	0.5	7.3	12.7	-	HA
6	24	5.520889	7.794333	579	190	355	450	6680	-	0.4	3	8.1	-	AA
7	25	5.523972	7.793222	583	107	499	165	546	-	0.7	1.2	8.2	-	KH
8	26	5.516333	7.790778	567	51	41	42	142	-	3.3	5.8	9.7	-	HA
9	27	5.511361	7.787889	575	101	228	31	115	801	1.2	0.4	7.5	5.8	KHA
10	28	5.515694	7.78578	588	169	288	557	-	-	0.9	1.3	-	-	A
11	30	5.525222	7.789278	590	1157	933	541	2902	-	2.7	7.2	45.3	-	QH
12	51	5.511111	7.811694	566	234	232	540	9414	-	1.5	3.2	27.2	-	HA
13	52	5.512974	7.808194	567	208	396	210	290	-	0.8	2.6	12.8	-	KH
14	53	5.516722	7.810556	557	209	765	51	6474	-	0.9	0.7	13	-	KH
15	54	5.516667	7.804806	572	208	114	1470	-	-	1	6.2	-	-	H
16	56	5.523806	7.796139	589	89	177	534	1228	-	1	6	1	-	AA
17	57	5.512056	7.798757	557	86	294	63	547	-	0.8	0.7	8.6	-	KH
18	58	5.515556	7.801389	575	221	2856	135	65	-	0.5	1.5	7.7	-	KQ
19	59	5.522806	7.802778	588	362	748	1383	2886	-	0.5	5	6.3	-	AA
20	61	5.527639	7.80075	586	55	294	86	241	-	0.6	3.3	22	-	KH
21	62	5.530833	7.801917	581	34	143	73	893	-	1	4.7	9.3	-	KH
22	63	5.534667	7.803694	591	218	415	153	2813	-	1.1	3.9	9.2	-	KH
23	64	5.539111	7.804361	591	61	210	311	904	-	0.9	0.3	8.5	-	AA
24	65	5.532639	7.799528	597	173	813	547	6125	-	0.4	2.9	12	-	KH
25	66	5.530917	7.795944	588	127	369	1441	-	-	0.9	6.9	-	-	A
26	67	5.535278	7.792833	586	304	984	377	4345	-	0.6	7	32	-	KH
27	68	5.537889	7.790139	575	312	283	4502	-	-	0.9	3.1	-	-	H

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Malaysian Journal of Science 44(1): 42-54 (March 2025)

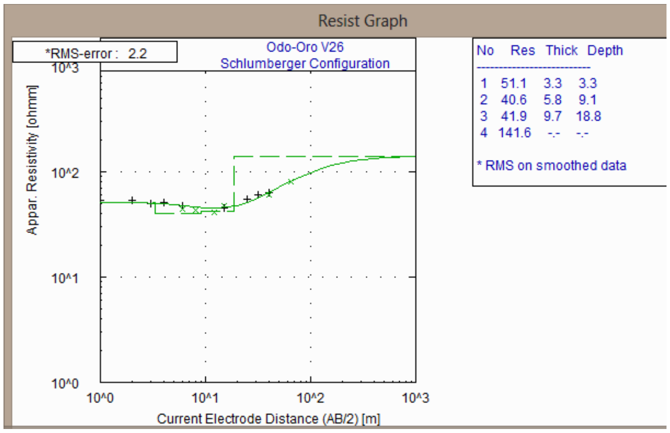

Figure 4. HA Curve type in the area

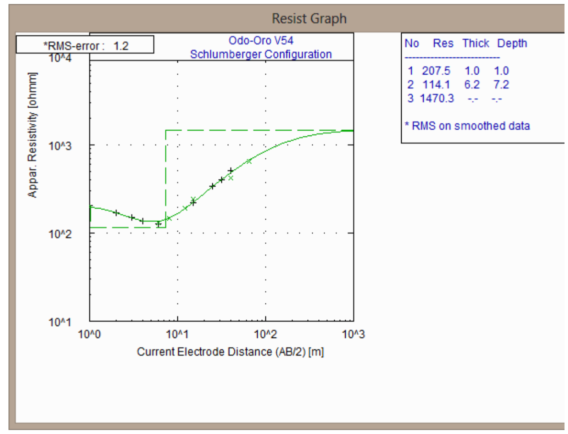

Figure 5. H Curve type in the Study Area

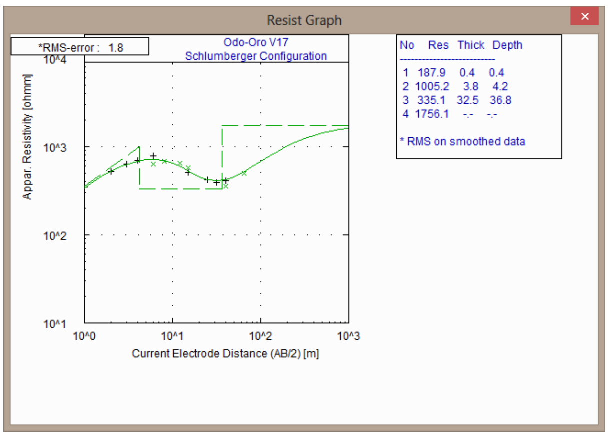

Figure 6. KH Curve type in the area

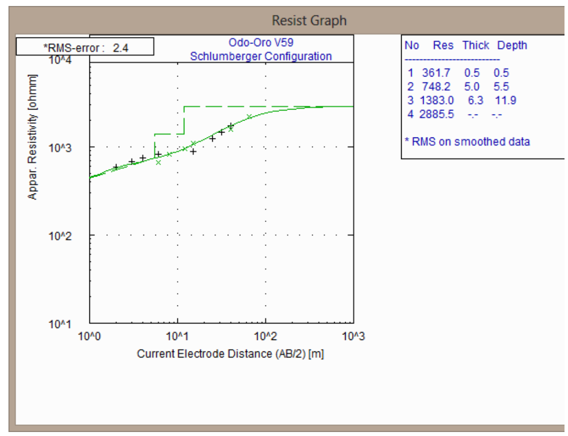

Figure 7. AA Curve type in the Study Area

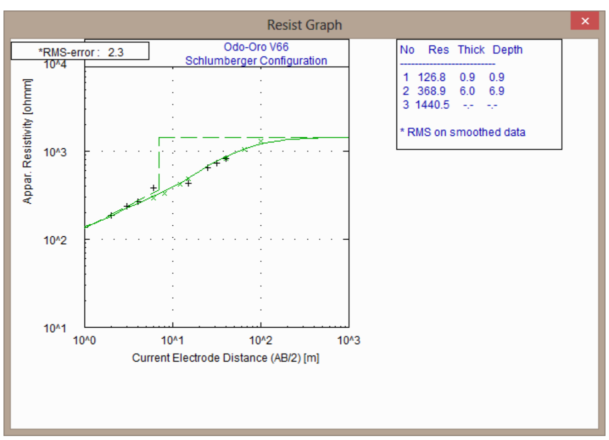

Figure 8. A Curve type in the area

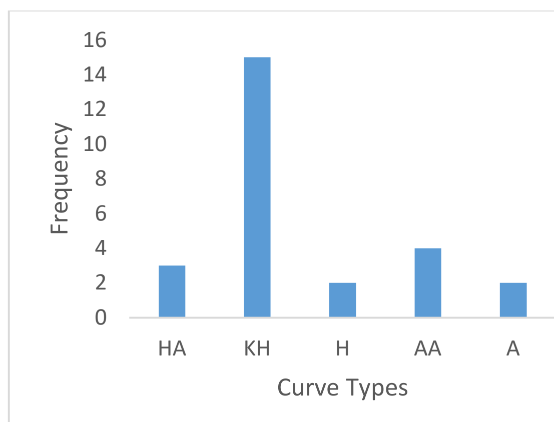

Figure 9. Occurrence of Curve Types in the Area

DOI:https//doi.org/10.22452/mjs.vol44no1.6
Malaysian Journal of Science 44(1): 42-54 (March 2025)

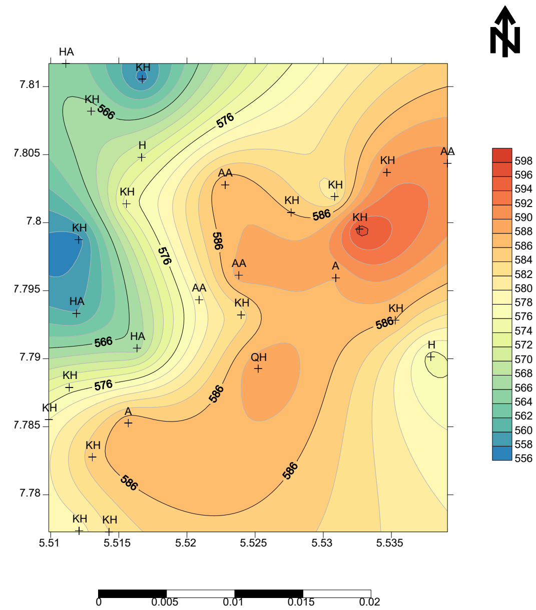

Figure 10. VES Curve (Ohms) Types and their elevation (meter) across the Study Area

Regolith Thickness Map

The regolith thickness, i.e., the depth to the rock head, is a significant factor controlling groundwater accumulation in any basement Complex region. The regolith thickness or overburden in the present study varies from 2 to 56 m across the area, as depicted in Figure 11, which, according to the claims of Oyedele and Olayinka (2012), Ademilua and Eluwole (2013) that the depth of overburden ranges from 1 m to 80 m in southwestern Nigeria. Ademilua and Eluwole (2013) suggested a depth of overburden of 25 m for good groundwater development around the region (of study). Therefore, the southern region of this investigation should be noted for groundwater development, as shown in Figure 11.

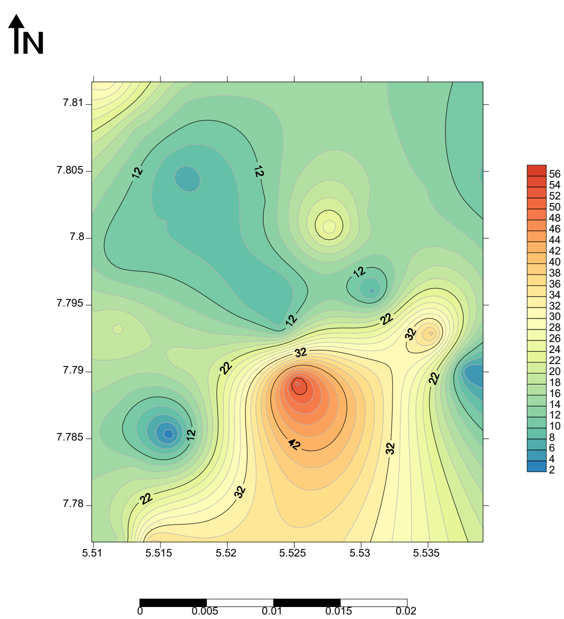

Figure 11. Regolith thickness across the Study Area (meters)

DOI:https//doi.org/10.22452/mjs.vol44no1.6
Malaysian Journal of Science 44(1): 42-54 (March 2025)

Geoelectric Sections

Three (3) geo-sections were established in the study area. Figures 12, 13, and 14 showed 2-D geoelectric sections along traverses 1, 2, and 3, respectively. TR1 relates VES 16, 27, 22, 57, and 51 (Fig. 11); TR2 relates VES 68, 67, 66, 61, 59, and 53 (Fig. 12); and TR3 relates VES 27, 26, 24, 56, 62 and 63(Fig. 14). The geo-sections showed four layers as topsoil, lateritic layer, weathered layer, and fresh basement. These sections depict thickness and respective resistivity values; the geoelectric sections were characterised as follows.

i. Topsoil - this has resistivity values ranging from 33 - 362 Ω-m. The topsoil has a thickness of 0.4 to 3.3 m.
ii. Upper Saprolite: The upper saprolite is lateritic in nature. Its resistivity value ranged from 199 - 984 Ω-m, having a thickness of 0.7 to 3.1m.
iii. Lower Saprolite: The lower saprolite is weathered and saturated. Its resistivity values vary from 42 - 138 Ω-m with a thickness ranging between 1.5m – 10.0 m.
iv. Saprock: This layer registered resistivity that varied from 142 to 9141 Ω-m.

Layers Thickness above the Aquifer

The thickness of the aquifer layers, among other factors, determines the rate at which the aquifer gets polluted by the surface contaminant. The higher the thickness, the higher the protective capacities, assuming all other conditions are constant. The southwestern region of the area under investigation has the highest thickness, as shown in Figure 15, which is also correlated by layers dominated by KH curves. The thickness of the above aquifer layer and the geological composition of these layers determine the ease with which the aquifer gets polluted. The southwestern region of the study area should be considered for groundwater potential development to avoid pollution.

Longitudinal Conductance (LC)

The longitudinal conductance of the layers above the aquifer was calculated to determine the protective capacity of the aquifers at each VES point. The protective ability of the area is generally poor according to the longitudinal conductance rating. A longitudinal conductance map was generated, as shown in Figure 16, to provide an overview of the aquifer's protective capacity in the entire investigation region. The southwestern part of the area has moderate aquifer protective capacity, which correlates with the area's highest depth of the aquifer layers. The aquifer protective capacity is characterised by the values of the longitudinal conductance unit of rocks' regolith (thickness). In the present study, the longitudinal unit of conductance obtained ranged between 0.02 to 0.44 mhos resulting in the classification of this region as having low to moderate protective capacity as shown in Figure 16 while the region having longitudinal unit of conductance ranged between 0.1 – 0.19 is classified as area of weak protective capacity Rahaman (1988); Odeyemi(1977) and Grant (1978) while 0.7 - 4.9 is classified as good protective capacity, although not obtained in this present study.

Geoelectric Layers Susceptibility Index (GLSI)

In order to examine the inherent weakness in the longitudinal conductance rating of the aquifer protective capacity, GLSI was used as it considers the existence of a lateritic layer in the Nigeria Basement Complex. A GLSI map was generated to give an overall view of the aquifer protection ability in the entire area, as shown in Figure 17. Figure 17 shows that unlike in the southern part, highly vulnerable aquifers in the northern and western areas could be protected by appreciable thickness of lateritic layer (LC does not account for that).

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Malaysian Journal of Science 44(1): 42-54 (March 2025)

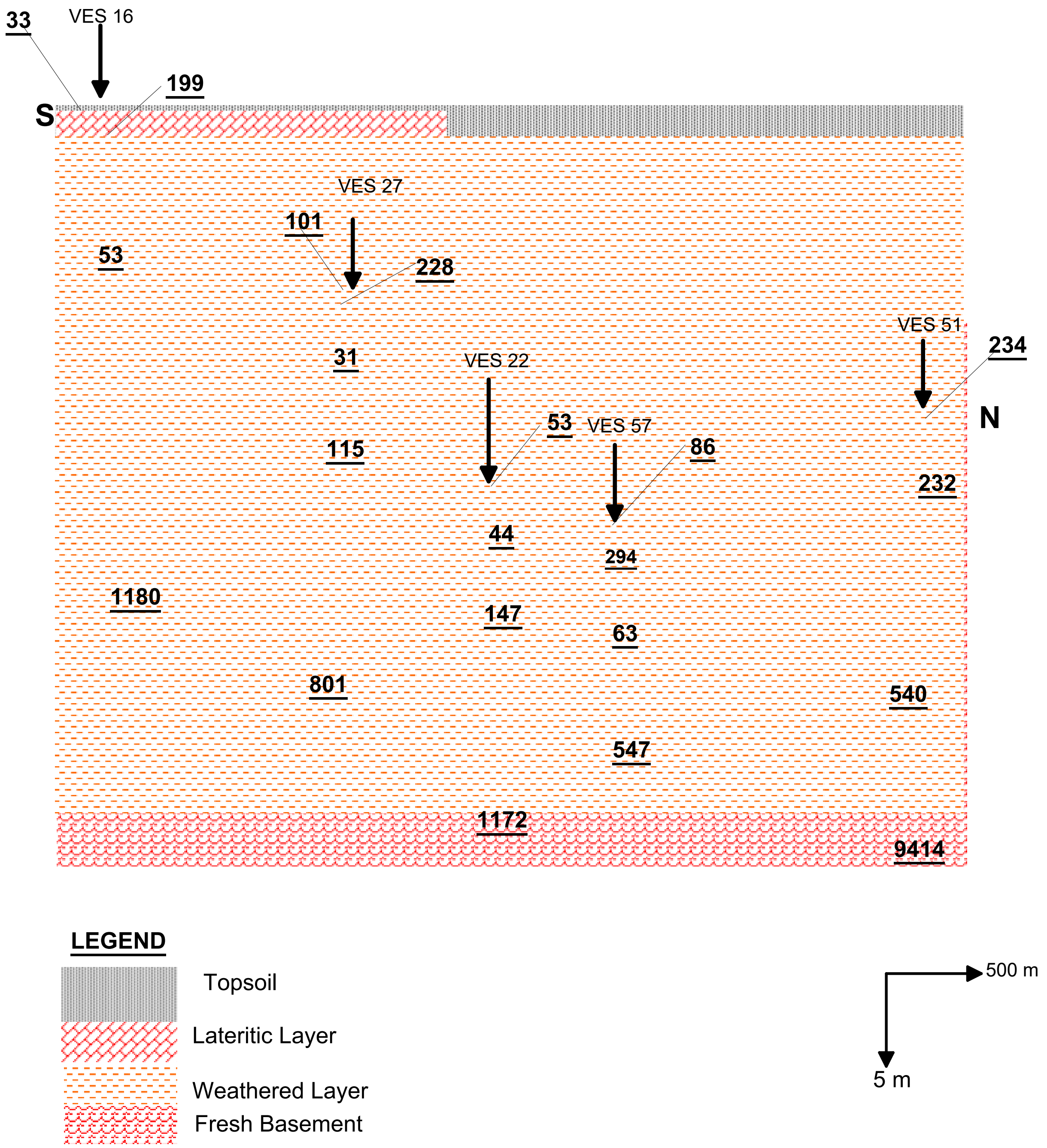

Figure 12. Geo-section of Traverse One (1)

DOI:https//doi.org/10.22452/mjs.vol44no1.6
Malaysian Journal of Science 44(1): 42-54 (March 2025)

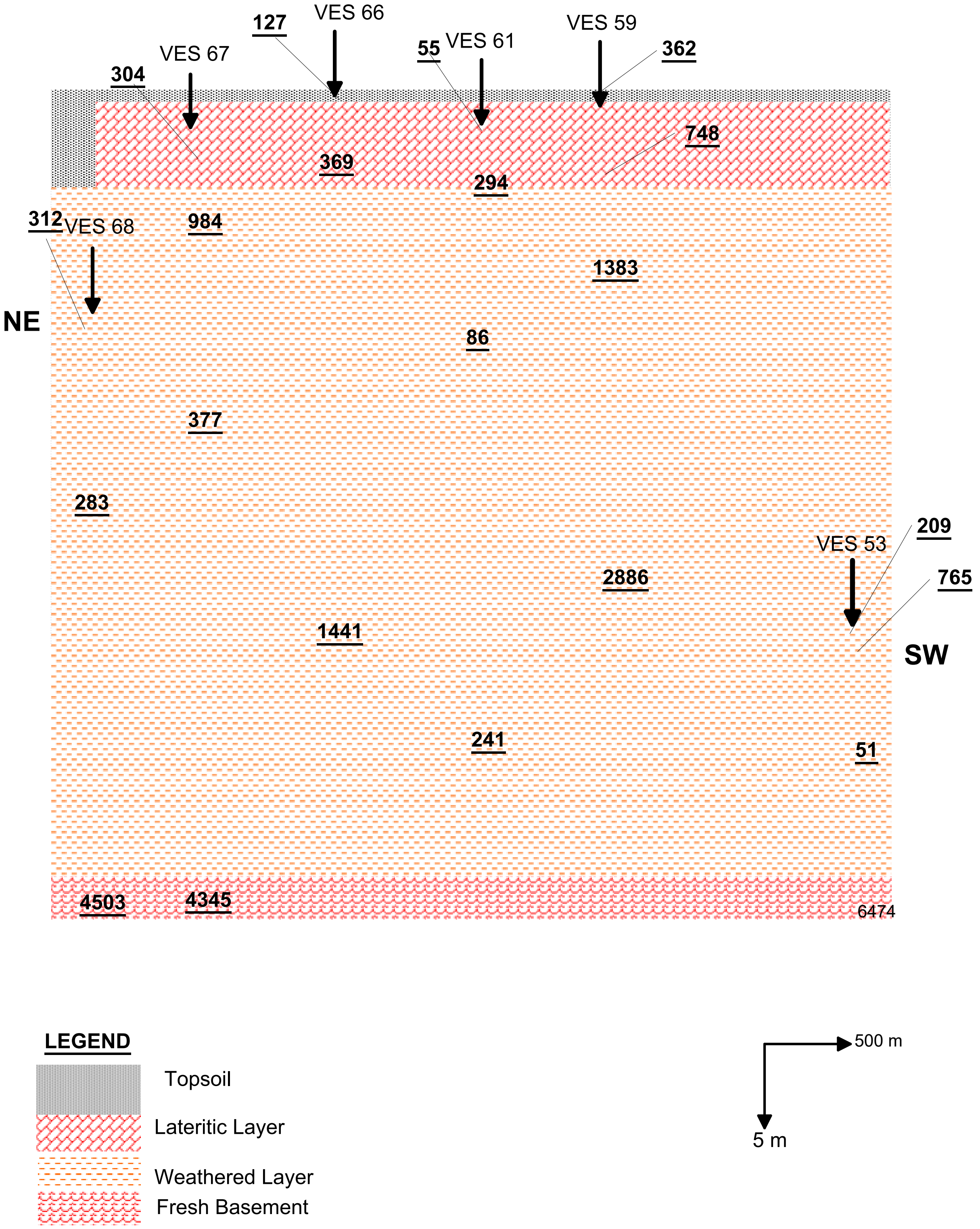

Figure 13. Geo-section of Traverse Two (2)

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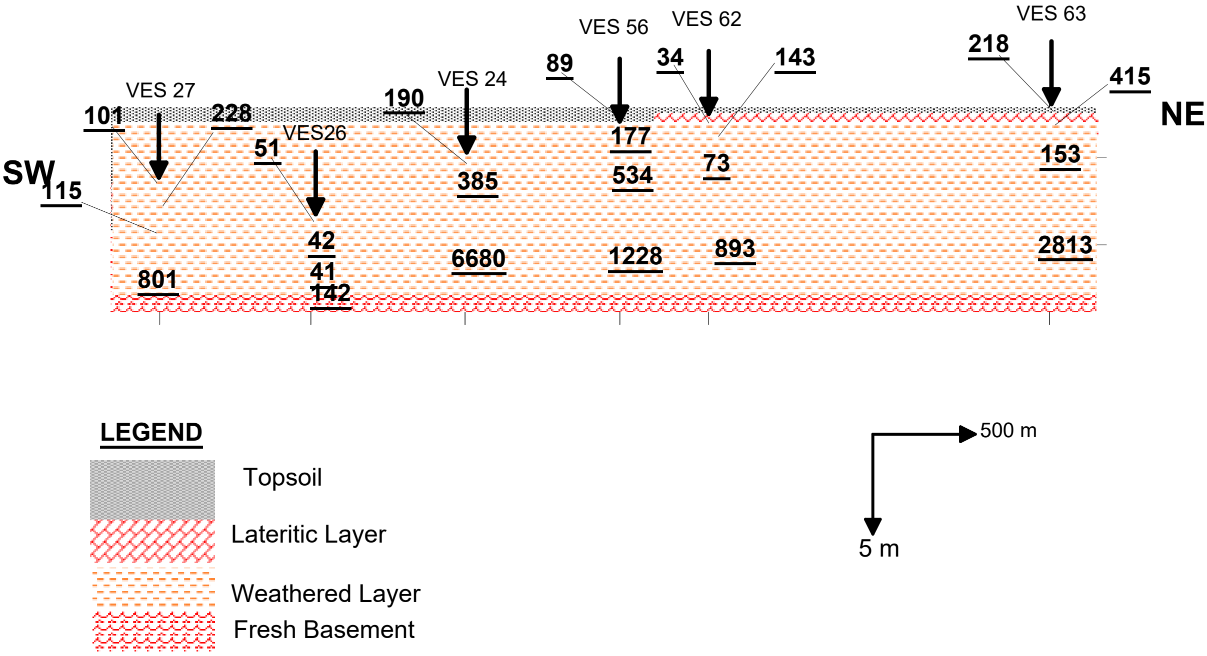

Figure 14. Geo-section along Traverse Three (3)

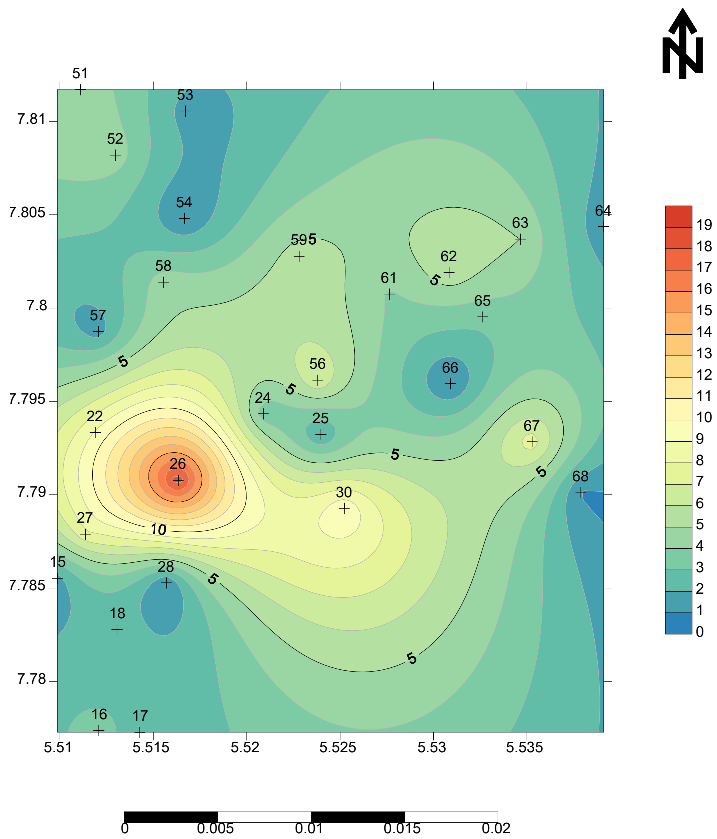

Figure 15. Layer thickness above the aquifer (meters).

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Malaysian Journal of Science 44(1): 42-54 (March 2025)

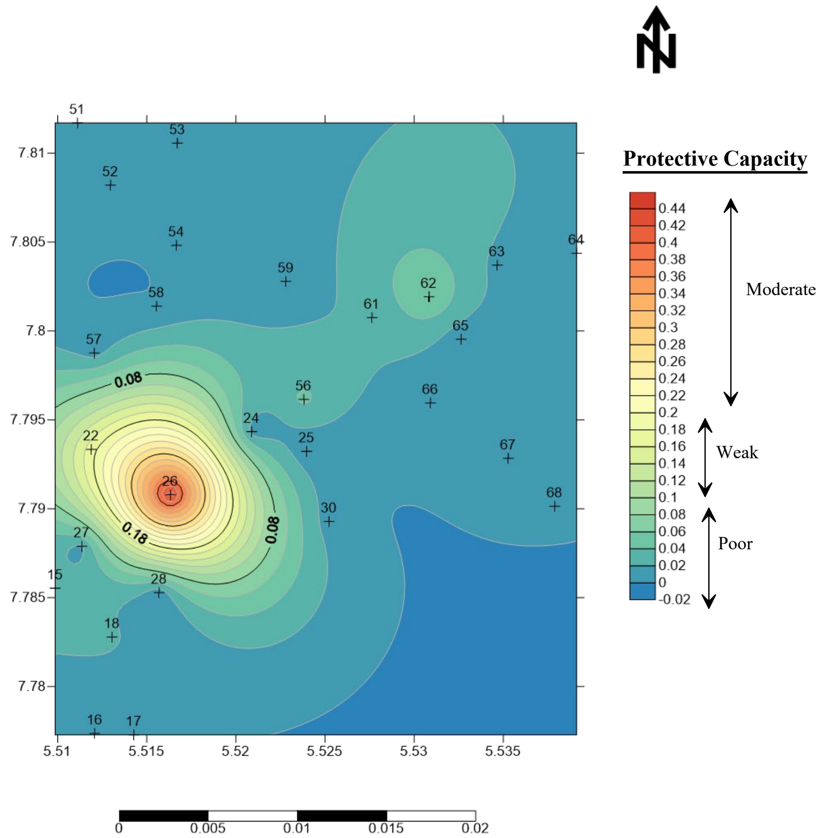

Figure 16. Longitudinal Conductance (Ohms^{-1}), Map of the Study Area.

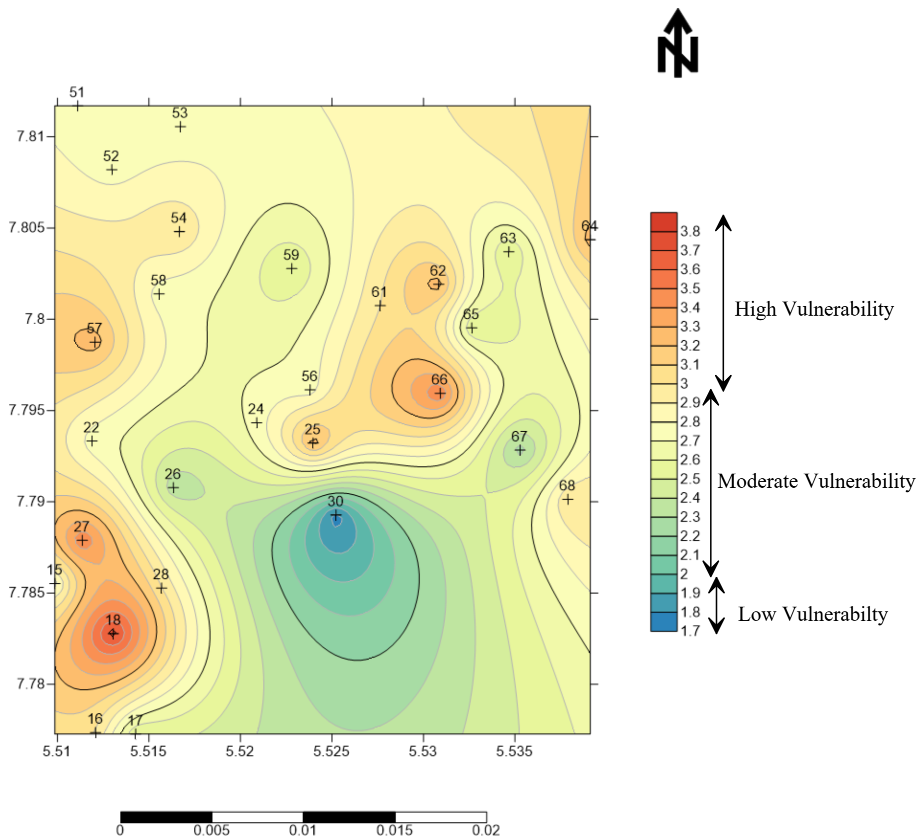

Figure 17. Geoelectric Layers Susceptibility Index (GLSI) Map

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Malaysian Journal of Science 44(1): 42-54 (March 2025)

4. Conclusion

Groundwater aquifer potential and protective capacity evaluation at Ikole Ekiti, Southwestern Nigeria, used an electrical resistivity method to determine its viability and susceptibility. The Vertical Electrical Sounding (VES) technique was employed, and the Schlumberger configuration was adopted. The data obtained was partially curve-matched and iterated using WinResist software. The processed results were employed, and charts, geoelectric sections, tables, and maps were generated to aid in interpreting the results.

The thickness of the regolith was appreciable and ranged from 2 to 56 m, which can sustain moderate groundwater yield in the southern region of the area. The weathered layer is the principal aquifer unit in the area, as it is appreciably thick and has a fresh basement. Since the layer thickness above the aquifer is less than 20 m, areas without lateritic cover will be prone to pollution.

The study area's KH curve types are predominant, indicating good protective capacity. The geoelectric sections showed four (4) layers, i.e., topsoil, lateritic, weathered, and fresh basement rock. The lateritic layer has high porosity but very low permeability, making it a good layer to protect the aquifer from surface pollutants. The longitudinal conductance rating and Geoelectric Layer Susceptibility Index (GLSI) rating were employed to assess the aquifer's protective ability. The longitudinal conductance map showed a southwestern area with moderate protective capacity, whereas the GLSI map showed the southern part as a region with moderate to low vulnerability. The inherent weakness of the longitudinal conductance map was complemented by the Geoelectric Layer Susceptibility Index (GLSI) map. Considering the resistivity results alongside the maps obtained using the two models employed, the southern region of the study area is most viable for groundwater exploitation with moderate to low vulnerability. In contrast, groundwater projects in the northern region can only occur after due consideration for contamination mitigations.

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