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Application of Electrical Resistivity Sounding in delineation of the Aquifer Transmissivity and Basement Structure at Igarra, Southwestern Nigeria

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Abstract

Information on the aquifer transmissivity and basement structure of Igarra, southwestern Nigeria, is scarce. Thus, this study aimed to apply electrical resistivity sounding and drilled borehole information to determine the underlying bedrock structure (basement structure) and the aquifer transmissivity of Igarra. Twenty vertical electrical soundings (VES) were carried out along 4 established E-W traverses intending to intercept the fracture systems. The resistivity data acquired were curved matched, and iterated using Schlumberger O' Neil software to obtain layer parameters. The layer parameters were evaluated to obtain the Dar-`Zarrouk parameters, which were used to determine the aquifer transmissivity. The resistivity-sounding result revealed four to six geoelectric layers that comprised topsoil, lateritic soil, weathered basement, fractured basement, partially fractured basement and fresh basement. The VES result revealed an undulating basement, with depths varying from 20.1 m to 53.8 m, suggesting evidence of fracturing and faulting within the basement. Correlation of the VES data and borehole log revealed that the weathered and the fractured basement constitute the aquifers, found between 2.4 – 53.8 m depths, and aquifer thickness ranged from 0.7 – 44.3 m. Analysis of the VES result showed an average computed transmissivity value of 18.48 m^2/day. These values indicate that the basement is undulating with adequate groundwater-yielding materials (aquifer), capable of promoting adequate recharge potentials from precipitation.

Keywords: Aquifer transmissivity, basement structure, vertical electrical sounding, delineation, groundwater.

Introduction

Igarra has witnessed rapid industrialization recently, resulting in population increase and urbanization. Apart from being the headquarters of Akoko Edo Local Government Area, it is one of the Schist belts (Precambrian Basement Complex) of Southwestern (SW) Nigeria, and its choice as a field laboratory has been fully tested and justified [1]. Its proximity to most universities in SW and southsouthern (SS) Nigeria makes it suitable for training field geologists and environmental scientists. This has attracted a lot of tourists, researchers and students to the area. The inhabitants mainly rely on surface and groundwater from streams, dam, hand dug well and few shallow boreholes (susceptible to contamination) for their water supply needs. The Moribund Ojirami dam, established by the Federal Government of Nigeria, which used to be the major source of water supply to the people, has failed to supply water for over two decades. Hence, the rapid population growth caused by the influx of people to Igarra has made the water supply grossly inadequate for the populace and establishments that depend on these water sources for their domestic, industrial and agricultural uses. Moreover, some boreholes drilled

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in the area by successive governments and agencies have failed due to a poor understanding of the aquifer characteristics and geometry. Therefore, knowledge of aquifer characteristics and geometry becomes crucial for proper groundwater resource management.

Groundwater availability in Precambrian Basement Complex (PBC) is usually caused by the development of secondary porosity and permeability resulting from both fracturing and weathering [2, 3, 4, 5]. [4] asserted that "for a perennial and maximum borehole yield, a potential borehole should be sited in an area with maximum possible regolith thickness". In most of the crystalline basement areas (as is the case of Igarra), groundwater accumulation areas and drainage distribution are crucial for aquifer research. Nevertheless, due to the significant spatial variations in the aquifer's characteristics, the aquifers are considered discontinuous and seem complex [5]. Hence, the characterization of the major factors that influence borehole productivity as well as the techniques for selecting suitable areas for drilling successful boreholes, becomes an issue of significant interest.

The survey area is the Igarra Precambrian Basement Complex (IPBC). Presently, in IPBC, access to potable water remains challenging due to increasing pressure on the groundwater resources occasioned by the growing demographics. The application of geophysical investigations to increase the knowledge of groundwater availability in crystalline basement terrains is now known [6, 7, 8, 5]. Several works by [9, 10, 11, 12] have been carried out in IPBC, but none of these studies focused on the aquifer transmissivity and the basement structure of the fissured layer. Hence, this study aims to determine the depth of the water table (aquifer), aquifer thickness, subsurface lithology, and the aquifer characteristics, such as transmissivity and protective capacity of the fissured layer of the IPBC, to assist Igarra people source for potable water that will meet the needs of the population. Inhabitants of IPBC mainly depend on hydrogeologic characteristics or information of the weathered or fractured basement for groundwater exploration, as most aquifers are located dominantly in the weathered or fractured basement. This study will provide information on groundwater distribution and the possible water borehole sites for a sustainable water supply that will complement the supply from surface water resources in Igarra.

Location and geology of the study area

The survey was conducted within Igarra, Akoko Edo Local Government Area, Edo State, Nigeria. It lies within longitude $6^0\ 04^{'}00^{''}$ and $6^0\ 07^{'}48^{''}$ E and latitude $7^0\ 15^{'}$ and$7^0\ 18^{'}$N (Figure 1). The total survey area covers an estimated area of 70 km^2, with an average elevation of 257 m above sea level. The Precambrian basement rocks underlie the area. The IPBC features a complex geological framework of different structures and rocks [13]. The major rock types are schists, metaconglomerate, quartzite and calc-silicate gneiss. The Pan African orogeny (750 – 450 Ma) affected the area, during which calc-silicate gneiss was folded and later metamorphosed at low-to-medium grade [14]. The older granites which constitute about half of the basement rocks are the last rock types in the basement sequence, associated with the Pan African thermotectonic activities [15].

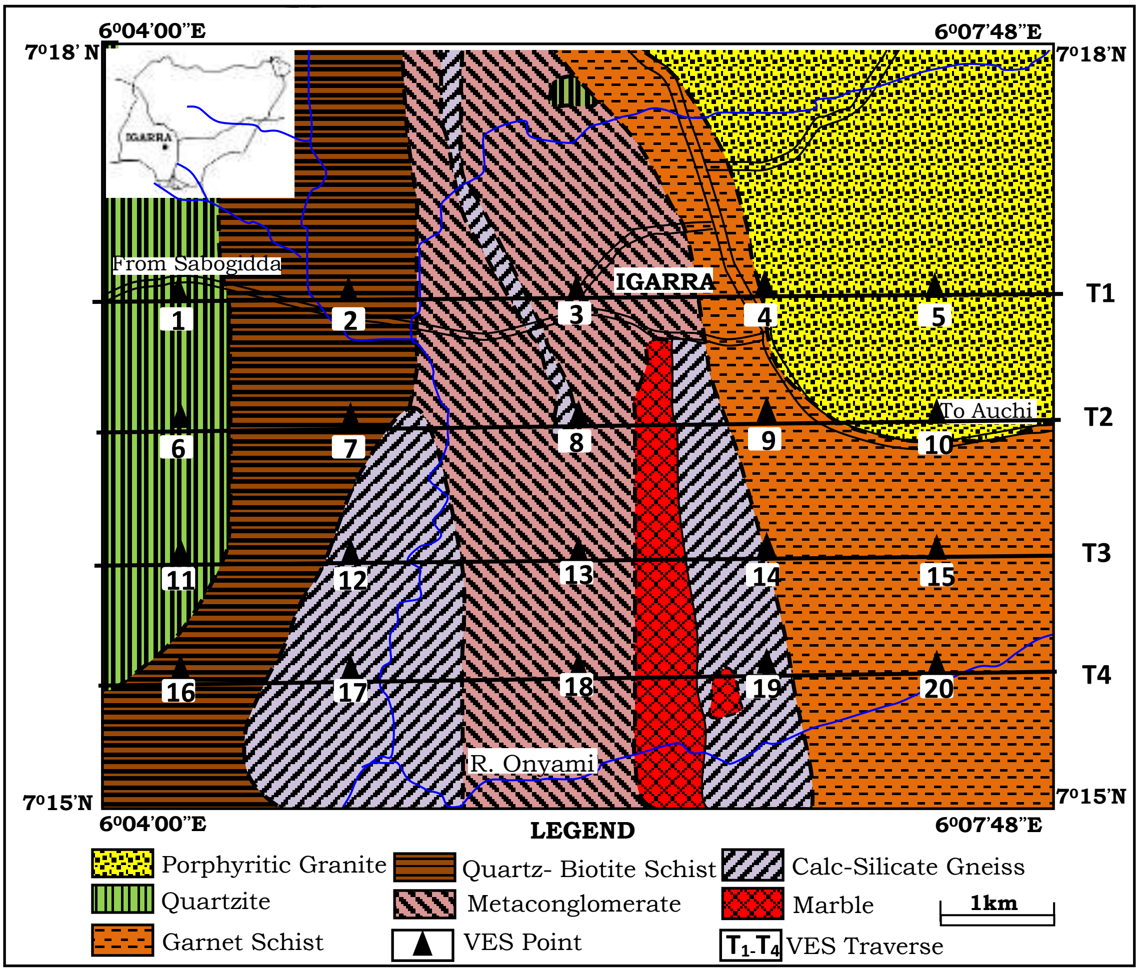


Figure 1. Geologic map of Igarra showing data acquisition points, modified after [14]; insert map of Nigeria, to the northwest.

Materials and Methods

Vertical electrical sounding

Twenty vertical electrical soundings (VES) stations were conducted in the area, employing the Schlumberger configuration. The ABEM SAS 1000 Terrameter was used for the VES data acquisition, with current electrode spacing (AB/2) ranging from 100 to 150 m. The acquired data were plotted on a log graph paper with the apparent resistivity on the ordinate and the electrode separation (AB/2) on the abscissa. The data were subjected to a curve-matching technique using the master curves with the corresponding auxiliary curves to obtain the actual resistivity and their respective thicknesses. The results obtained were then used for computer iteration using the Schlumberger O' Neil package, to plot the sounding curves (Figure 2). The obtained parameters (resistivity and thickness of the subsurface) were used to generate the geoelectric sections (Figure 3a-3d). The geoelectric sections were constructed from the information obtained from the sounding curves, while the aquifer thickness was determined from the geoelectric section.

In this work, VES data was used to determine the aquifer transmissivity at various sounding locations as well as map the basement topography. Aquifer transmissivity is the ability of the aquifer to transmit water. Hence, knowledge of aquifer transmissivity is crucial for sustainable groundwater (aquifer) development. It is an important tool for sustainable groundwater exploration in Igarra. Therefore, using a representative average hydraulic conductivity of 1.05m/day, courtesy of [16] for two separate boreholes (drilled water wells) in the area, the aquifer transmissivity was computed from the relationship already established by several authors like [17, 18, 19] as follows:

$$T = k\sigma R \quad (1)$$

$$T = \frac{k}{\sigma} * S \quad (2)$$

Where T is the transmissivity (m^2/day), K is the hydraulic conductivity (m/day), S is the longitudinal conductance (Ω^{-1}) and R is the transverse resistance (Ωm^2) of the aquifer.
Some parameters crucial for understanding the geologic model were also evaluated. These parameters, "commonly called Dar Zarrouk parameters," include longitudinal conductance (S) and transverse resistance (R) and are related to the combinations of geoelectric layers resistivity and thickness [20, 21]. According to [20], "the parameters S and R respectively can be given as:

$$S = \frac{h}{\rho} \quad (3)$$

$$T = h\rho \quad (4)$$

Where h is the layer thickness (meters), while ρ is the layer resistivity (Ohms-meter).

Pumping test analysis

Conventionally, pumping test analysis was conducted at two separate drilled boreholes in the area and analysis was done using Cooper and Jacob's analytical method, as expressed in [22,23]. Subsequently, the aquifer transmissivity T was determined and compared with the surface geoelectric data using a representative average hydraulic conductivity K of 1.05m/day [16] for two separate boreholes.

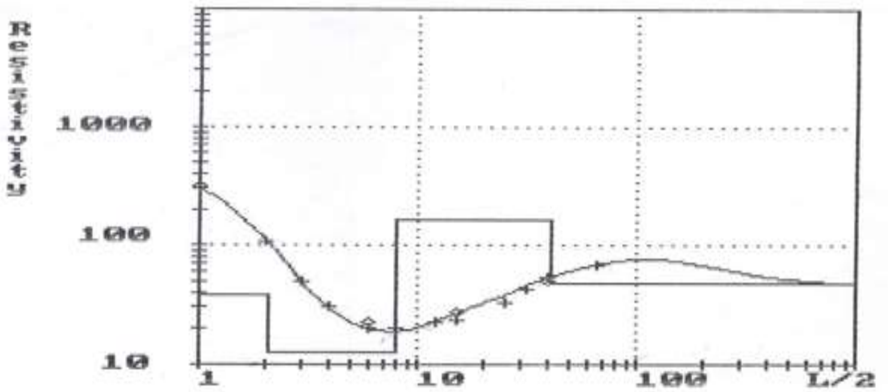
Results and Discussion

Vertical electrical sounding

The VES data obtained from the Igarra area were interpreted and presented in Table 1 and as sounding curves (Figure 2). Ten VES curve types were delineated in the area, identifying four to six geoelectric layers that comprised topsoil, lateritic soil layer, weathered layer, fractured basement, partially fractured basement and fresh basement, respectively. Geoelectric sections, presented as Figures 3a-3b, were constructed and guided by the VES result and borehole lithologic log (Figure 4) obtained from [16]. In locations delineated with four geoelectric layers, the inferred lithology corresponds to topsoil, weathered basement, fractured basement and fresh basement, respectively. Locations delineated as five geoelectric layers correspond to topsoil, lateritic soil layer, weathered basement, fractured basement and fresh basement. In comparison, locations delineated as six geoelectric layers correspond to topsoil, lateritic soil layer, weathered layer, fractured basement, partially fractured basement and fresh basement, respectively.

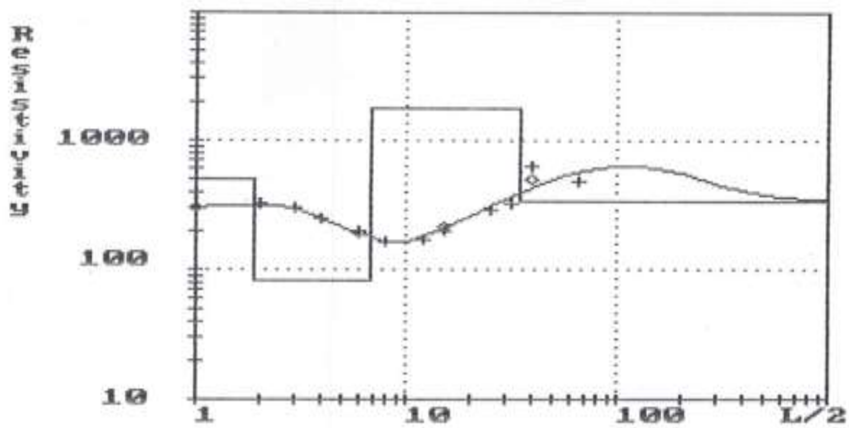
The summarized VES results are presented in Table 2. Table 2 reveals the minimum and maximum values of layer resistivity, depth, and thickness, respectively in addition to their inferred lithology. The model curve types are HAK, QQHA, HAA, QHA, HKH, QHK, HK, HKHA, KHAA and KHA, respectively. The most predominant curve type is the QHA consisting of 30%, while HAA type constitutes 20% of the curve. The QHK and KHAA types make up 10%, while the remaining curve types include 5% each. According to [24, 25, 7], "quantitative hydrogeologic deductions are often possible from curve types". The identified HK, HKH, QHK, QHA and HKHA curves have great hydrogeologic implications as they apparently suggest areas favourable for groundwater exploration.

In the area, two aquifer systems were delineated by the VES results. They are the weathered basement and the fractured basement aquifers, respectively. These aquifer systems are connected, exist together and are not isolated, as the fractured zone underlies the weathered zone. The resistivity of the weathered layer ranges between 28 - 273 Ωm in some locations, while it is 33 - 2810 Ωm in some points. The fractured zone resistivity varies between 33 - 2810 Ωm and 40 - 3340 Ωm, respectively. The two aquifers delineated have a thickness range from 0.7 – 44.3 m, and aquifer depths (depth to the watertable) range from 2.4 – 53.8 m (Table 2). Moreover, in a basement setting, basement topography or structure is significant in hydrogeologic assessment. Groundwater potential zones identified are areas having thick overburden. Depressions (troughs) with thick overburden (Figure 3a – 3d) are identified as significant features for assessing groundwater potentials. The VES results revealed that the depth to the basement is deep in VES locations 1, 5, 11, 19 and 20 while it is shallow in VES locations 16, 17 and 18, respectively. This implies that locations with deeper basement depths have thicker weathered and fractured layer and vice versa. These areas will provide suitable groundwater materials (aquifers) that can be explored. Thus, locations having aquifer thickness greater or equal to 15m, in the basement terrain (Igarra) are associated with groundwater development. Table 2 shows the identified geoelectric formation, and this correlates with the drilled borehole (BH) in Figure 4, close to VES 19 and VES 20. Analysis of the VES revealed that layers 3 and 4 (Table 2) are associated with weathered/fractured zone and show moderate to high groundwater potential zones.



Current Electrode distance (AB/2) (m)

VES 1



Current Electrode distance (AB/2) (m)

VES 2

Figure 2: Typical VES curves of Igarra

Table 1: Results of VES interpretation

VES station	Layer number	Resistivity (Ωm)	Depth (m)	Thickness (m)	Curve type	Inferred lithology
1	1	356	0.7	0.7	HAK	Top soil
	2	46	4.9	4.2		Lateritic soil
	3	930	19.1	14.2		Weathered basement
	4	1240	53.8	34.7		Fractured basement
	5	1140	∞	∞		Fresh basement
2	1	635	0.8	0.8	QQHA	Top soil
	2	521	1.7	0.9		Lateritic soil
	3	126	2.4	0.7		Weathered basement
	4	40	4.6	2.2		Fractured basement
	5	147	29.9	25.3		Partly fractured basement
	6	8900	∞	∞		Fresh basement
3	1	860	0.7	0.7	HAA	Top soil
	2	194	3.8	3.1		Lateritic soil
	3	255	14.4	10.1		Weathered basement
	4	302	36.0	21.6		Fractured basement
	5	5390	∞	∞		Fresh basement
4	1	2230	0.4	0.4	QHA	Top soil
	2	723	2.3	1.9		Lateritic soil
	3	75	5.4	3.1		Weathered basement
	4	299	34.9	29.5		Fractured basement
	5	8000	∞	∞		Fresh basement
5	1	2040	0.3	0.3	QHA	Top soil
	2	359	2.2	1.9		Lateritic soil
	3	57	5.9	3.7		Weathered basement
	4	389	50.2	44.3		Fractured basement
	5	8000	∞	∞		Fresh basement

Table 1: Results of VES interpretation (continued)

VES station	Layer number	Resistivity (Ωm)	Depth (m)	Thickness (m)	Curve type	Inferred lithology
6	1	505	1.8	1.8	HKH	Top soil
	2	110	6.2	4.4		Lateritic soil
	3	238	13.4	7.2		Weathered basement
	4	142	28.4	15.0		Fractured basement
	5	9400	∞	∞		Fresh basement
7	1	585	0.3	0.3	QHK	Top soil
	2	250	3.3	3.0		Lateritic soil
	3	88	8.1	4.8		Weathered basement
	4	2590	29.5	21.4		Fractured basement
	5	1130	∞	∞		Fresh basement
8	1	677	0.7	0.7	HAA	Top soil
	2	193	1.7	1.0		Lateritic soil
	3	288	12.1	10.4		Weathered basement
	4	681	14.7	2.6		Fractured basement
	5	729	∞	∞		Fresh basement
9	1	157	0.4	0.4	KHA	Top soil
	2	372	0.9	0.5		Lateritic soil
	3	96	7.1	6.2		Weathered basement
	4	126	32.1	25.0		Fractured basement
	5	3760	∞	∞		Fresh basement
10	1	3530	0.3	0.3	QHK	Top soil
	2	156	0.4	0.1		Lateritic soil
	3	33	4.6	4.2		Weathered basement
	4	2200	38	33.4		Fractured basement
	5	5090	∞	∞		Fresh basement
11	1	559	1.5	1.5	HK	Lateritic top soil
	2	77	12.6	11.1		Weathered basement
	3	2810	49.2	36.6		Fractured/fresh basement
	4	2040	∞	∞		Fresh basement
12	1	188	1.5	1.5	HKHA	Top soil
	2	53	3.3	1.8		Lateritic soil
	3	860	8.1	4.8		Weathered basement
	4	82	19.1	11.5		Fractured basement
	5	576	30.4	10.8		Partly fractured basement
	6	8200	∞	∞		Fresh basement
13	1	237	0.7	0.7	KHAA	Top soil
	2	604	1.7	1.0		Lateritic soil
	3	40	5.3	3.6		Weathered basement
	4	166	20.4	15.1		Fractured basement
	5	295	38.4	18.0		Partly fractured basement
	6	3740	∞	∞		Fresh basement

Table 1: Results of VES interpretation (continued)

VES station	Layer number	Resistivity (Ωm)	Depth (m)	Thickness (m)	Curve type	Inferred lithology
14	1	382	1.1	1.1	KHAA	Top soil
	2	511	2.9	1.8		Lateritic soil
	3	41	7.8	4.9		Weathered basement
	4	159	25.9	18.1		Fractured basement
	5	233	41.0	15.1		Partly fractured basement
	6	2370	∞	∞		Fresh basement
15	1	549	0.9	0.9	QHA	Top soil
	2	151	4.7	3.8		Lateritic soil
	3	60	22.5	17.8		Weathered basement
	4	3340	40.3	17.8		Fractured basement
	5	6460	∞	∞		Fresh basement
16	1	549	0.9	0.9	QHA	Top soil
	2	151	5.4	4.5		Lateritic soil
	3	60	12.9	7.5		Weathered basement
	4	3340	20.1	7.2		Fractured basement
	5	6460	∞	∞		Fresh basement
17	1	634	0.9	0.9	QHA	Top soil
	2	160	5.7	4.8		Lateritic soil
	3	34	12.9	17.2		Weathered basement
	4	140	19.8	6.9		Fractured basement
	5	7200	∞	∞		Fresh basement
18	1	433	1.0	1.0	QHA	Top soil
	2	74	4.0	3.0		Lateritic soil
	3	38	7.0	3.0		Weathered basement
	4	345	11.7	4.7		Fractured basement
	5	679	∞	∞		Fresh basement
19	1	311	2.5	2.5	HAA	Top soil
	2	28	6.2	3.7		Lateritic soil
	3	460	26.1	19.9		Weathered basement
	4	565	47.8	21.7		Fractured basement
	5	1200	∞	∞		Fresh basement
20	1	361	1.3	1.3	HAA	Top soil
	2	38	5.8	4.5		Lateritic soil
	3	238	22.6	16.8		Weathered basement
	4	625	38.0	15.4		Fractured basement
	5	3220	∞	∞		Fresh basement

Table 2*:* Summarized VES Interpretation result

Layer number	Resistivity (Ωm) min max	Depth (m) min max	Thickness(m) min max	lithological description
1	157 - 3530	0.3 - 2.5	0.3 - 2.5	Top soil (lateritic/sandy clay)
2	28 - 273	0.4 - 12.6	0.1 - 10.1	Weathered layer (clay /sandy clay)
3	33 - 2810	2.4 - 49.2	0.7 - 36.6	Weathered bedrock (clay /sandy clay/clayey sand/sand)
4	40 - 3340	4.6 - 53.8	2.2 - 44.3	Fractured bedrock (clay/clayey sand/sand)
5	223 - 9400	29.9 - 41.0	10.8 - 25.3	Partially fractured bedrock (clayey sand/ sand)
6	2370 - 8200	∞	∞	Fresh bedrock

Aquifer hydraulic characteristics

The summary of aquifer parameters computed from the resistivity sounding data is presented in Table 3. An average transmissivity value of 18.48 m^2/day was obtained in the area. This value is believed to be adequate and good for the inhabitants of IPBC. This value is in the same range with the work of [19] where he carried out a similar work in the basement complex of Jos Plateau and obtained an average transmissivity value of 26 m^2/day. Table 3 indicates that high transverse resistance, R is associated with intermediate to high transmissivity zones. Hence, VES 2, 3, 4, 5, 6, 9, 10, 13, 14, 15, 19 and 20 locations are associated with intermediate to high transmissivity and the aquifer is unconfined. Figure 5 shows the aquifer transverse resistance map, while Figure 6 shows the aquifer transmissivity map. Figure 5 indicates that the southeastern area of study has high R, which implies high transmissivity, while the northwestern and northeastern areas have moderate transmissivity (Figure 6). According to [23], "areas with high transverse resistance indicate areas with high transmissivity". Hence, suitable aquifers can be explored in these areas. From the ranking of [26] transmissivity standard, the computed aquifer transmissivity is intermediate (10 – 100 m^2/day) and is capable of supplying water to communities and plants.

The aquifer protective capacity (vulnerability) was evaluated from the computed longitudinal conductance value S (Table 3) and according to [27] classification. From [27], given as < 0.1Ω m (poor), 0.1 – 0.19 Ωm (weak), 0.2 – 0.69 Ωm (moderate), and using the Dar – Zarrouk parameters, the aquifer protective capacity computed ranged from 0.0152 – 0.2967 Ω^{-1}, implying a poor, weak to moderate protective capacity. The longitudinal conductance map (Figure 7) indicates that the southeastern part has poor protective capacity, while the northwestern part indicates weak to moderate aquifer protective capacity. Fifty percent of the VES locations (VES 1, 3, 4, 7, 8, 10, 13, 18, 19, 20) showed poor protective capacity. Forty percent of the VES locations (VES 2, 5, 6, 9, 11, 12, 14, and 16) showed weak protective capacity, while ten percent of the VES locations showed moderate capacity against contamination. The basement rock fracturing and the insufficient clays cannot offer enough protection to the aquifers. Though they possess low storage potential, the fractured basement aquifers are less vulnerable to contamination than weathered basement aquifers. Again, due to the unconfined nature of the aquifer, the protective capacity is dominantly poor, making it vulnerable to contamination in the event of the release of contaminant in the area. This is why it is imperative to conduct a hydrogeochemical study of the groundwater to ascertain the groundwater quality.

Table 3: Aquifer parameters estimated from resistivity sounding data

VES Station	p (Ωm)	h(m)	S (Ω^{-1})	R (Ωm^2)	σ (Ω^{-1})	K (m/day)	Kσ	Tc (m^2/day)
1	930	14.2	0.0153	13206	0.001075	1.05	0.001129	14.91
2	147	25.3	0.1721	3791	0.006803	1.05	0.007143	27.08
3	302	21.6	0.0721	6523	0.003311	1.05	0.003477	22.68
4	299	29.5	0.09887	8821	0.003344	1.05	0.003511	30.97
5	389	44.3	0.1139	17233	0.002571	1.05	0.002700	46.53
6	142	15	0.1056	2130	0.007042	1.05	0.007394	15.75
7	88	4.8	0.0545	422	0.011364	1.05	0.011932	5.04
8	288	10.4	0.0361	2995	0.003472	1.05	0.003646	10.92
9	126	25.0	0.1984	3150	0.007937	1.05	0.008334	26.25
10	2200	33.4	0.0152	73480	0.000455	1.05	0.000478	35.12
11	77	11.1	0.1442	855	0.012987	1.05	0.013636	11.66
12	82	11.5	0.1402	943	0.012195	1.05	0.012804	12.07
13	166	15.1	0.0910	2507	0.006024	1.05	0.006325	15.86
14	159	18.1	0.1138	2878	0.006289	1.05	0.006603	19.00
15	60	17.8	0.2967	1068	0.016667	1.05	0.017500	18.69
16	60	7.5	0.1250	450	0.016667	1.05	0.017500	7.88
17	34	7.2	0.2118	245	0.029412	1.05	0.030883	7.57
18	38	3.0	0.0789	114	0.026316	1.05	0.027632	3.15
19	460	19.9	0.0433	9154	0.002174	1.05	0.002283	20.90
20	238	16.8	0.0706	3998	0.004202	1.05	0.004412	17.64
Average		**17.58**						**18.48**

VES=Vertical electrical sounding; p=aquifer resistivity; h= aquifer thickness;σ=aquifer electrical conductivity; S = aquifer longitudinal conductance; R= aquifer transverse resistance; K=hydraulic conductivity from pumping test; $K\sigma$=constant;T_{C}= computed transmissivity

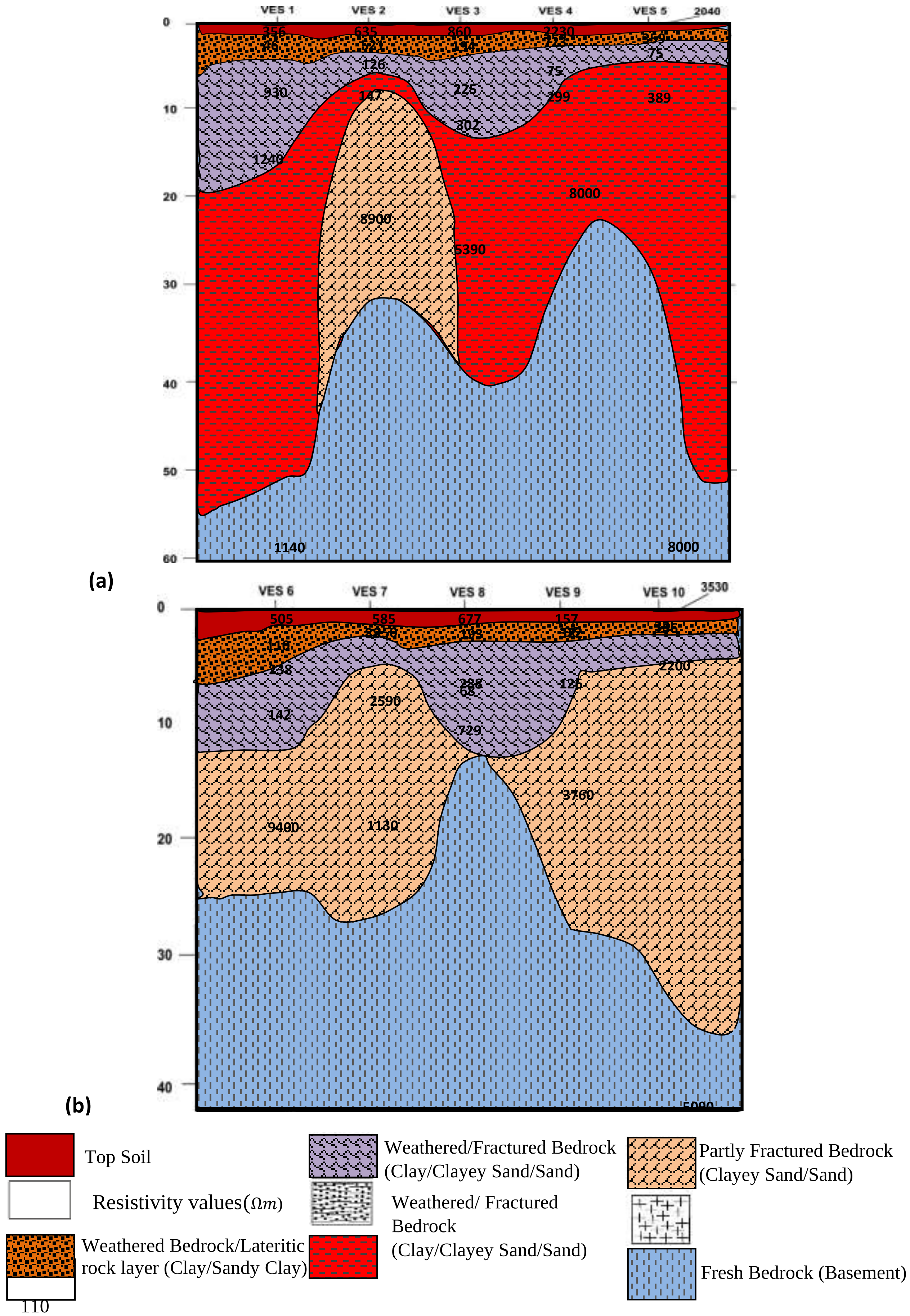


Figure 3a – 3b: Geoelectric Section along traverse 1 and 2

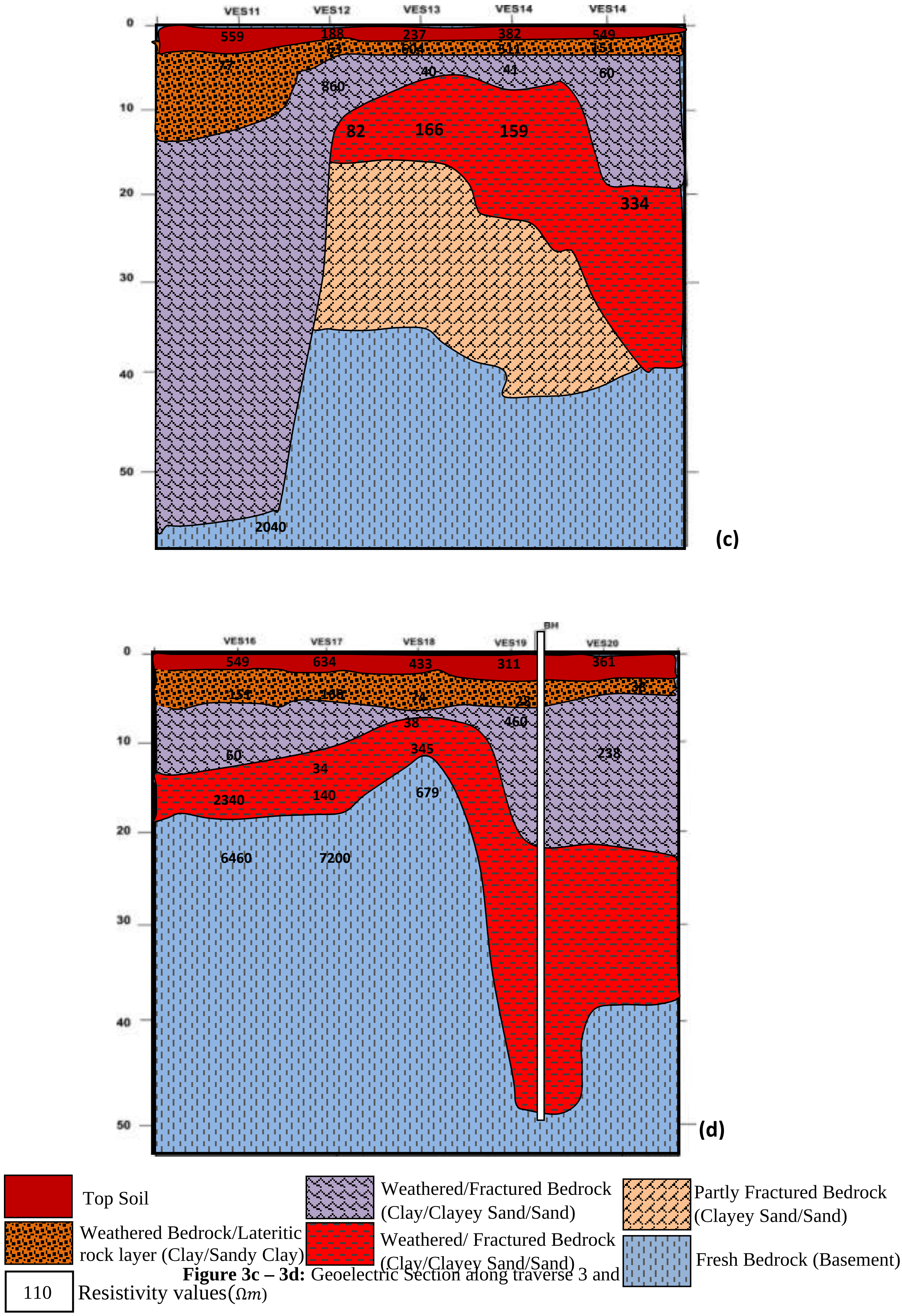


Figure 3c – 3d: Geoelectric Section along traverse 3 and

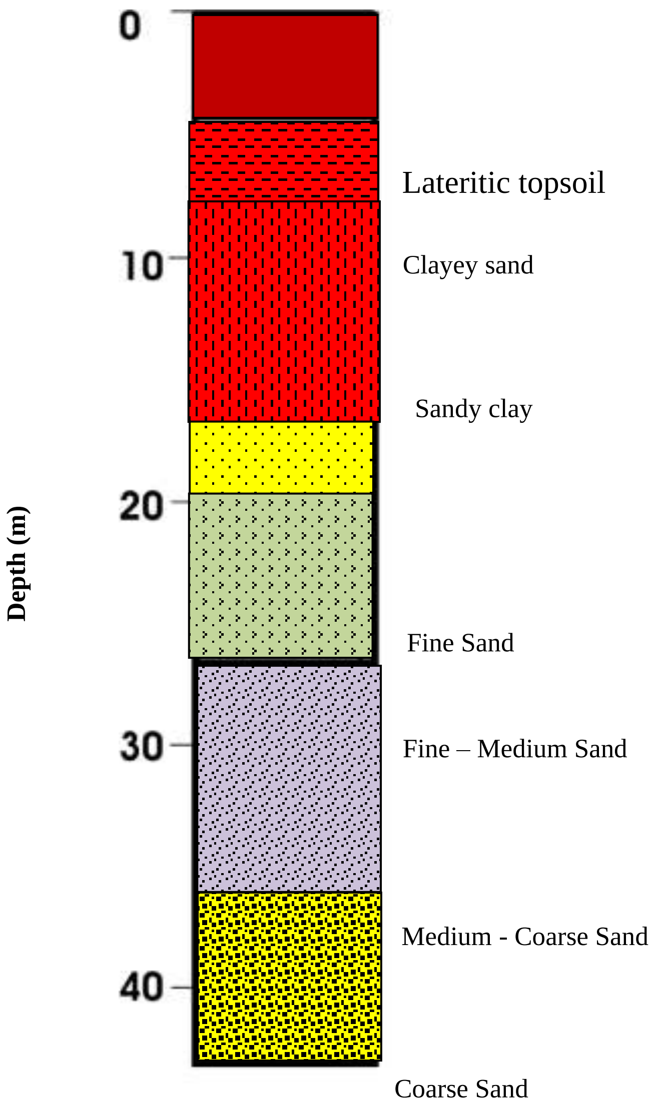


Figure 4: Borehole lithologic log of Igarra, courtesy [16]

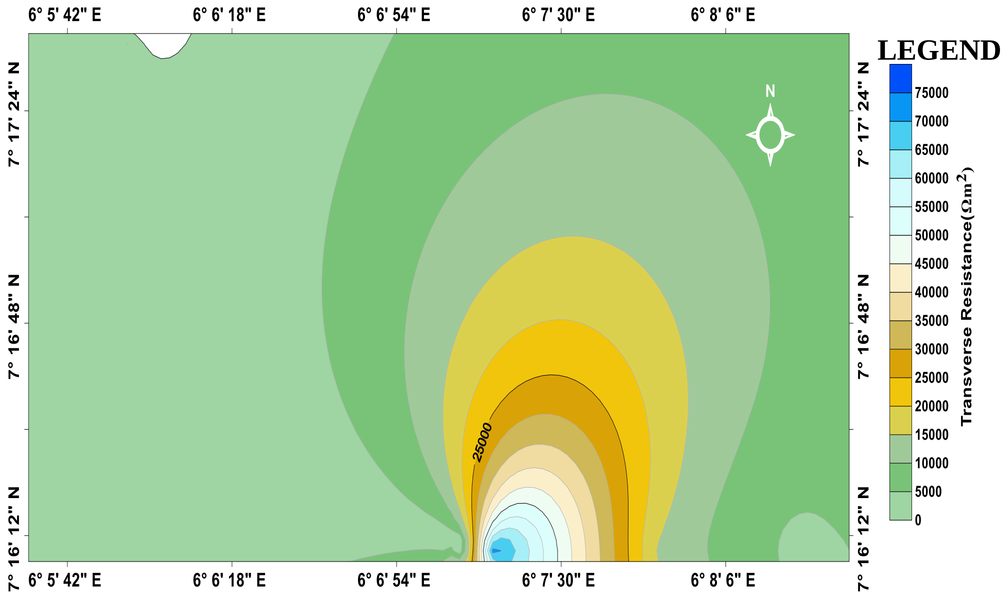


Figure 5: Aquifer transverse resistance map

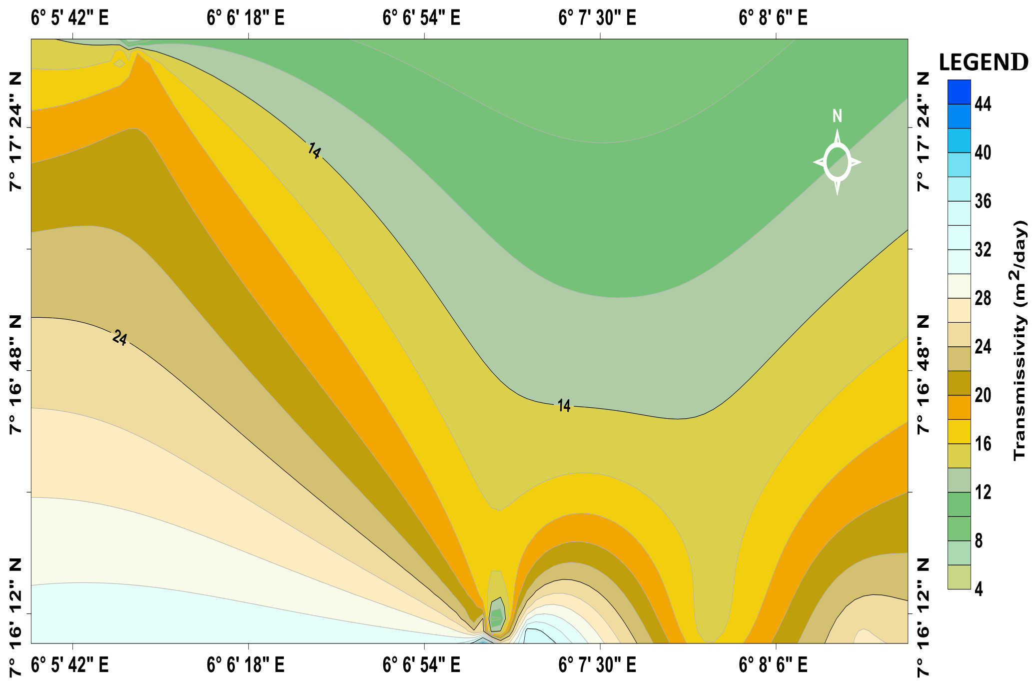


Figure 6: Aquifer transmissivity map

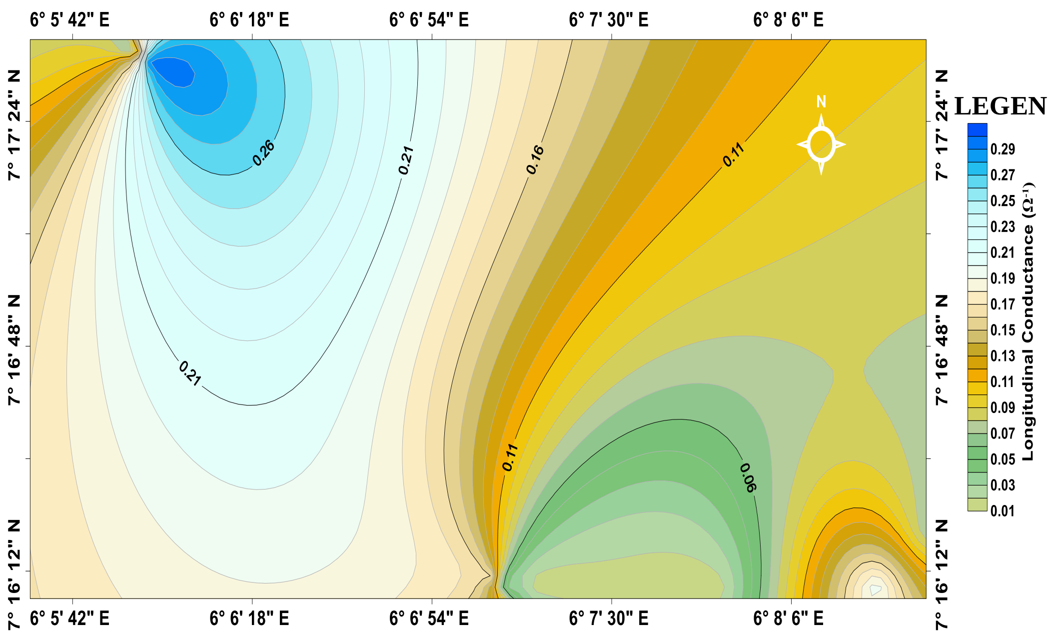


Figure 7: Longitudinal conductance map

Conclusion

This study has helped delineate the aquifer transmissivity and basement structure of Igarra, SW Nigeria, by applying resistivity-sounding data. The resistivity-sounding result revealed four to six geoelectric layers that comprised topsoil, lateritic soil, weathered basement, fractured basement, partially fractured basement and fresh basement. The resistivity of the weathered layer ranged from 28 – 2810 Ωm, while the fractured zone resistivity ranged from 33 - 3340 Ωm. The VES result revealed that the depth to the basement (basement structure) is undulating, with the weathered basement and the fractured basement constituting the shallow and deep aquifers, respectively, at different depths. The two delineated aquifers have a thickness range of 0.7 –

44.3 m and aquifer depths of 2.4 – 53.8 m. This implies that areas with deeper basement depths have thicker weathered, and fractured layers, respectively. An average computed transmissivity value of 18.48m^2/day was delineated. This value obtained is believed to be adequate and could provide sufficient groundwater pressure to the Igarra people. Thus, establishing a water scheme that will provide enough potable water to the people of IPBC is hereby advocated. These areas will provide suitable groundwater material (aquifer) that can be explored. Furthermore, the aquifer protective capacity values computed ranged from 0.0152 – 0.2967 Ω^{-1}. These values imply a poor, weak and moderate aquifer protective capacity, making it vulnerable to contamination. This study will provide a veritable tool for sustainable groundwater exploration in Igarra.

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